POLITYKA ENERGETYCZNA – ENERGY POLICY JOURNAL

2025 ✦ Volume 28 ✦ Issue 1 ✦ 33–54

DOI: 10.33223/epj/193725

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Development of waste-free technology for processing of all types of limestone waste using solar energy

Abstract: In light of growing environmental concerns and the gradual depletion of conventional energy sources, the development of an efficient technology to process all types of limestone waste using solar energy becomes a crucial step towards a sustainable and environmentally friendly industry. The purpose of this study was to create an innovative technology that can efficiently process various limestone wastes with minimal environmental impact and utilize solar energy as the primary energy source. The study used data on geographical coordinates, solar radiation, hours of sunlight, radiation, climate, and lighting conditions of the Republic of Kazakhstan to assess the potential of solar energy and its impact on the radiation balance and climatic conditions of the country. The creation of innovative technology for processing limestone waste to produce a new building material will reduce the cost of stone extraction, minimize waste accumulation, and improve the environmental situation. This is achieved by optimizing the processing using solar energy, which contributes to the environmental sustainability of production and reduces the consumption of fuel and energy resources in concrete production. The study involved both theoretical and practical

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experiments to optimise the technological processes of limestone waste processing using solar energy. Furthermore, the environmental conditions of the quarries and solar energy resources were analyzed for the application of solar technology.

Keywords: resource analysis, direct radiation, coquina, heliostructures, rock

Introduction

Modern industry is faced with an increasing amount of waste that not only harms the environment but also requires considerable resources to treat and dispose of. In recent years, the energy sector has undergone notable shifts towards sustainability, driven by global initiatives to reduce greenhouse gas emissions and reliance on fossil fuels. A significant aspect of this transformation is the increasing adoption of renewable energy sources, with solar energy assuming a pivotal role in sustainability policies. Solar energy is in accordance with these global trends, offering a clean and abundant energy source that facilitates the transition towards a more sustainable and environmentally responsible future. This study examines the role of solar energy in limestone waste processing in achieving these overarching goals, with a particular emphasis on the relevance of such technologies within the context of the global renewable energy movement. At the same time, energy systems are increasingly switching to renewable energy sources, such as solar power, to reduce dependence on dwindling natural resources and reduce carbon emissions. The research and development of efficient technologies for processing limestone waste using solar energy will not only help to reduce the adverse environmental impact and waste disposal costs but also promote the development of sustainable production methods, which is essential for future environmental sustainability and energy security.

The problem of the study lies in the inefficiency of the existing methods of limestone waste processing from the standpoint of their impact on the environment and economic feasibility. Underdevelopment of efficient technologies leads to the accumulation of large volumes of waste, environmental pollution, and unnecessary expenditure of resources for its treatment and disposal (Syrlybayev et al. 2016; Floqi et al. 2009). The need to reduce dependence on conventional energy sources in production processes is also a prominent issue, which emphasizes the relevance of the research in the context of the transition to sustainable production methods and energy efficiency.

The study conducted by Kolesnikova et al. (2023) emphasizes the significance of the use of renewable energy sources to reduce the adverse environmental impact of limestone waste treatment. The study does not consider the effectiveness of new methods and processes for processing limestone waste to produce building materials. Bek et al. (2022) emphasize the practical aspects of implementing limestone waste processing in the industry, identifying economic benefits and opportunities to reduce production costs. The researchers do not explore the potential barriers and constraints to the introduction of new waste treatment technology that may affect the reduction of quarry production costs.

Zhakupova and Tsygulev (2023) propose innovative approaches to waste treatment based on the use of solar energy and evaluate their potential for the creation of innovative building materials. Their study emphasizes the significance of continued research to determine effective methods of preventing the accumulation of limestone waste during extraction and processing. Ospanov et al. (2023) consider the environmental consequences of quarries and possible ways to mitigate them through the use of effective methods of waste treatment. The environmental impact of the new technology needs to be investigated in greater detail, including analyzing its impact on biodiversity and water resources.

Shakulikova and Akhmetov (2021) emphasize the available solar energy resources and their applicability to provide waste treatment processes, highlighting the key areas of research in this field. The study does not address the determination of optimum parameters and conditions for optimizing limestone waste treatment processes using solar energy. Nurmanova et al. (2024) raise a critical question about the technical aspects of integrating solar energy into production processes, describing the technological solutions and engineering innovations required for the effective implementation of this approach. The study does not consider the extent to which theoretical and experimental research is applicable to real-world production conditions and what limitations their implementation may have.

The purpose of this study was to create a new technology capable of efficiently treating various types of limestone waste with minimal negative environmental impact, using solar energy as the principal energy source. Beyond the primary objective of this study, the following tasks are defined:

1. To optimize the parameters of the solar energy-based processing of limestone waste to maximize efficiency.
2. Assess the environmental benefits of using solar energy to reduce carbon emissions and waste accumulation.
3. Evaluate the cost-effectiveness of implementing solar energy in the industrial processing of limestone waste.

1. Materials and methods

The geographic coordinates of the Republic of Kazakhstan lie within 40–50 degrees North latitude and 70–80 degrees East longitude. The average summer solar irradiation power varies from region to region. In the south and west (Shymkent, Aktau, Uzen), it ranges within 215––250 W/m^2, and in the central part (Atyrau, Kyzylorda, Taraz, Almaty) – within 125–215 W/m^2. In other words, southern and western regions receive more sunlight than central regions. The difference in solar irradiation power between regions can be as high as 100 W/m^2. It is important to consider this when calculating the potential for solar energy utilization in different parts of the country. The maximum power of solar radiation reaching the Earth can be 1 kW/m^2. The number of hours of sunlight during the year varies in different regions of the Republic of Kazakhstan: from 2,050 h in the north to 3,000–3,080 h in the south. Most of the area is characterized by high hours of sunshine, sometimes reaching up to 3,200 h in the southern regions. The data analysis suggests that throughout the year, the highest total and direct radiation occurs in July, reaching about 4,700 kcal/m^2 per day, while the minimum value is observed in December (Fig. 1). In summer, the difference between the maximum and minimum amount of total radiation can reach 500–700 kcal/m^2 per day. The difference in the amount of direct radiation can be even more significant. Because of these variations in the amount of radiation, the peaks of total and direct radiation may shift in different years.

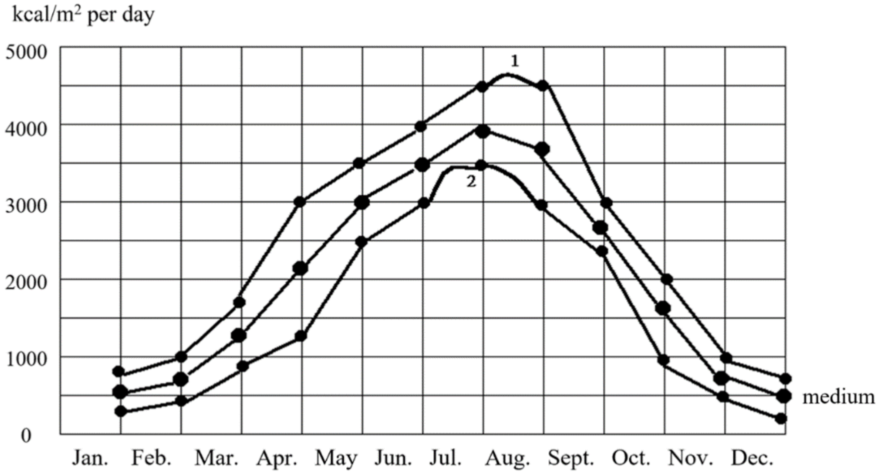

Fig. 1. Values of direct radiation (daily average)
1 – peak values; 2 – minimum values
Source: compiled by the authors of this study

Rys. 1. Wartości promieniowania bezpośredniego (średniodobowe)

In the Mangistau region, for eight or more months, there is a positive radiation balance reaching its maximum in June–July and decreasing from north to south due to the increase of reflected radiation in desert areas. This area experiences more extreme lighting conditions than others. The study of total solar radiation on the horizontal surface shows that the highest values are observed in the territory adjacent to Turkmenistan, reaching 2,500 kW/m^2. At the same time, in the mountainous areas of the Mangistau region, they are 1,605 kW/m^2. An important feature of solar radiation as an energy source is its uncontrollable natural character. Mangistau region, located in the desert zone, has a harsh climate with a lack of moisture and high evaporation (1,200 mm/year). Precipitation is low (140–200 mm/year). Despite its moderate latitude (42°N), the lack of forests and low cloud cover ensure high levels of solar irradiation (up to 9–10 kW/day). Summers are hot and dry, with maximum air temperatures of up to 47°C in July. In winter, temperatures can drop to –38°C. The difference between the average lunar temperatures for the year is 28–28°C (Fig. 2). Strong winds (up to 6.4 m/s) blow almost every month, mainly from the south-east. The period with air temperature above 21°C lasts about 100 days a year.

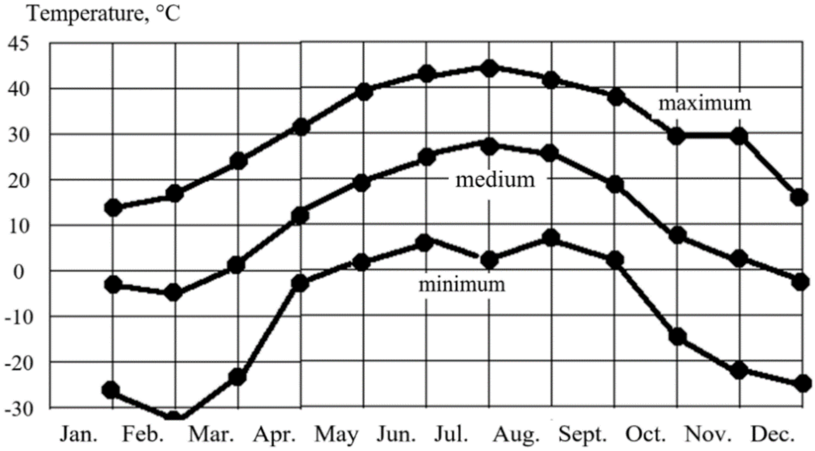

Fig. 2. Visualization of monthly average temperature dynamics at Kyzan meteorological station
Source: compiled by the authors of this study

Rys. 2. Wizualizacja miesięcznej dynamiki średniej temperatury na stacji meteorologicznej Kyzan

The following equations helped to describe heat transfer processes in different media and materials and to accommodate various factors such as heat transfer coefficients, temperature gradients, and material density:

$$q_r = q^+ - q^- \tag{1}$$

where:

q_r – radiation flux density,
$q+$ – effective flux density coming from the Sun,
q^- – scattered flux density falling on the irradiated surface.

$$q^+ = \int_0^{2\pi} \int_0^{\pi/2} I^+ (\theta, \varphi) \cos\theta \sin\theta d\varphi \tag{2}$$

where:

I^+ – radiation power incident per unit area and unit solid angle, provided that the vector I^+ coincides with the normal to the transparent surface.

$$q^- = \int_0^{2\pi} \int_0^{\pi/2} I^- (\theta, \varphi) \cos\theta \sin\theta d\varphi \tag{3}$$

Formula (1) demonstrates the decomposition of the radiation flux into two components. Formulas (2) and (3) combine in $d2$ and Ω, expressed as the effective flux density through the transparent surface, factoring in I+. Under conditions of medium atmospheric cloudiness, diffusely scattered radiation leads to the symmetry of the total solar radiation values in the actinometric tables (Moreno-SanSegundo et al. 2022). The intensity of direct solar radiation to the perpendicular surface, denoted as I_0, is assessed by an actinometer at meteorological stations on clear days with medium cloud cover.

2. Results

2.1. Geographical division of solar energy potential in Kazakhstan

The Republic of Kazakhstan's territory is divided geographically with regard to solar energy in latitudinal directions, which leads to the allocation of southern, central, and northern areas. Clearly, the southern regions are the most promising for the use of solar energy. For instance, the Mangistau region has considerable solar energy potential that can be applied to industry and households. The average annual temperatures in the Western and Southern regions are almost identical, making these regions even more attractive for solar energy development.

The probability of exceeding the average annual solar activity level by more than 50% during the period from October to March (Fig. 2) indicates the potential efficiency of solar energy utilization for various industrial purposes, such as thermal treatment of concrete and other applications in this region of Kazakhstan. The degree of optimality in the design and implementation of solar energy systems depends mainly on the level of solar radiation. A study of Kazakh methods for calculating solar radiation intensity shows that most of them are tied to the concrete conditions of a particular geographical area and are required to apply extensive climatological data (Kolesnikova et al. 2023; Bek et al. 2022; Zhakupova and Tsygulev 2023; Ospanov et al. 2023; Shakulikova and Akhmetov 2021; Nurmanova et al. 2024). This factor causes significant difficulties in the design and optimization of solar thermal systems. Climate handbooks provide tables containing monthly averaged values of Io (solar radiation intensity) at one-time intervals. These tables are based on the processing of data obtained over a multi-year period to estimate the average intensity of solar radiation in a particular month.

2.2. Analysis of solar radiation intensity and its impact on limestone waste processing

Analysis of solar radiation intensity shows a direct correlation with the efficiency of limestone waste treatment. Regions such as Mangistau, which have high levels of solar radiation throughout the year, are particularly suited to the use of solar energy. The ability to achieve consistent and high levels of irradiation helps to reduce energy costs and dependence on fossil fuels, making solar energy a sustainable option for large-scale limestone waste treatment.

The environmental impact of limestone waste is significant, particularly in terms of biodiversity and air quality. The improper management of limestone waste can have a detrimental impact on local flora and fauna, leading to alterations in habitats and the disruption of ecosystems (Buzhyn 2023). Furthermore, fine particles from limestone waste contribute to air pollution, particularly in regions with high winds, which results in reduced air quality and adverse health effects for nearby populations. It is thus imperative to take into account the ecological and atmospheric consequences of limestone waste when formulating waste management strategies.

An analysis of the total values of direct solar radiation to the perpendicular surface in the actinometric tables for the annual cycle at the accurate solar time showed that in some months, there is a symmetrical distribution of these values, while for other months, there is no such symmetry. For instance, for Ashgabat, such symmetry is observed in all months with clear weather. At the same time, for the Mangistau region, the sums of direct solar radiation are symmetrical in most months, except for January and May, indicating a considerable number of sunny days in this region. When strict fuel and energy conservation measures are particularly relevant, the use of solar radiation in energy-intensive technologies becomes a necessity (Rahman et al. 2022; Vyshnevska et al. 2022). Mangishlak quinoid limestone, which is a rock of biogenic origin, is a valuable material for construction. Its extraction is one of the energy-intensive industries (Babak et al. 2005).

An analysis of solar radiation patterns reveals that, in some months, solar radiation is symmetrical, whereas in others, this symmetry is absent. Such variation can be attributed to seasonal alterations in climatic conditions, which affect cloud cover, atmospheric transparency, and solar angles. For example, symmetrical distributions are frequently observed during the summer months, when weather conditions are relatively stable. Conversely, asymmetrical distributions are more prevalent during the transition periods between seasons, which are characterized by greater meteorological variability.

Due to the significant fracturing of the rocks, when they are sawn in quarries, large quantities of waste are generated, often amounting to more than half of the total output (Ondo Zue Abaga et al. 2023). The process of extraction and processing of coquinoid limestone at the deposits of the Mangistau region leads to the formation of significant volumes of waste. When individual blocks are extracted, their share can be as high as 60% and 75–80% when pulverizing slabs and large blocks. To date, about 2 million tonnes of such waste have been accumulated, which requires the allocation of vast areas for their storage. The remaining waste, such as fine cuttings and sawdust, is removed from the mining sites to dumps, which results in added costs and atmospheric pollution during high winds when the dust becomes suspended by air currents (Jain et al. 2023). Lime dust containing calcium oxide (ranging from 46.12–53.21%) and magnesium oxide (1.08–11.34%) is a serious environmental problem for local residents and residential areas. On contact with water, this dust forms hard crusts of calcium hydroxide ($Ca(OH)_2$) or calcium silicates ($3Ca \cdot SiO_2$) on the surface of plants; these particles prevent air infiltration and disrupt the gas exchange processes that are essential for healthy plant growth and photosynthesis. Exposure to dust with calcium origins can have a variety of effects on different aspects of life.

Currently, there is no unified approach to assessing and forecasting the use of reserves of each natural resource, considering the factual demand and environmental consequences of their depletion (Compernolle et al. 2023). Since mineral resources are not reproducible, depletion of their reserves requires digging deeper into the Earth's interior. The efficiency of quarry sawstone extraction mainly depends on the thickness, density, and strength of the rock mass. Let us suppose that at a certain point in time (t), a coquinoid limestone quarry has a limestone resource (k). The increase in limestone production (x) will be proportional to the quality of the available raw material (Δx-ah). There is the potential for a reduction in the extraction of coquinoid limestone with a concomitant increase in the amount of waste generated due to rock fracturing, which is often observed in quarries producing low-strength raw materials. This fact can be interpreted as a proportional increase in the square of available raw material stocks (Δx-ax^2). In differential form, the condition of change in the volume of coquinoid limestone mining is described by Formula (4):

$$\frac{dx}{dt} = kx - ax^2 \tag{4}$$

Consequently, given the decline in quarry productivity as a function of time and the impact of natural factors, there is a need to develop and implement technologies in mainstream production to help restore profits. Recovery of previous income levels in the future can be achieved through efficient waste recycling that does not affect the quality of output.

2.3. Application of zero-waste technology in industrial processing

To reduce the volume of waste in the primary production at coquinoid limestone quarries, it is advisable to develop and implement waste-free and integrated technologies. In this case, all components of raw materials and energy will be used rationally in a closed cycle, preserving the existing ecological balance (Fidanchevski et al. 2022). The environmental and economic efficiency of the waste treatment process is determined by the ratio between the volume and value of waste treated, as well as the cost of treating each tonne of waste (5). The reduction of waste in limestone mining is achieved by the integrated processing of all types of waste from this process using zero-waste technology, which produces a new building material.

$$E = \frac{\sum_i V_i}{\sum_k P_k d_k} \tag{5}$$

where:

E – environmental and economic efficiency of waste processing,

V_i – annual volume of processed waste of the i-th type,

P_k – price of resources for processing of waste of the i-th type,

d_k – consumption of resources for processing of waste of the i-th type.

The waste-free recycling process in the primary production of coquinoid limestone quarry seeks to provide two main aspects (Almadani et al. 2022). This complex process of processing raw materials involves the use of all its components and various waste streams to minimize the amount of discarded materials and make efficient use of resources. This strategy also focuses on the development and production of new products and materials with the possibility of reusing them. This not only reduces waste but also turns it into valuable resources, contributing to environmental sustainability and economic efficiency of production. A new approach to the recycling process is being introduced to improve the efficiency of all types of waste, including those that are not typically used in construction. This method is based on the use of transparent helio coating for the thermal treatment of carbonate concretes and bentonites using solar energy in the energy balance of the plant. The process of producing concrete, which is a basic building material, requires considerable consumption of fuel and energy resources, mainly in the form of low-potential heat (Selvakumar et al. 2024; Palianytsia et al. 2014). To heat and thermally treat concrete, according to calculations, between 209 and 230 thousand kJ are needed. However, when heat losses to the environment are considered, the standard consumption for heat treatment of products in pit chambers ranges from 691–733 thousand kJ.

It was found that to reduce the consumption of fuel and energy resources required for the heat treatment of limestone products, it is necessary to revise the methods of their production by introducing processes that utilize solar energy. Notably, the thermal energy required to achieve the desired temperature regime of plasticized concrete is mainly dependent on the effects of heat radiated from the surrounding space, as well as heat released during exothermic reactions of cement, which accounts for up to 50% of the total heat. To assess the environmental feasibility of a particular technological solution, a range of key parameters are analyzed, including raw material and energy efficiency, natural resource utilization, and the level of environmental impact (Ikram et al. 2021; Pona and Ouedrago 2023). The formulation of the introduction of solar energy process into concrete production technology can be expressed in the following mathematical formulation:

$$\sum_i \sum_j x_{ij} \cdot g_{ijn} < B_n \tag{6}$$

where:

x_{ij} – expected production volume of the i-th product using the j-th process scheme,

g_{ijn}– specific energy consumption or change in energy for type *n* in case of process introduction,

B_n – energy consumption for thermal treatment of concrete before process introduction.

The direct exposure of curing concrete to solar radiation results in considerable heat transfer, which can cause local condensate accumulations in the form of small puddles and drops on the surface of the product (Yu et al. 2023; Lyubchyk et al. 2015). The size and number of such clusters depend on the heating intensity, mainly determined by the temperature difference. During the heating phase, when the temperature peaks at about 76% for 16 h, heat exchange takes place within the material, both on the surface of the product by sunlight and from below, at its base, due to heat conduction and heat transfer by moisture penetrating the pores of the material. In this case, the first method of heat transfer plays an important role. Concrete products, especially polymer-cement compositions, with a high open surface modulus are particularly at risk. Despite the general tendency for strength to decrease in concrete and polymer concrete, in this case, the increase in strength is proportional.

During the heat treatment of the concrete under the solar coating, the air contained in the pores of the material expands in proportion to the increase in its temperature, which can lead to a partial release of air into the environment (Fig. 3). The increase in air volume due to temperature rise is negligible. For instance, when air temperature changes from 20°C to 80°C, its specific volume increases by merely 20%, from 0.854–1.09 m^3/kg. Most limestone concrete and bentonite products have lengths and widths more extraordinary than their thicknesses, which

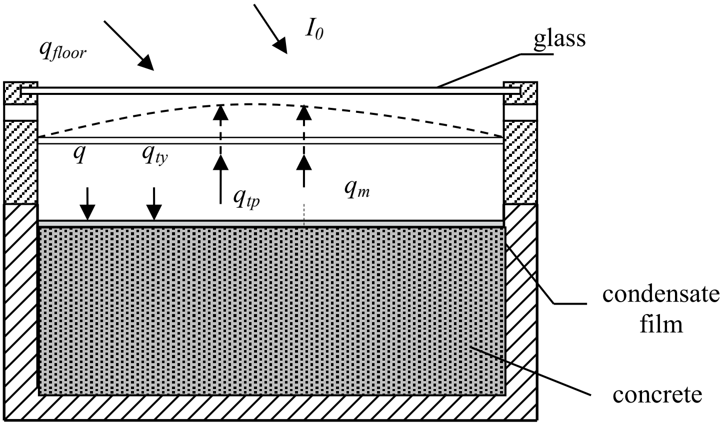

Fig. 3. Scheme of thermal processes under heliocoating

Note: I_0 – flux density of radiant energy falling on a surface element of area AS at point M, which is called solar radiation intensity; q – heat flux from the surface to the inside of concrete; q_{ty} – moisture flux caused by the difference in moisture content; q_{tp} – moisture flux caused by the difference in temperature; q_m – moisture flux caused by the difference in pressure

Source: compiled by the authors of this study

Rys. 3. Schemat procesów cieplnych pod powłoką helio allows them to be considered unbounded plates with a one-dimensional temperature distribution inside. The amount of heat received by the product during the various stages, such as heating and isothermal temperature equalization, both from the top surface facing the helio coating Q_0 and from the surface near the bottom Q_D, depends on the ratio R'_1/R'_2. In the thermal double-sided concrete treatment process based on heat transfer from storage tanks for 16 h, asymmetrical heating occurs. However, this has a negligible effect on the curing process of products up to 200 mm thick.

In asymmetric heating, the heat penetration depth R is defined as the result of multiplying the heating asymmetry factor (χ) by the thickness of the product towards the heat flux (S). The value of the coefficient χ is used to estimate both the heating asymmetry from the top surface (χ'_1) and from the bottom of the mold (χ'_2) and is calculated using the corresponding Formula:

$$\chi'_1 = \frac{R'_1}{R_1} + R_2 \tag{7}$$

where:

χ'_1 – estimate of the heating asymmetry from the top surface,
R'_1 – depth of heat penetration through the translucent coating.

$$\chi'_2 = \frac{R'_2}{R_1} + R_2 \tag{8}$$

where:

χ'_2 – estimate of the heating asymmetry from the bottom of the mould,
R'_2 – depth of heat penetration through the bottom.

By accounting for compressive stresses caused by temperature gradients in the product, an equation for thermal processes describing the temperature boundary conditions at the top and bottom surfaces of the product can be derived. The dynamics of the temperature change of the heated product are not solely due to the rate of temperature increase of the surrounding vapor-air medium. This is explained by the complex regularities of external heat and mass transfer, which depend on many factors, making it challenging to analyze. Consequently, the most reasonable approach is to represent the rate of change of vapor-air medium temperature b as a linear function (9):

$$R = R_0 - \alpha b \tag{9}$$

where:

R – depth of heat penetration,
R_0 – distance to which the heat penetrates at the initial moment of time of the product heating process;
b – rate of temperature change under the transparent coating.

When the product is exposed to heat on both sides, the distance R to which heat penetrates is equal to half the thickness of the product minus the depth of heat penetration on one side R'_1 and the other side R'_2. In this context, an equation for the solidification process of a product under asymmetric heating may be formulated as follows:

$$\frac{dR}{dt} = \varphi_1(t)(\chi'_1 + C_1 R'_1) S_1(0) = 0 \tag{10}$$

where:

$\varphi_1(t)$ – dimensionless function of the rate of change of the top layer temperature,
C_1 – constant coefficient specific for given types of concrete and heat treatment conditions for the top layer at two-sided treatment,
α = 91,
S_1 – value of the change of the top surface thickness towards the heat flux.

$$\frac{dR}{dt} = \varphi_2(t)(\chi'_2 + C_2 R'_2) S_2(0) = 0 \tag{11}$$

where:

$\varphi_2(t)$ – dimensionless function of the rate of change of the bottom layer temperature,
C_2 – constant coefficient specific to the given types of concrete and heat treatment conditions for the bottom layer in two-sided treatment,
α = 91,
S_2 – value of the change in the thickness of the bottom surfaces towards the heat flux.

The heating kinetics of coarse-grained concrete is substantially different from the heating kinetics of dense limestone concrete in this context. When limestone concrete is heated through its open-top surface, the amount of heat input is 1.5 times higher than the heat input from the lower closed surface, while this ratio for coarse-porous concrete reaches already 9. Porous concrete heats up almost 3 times faster, even though heat transfer through the lower closed surface plays a minor role. With two-way heating, both the upper and lower layers receive approximately the same amount of heat over the course of a day, as do the central zones of the concrete. The maximum temperature difference across the thickness of the specimen when it is heated is 25°C. The maximum rate of temperature rise for the surface layers is 13°C/h, and for the underlying layers, it is 7°C/h.

Compared to the conventional approach, heat treatment of limestone concrete with the addition of plasticizing components uses significantly less heat (1,680 kJ/kg). Up to 50% of the heat used to warm concrete comes from an internal source – the exothermic reaction of cement. The use of heliocoating reduces heat losses by reducing moisture evaporation, $CaCO_3$ dissociation, and liquid phase formation, as well as by reducing the modulus of the exposed surface. The study of the shrinkage curves of bentonite revealed the following characteristics (Fig. 4). Unlike heavy concrete, bentonite shrinkage is more rapid and reaches stability faster.

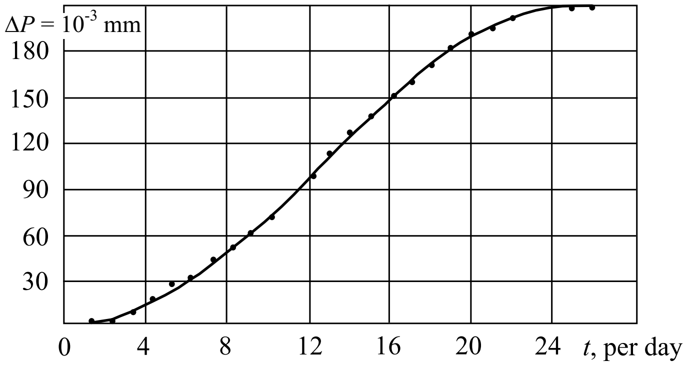

Fig. 4. Diagram of bentonite shrinkage during drying process
Source: compiled by the authors of this study

Rys. 4. Wykres skurczu bentonitu podczas procesu suszenia

The nature and rate of bentonite shrinkage depend significantly on the limestone aggregate used, which, furthermore, varies its properties depending on the level of water saturation, which affects its ability to expand and shrink. During the formation and curing of concrete, volumetric changes in the gel structure of cement occur due to the gradual evaporation of excess water and interaction with the water absorbed by the cement grains during hydration. When water is removed from the gel, it compacts, and the water remaining in the structure causes the gel particles to shrink, which is the cause of concrete shrinkage. Furthermore, the limestone microfilter can interact with the alumina-containing components of Portland cement clinker C3A and C4AF to form calcium carbo aluminate, which is substantially different from the parent minerals and affects the shrinkage and creep of concrete. C4AF, being a gel-forming mineral, transforms into new compounds such as 3CaO, Al_2O_3, $6H_2O$ (crystalline aggregate), and CaC, Fe_2O_3, nH_2O (gel) during hydration, which also contributes to shrinkage and creep of concrete. The interaction of C4AF with carbonate microfilter probably reduces the total amount of gel in the cement material, which entails a reduction in bentonite shrinkage.

A new technology for thermal treatment of concrete, based on the use of carbonate aggregates from waste materials, aims to save fossil fuels by replacing conventional fuel-fired thermal units and reduce emissions into the atmosphere.

The results demonstrate the feasibility and environmental benefits of using solar energy to process limestone waste. The technology not only significantly reduces the environmental footprint but also proves to be cost-effective. These results support the initial hypothesis that solar energy can serve as an efficient and sustainable alternative for industrial waste processing.

3. Discussion

The development of a zero-waste technology for processing all types of limestone waste using solar energy is a major area of environmental sustainability and resource efficiency. This research has attracted attention due to its potential to reduce waste, reduce environmental impact, and improve energy efficiency of production processes.

3.1. Utilization of solar energy in limestone waste processing

One of the key aspects of this technology is the utilization of solar energy as a renewable energy source. Solar energy can be efficiently utilized in various processing steps such as heating and drying, reducing dependence on conventional energy sources such as fossil fuels. The advantages of such technology are clear. It contributes to waste reduction as all raw material components can be recycled rather than sent to landfills. This also reduces the need for extensive land for their storage. The use of solar energy helps reduce greenhouse gas emissions and other pollutants, which improves the quality of the environment (Abdibattayeva et al. 2020). However, there are some challenges and limitations to consider when developing and implementing such technology. It is important to ensure that such solutions are economically viable and competitive.

Furthermore, the reliability and efficiency of solar systems must be ensured, especially when the weather is variable. Overall, the development of a zero-waste technology for processing all types of limestone waste using solar energy is a promising area that can bring significant environmental and sustainability benefits. Further research and innovation in this area will be essential for future generations.

The distribution of solar radiation, whether symmetrical or asymmetrical, has a direct impact on the efficiency of solar energy systems employed in limestone waste processing. The presence of symmetrical radiation patterns, which are typically observed during periods of stable weather, allows for a more consistent energy collection, thereby optimizing the efficiency of the proposed technology. In contrast, asymmetrical radiation patterns, which occur in months with variable weather, can result in fluctuations in energy availability, necessitating the implementation of adaptive strategies to ensure the continuous operation of waste processing systems. These variations must be taken into account during the design and optimization of the technology in order to guarantee its ability to perform efficiently under a range of solar conditions.

3.2. Seasonal variations and system optimization

The analysis of solar radiation and temperature data is of paramount importance in the design and optimization of the proposed waste processing technology. The combination of high levels of solar radiation and elevated temperatures during the summer months enables the system to operate at peak efficiency, as the technology relies on consistent and intense solar energy input. However, during periods of reduced solar radiation or temperature fluctuations, the system must be adjusted to ensure optimal efficiency. This may entail the incorporation of supplementary thermal storage systems or hybrid energy solutions, with the objective of ensuring the stability and efficacy of the waste treatment processes on a year-round basis (Sadykov et al. 2024).

Recent studies by Taha et al. (2021) highlight the urgent need for zero solid waste in the treatment of sedimentary phosphate in the industry. This is due to the complex nature of the process, which involves treating and disposing of large volumes of phosphate, which is time-consuming, resource-intensive, and costly. The environmental impact of different treatment and disposal methods must be considered, as incorrect choices can lead to environmental pollution. However, there are prospects for achieving zero solid waste in the industry, such as developing innovative technologies and treatment methods for more efficient phosphate use and disposal.

Gao et al. (2023) define a zero-waste strategy in urban construction and demolition as a crucial step toward sustainable urban infrastructure development. This strategy focuses on full resource utilization, aiming for maximum efficiency and minimal environmental impact. This includes a circular economy, where resources are reused and recycled, reducing landfill waste and greenhouse gas emissions. The zero-waste strategy is effectively implemented through technical and engineering innovations and changes in legislation, standards, regulations, and practices of construction market participants. Social aspects, such as training for industry workers and public information campaigns, are also essential.

The study conducted by Hein et al. (2020) emphasizes the potential of deep-ocean polymetallic nodules as a source of critical materials, including nickel, cobalt, and rare earth elements. It is emphasized that while these nodules offer a significant supply of necessary resources for modern technologies, the environmental impacts of seabed mining must be carefully managed. This can be related to the environmental sustainability concerns addressed in the study, particularly in terms of developing waste-free technologies using renewable energy sources with the objective of minimizing environmental impacts, which are similar to the challenges in seabed mining.

Da Silva et al. (2023) demonstrate the synergistic effects of combining recycled aggregate, fly ash, and hydrated lime in concrete production. This resulted in improvements in both mechanical performance and sustainability. This finding is consistent with the objectives of the study on the processing of limestone waste, which emphasizes the importance of recycling materials to enhance the performance of concrete and reduce waste in the construction industry.

The comparative study by Chen et al. (2022) investigates the modeling of concrete properties using the physical and mechanical properties of recycled coarse aggregate. The results indicate that the use of recycled materials does not significantly compromise concrete performance, which supports the argument put forth in the research presented here that processing limestone waste for concrete production can lead to effective and sustainable outcomes.

Yang et al. (2022) found that pyrometallurgical treatment of ferrous slag plays an essential role in the strategy for waste elimination and full utilization of materials in the metallurgical industry. This process aims to extract valuable metal components from the slag and then utilize them in production, thereby reducing waste and environmental impact. These findings confirm earlier research, as it is important to consider not only the technical aspects of the process, but also its impact on the environment, worker health, and public welfare. Attention should also be paid to possible issues, such as emissions and waste management, that may arise during pyrometallurgical processing.

Mittal and Anand (2022) proved that the reductive ammonia leaching process is a promising method for the recovery of metals from polymetallic nodules, including copper, nickel, cobalt, and other valuable metals. Based on the use of ammonia solution as a leaching agent, this method effectively releases metals from mineral materials. One important aspect of considering this process in the context of the pursuit of zero waste is the ability to regenerate and reuse chemicals. With the proper process and efficient handling of chemicals, waste generation can be minimized, and resources can be used as efficiently as possible. To implement a zero-waste approach, attention needs to be paid not only to the technical aspects of the process but also to waste management, emission control, and labor safety. Furthermore, it is important to conduct a comprehensive life cycle analysis of the leaching process to identify and eliminate potential sources of waste at each stage of production.

As noted by Soharu et al. (2021), the concept of zero-waste building construction is a strategy that aims to reduce waste at all stages of the building life cycle, from design and construction to operation. It is based on the application of advanced technologies, materials, and working methods that contribute to the optimal utilization of resources and reduce the negative impact on the environment. An essential aspect of this approach is the principle of circular construction, whereby buildings are designed to allow for their subsequent dismantling and recycling of materials for reuse. This includes the use of recycled materials, the development of modular designs, and the use of dismantling techniques to minimize losses and simplify the recycling process. By analyzing the data and findings, the concept of zero-waste construction also includes optimization of production processes and the application of energy-efficient technologies to reduce energy and water consumption. This approach not only helps to reduce waste but also reduces the negative impact on the climate and the environment in general.

Rahman and Amritphale (2023) found that advanced geopolymer is an innovative material made from industrial waste and has properties that allow it to be used to achieve the goal of zero waste. This material is highly durable, resistant to various influences, and natural. The key advantage of advanced geopolymer is that its production does not require additional extraction of natural resources, as it is created based on already existing industrial waste. This reduces waste by recycling it and turning it into valuable resources. Furthermore, due to its versatility and applicability in various areas of construction and production, advanced geopolymer can be used to create a variety of structures, pavement elements, packaging materials, and household items. This approach not only helps to reduce waste but also contributes to a sustainable and efficient circular economy.

Conclusions

The study of the creation of waste-free technology for processing all types of limestone waste with the use of solar energy leads to the following conclusions. Solar energy represents a promising resource for sustainable and environmentally friendly processes for limestone waste processing. Its use reduces dependence on petroleum products and lowers greenhouse gas emissions, helping to reduce the adverse impact on the environment. The technology enables the efficient utilization of various types of limestone waste, which was previously unattainable. Solar energy is an affordable and sustainable source of energy with economic and environmental appeal. The development of a zero-waste technology for processing limestone waste using solar energy contributes to the circular economy and the creation of sustainable production processes.

The conducted research, both theoretical and experimental, helped to solve scientific problems on the decolonization of production in the utilization of limestone waste using biotechnology, which resulted in considerable economic and social benefits. The main results of the study include scientific substantiation of the technological principles of changing the processes of limestone waste utilization using solar technologies to reduce costs while maintaining the quality of products, as well as analysis of the environmental condition of quarries and solar energy resources for the use of heliotechnologies. Furthermore, a plasticized concrete mix with limestone waste aggregates was developed, and the dependence of the depth of heat penetration in concrete on various factors, including the rate of temperature change and open surface modulus, was established. In addition, the conditions of changing dynamics of natural materials extraction were found, and a calculation formula was obtained to determine the annual fossil fuel savings when using solar energy with helio devices.

Thus, this technology opens new opportunities for sustainable and environmentally friendly resource use and is promising for practical implementation in industry. Further investigation is necessary to determine the economic efficiency and practical feasibility of waste-free limestone waste processing using solar energy in different industrial conditions.

In conclusion, the creation of a zero-waste technology for the processing of limestone waste using solar energy represents a promising solution that is aligned with global sustainability trends. The utilization of solar energy serves to reduce reliance on fossil fuels and to minimize the environmental impact of limestone waste processing. The analysis of solar radiation patterns indicates the necessity for adaptive design strategies to guarantee the technology's efficacy under diverse environmental circumstances. This study highlights the necessity for further research into the optimization of solar energy integration in industrial waste treatment processes, which will contribute to the broader goals of environmental sustainability and resource efficiency.

The Authors have no conflicts of interest to declare.

References

Abdibattayeva et al. 2020 – Abdibattayeva, M., Bissenov, K., Zhubandykova, Z., Orynbassar, R. and Tastanova, L. 2020. Complex Oil-containing Waste Treatment by Applying Solar Energy. *Environmental and Climate Technologies* 24(1), pp. 718–739. DOI: 10.2478/rtuect-2020-0045.

Almadani et al. 2022 – Almadani, M., Razak, R.A., Abdullah, M.M.A.B. and Mohamed, R. 2022. Geopolymer-based artificial aggregates: A review on methods of producing, properties, and improving techniques. *Materials* 15(16), p. 5516, DOI: 10.3390/ma15165516.

Babak et al. 2005 – Babak, V., Filonenko, S. and Kalita, V. 2005. Acoustic emission under temperature tests of materials. *Aviation* 9(4), pp. 24–28, DOI: 10.1080/16487788.2005.9635914.

Bek et al. 2022 – Bek, A.A., Yestemesov, Z.A., Nurpeisova, M.B., Suvorov, A.S. and Dadin, A.D. 2022. Embedded mixtures based on limestone tailings. News of the Academy of Sciences of the Republic of Kazakhstan. *Chemistry and Technology Series* 450(1), pp. 11–19.

Buzhyn, O. 2023. Environmental safety management – classification method of solid combustible fossils. *Ecological Safety and Balanced Use of Resources* 14(1), pp. 33–42, DOI: 10.31471/2415-3184-2023-1(27)-33-42.

Chen et al. 2022 – Chen, X., Capiau, L., Reynaert, I., Zheng, K., Gruyaert, E. and Li, J. 2022. Comparative study on modeling concrete properties using physical and mechanical properties of recycled coarse aggregate. *Construction and Building Materials* 345, DOI: 10.1016/j.conbuildmat.2022.128249.

Compernolle et al. 2023 – Compernolle, T., Eswaran, A., Welkenhuysen, K., Hermans, T., Walraevens, K., van Camp, M., Buyle, M., Audenaert, A., Bleys, B., van Schoubroeck, S., Bergmans, A., Goderniaux, P., Baele, J.M., Kaufmann, O., Vardon, P.J., Daniilidis, A., Orban, P., Dassargues, A., Serge, B. and Piessens, K. 2023. Towards a dynamic and sustainable management of geological resources. *Geological Society, London, Special Publications* 528, pp. 101–121, DOI: 10.1144/SP528-2022-75.

da Silva et al. 2023 – da Silva, S.R., de Brito, J. and de Oliveira Andrade, J.J. 2023. Synergistic effect of recycled aggregate, fly ash, and hydrated lime in concrete production. *Journal of Building Engineering* 70, DOI: 10.1016/j.jobe.2023.106370.

Fidanchevski et al. 2022 – Fidanchevski, E., Šter, K., Mrak, M., Kljajević, L., Žibret, G., Teran, K., Poletanovic, B., Fidanchevska, M., Dolenec, S. and Merta, I. 2022. The valorisation of selected quarry and mine waste for sustainable cement production within the concept of circular economy. *Sustainability* 14(11), DOI: 10.3390/su14116833.

Floqi et al. 2009 – Floqi, T., Shumka, S., Malollari, I., Vezi, D. and Shabani, L. 2009. Environment and sustainable development of the Prespa park. *Journal of Environmental Protection and Ecology* 10(1), pp. 163–175.

Gao et al. 2023 – Gao, Q., Li, X.G., Jiang, S.Q., Lyu, X.J., Gao, X., Zhu, X.N. and Zhang, Y.Q. 2023. Review on zero waste strategy for urban construction and demolition waste: Full component resource utilization approach for sustainable and low-carbon. *Construction and Building Materials* 395, DOI: 10.1016/j.conbuildmat.2023.132354.

Hein et al. 2020 – Hein, J.R., Koschinsky, A. and Kuhn, T. 2020. Deep-ocean polymetallic nodules as a resource for critical materials. *Nature Reviews Earth & Environment* 1, pp. 158–169, DOI: 10.1038/s43017-020-0027-0.

Ikram et al. 2021 – Ikram, M., Ferasso, M., Sroufe, R. and Zhang, Q. 2021. Assessing green technology indicators for cleaner production and sustainable investments in a developing country context. *Journal of Cleaner Production* 322, DOI: 10.1016/j.jclepro.2021.129090.

Jain et al. 2023 – Jain, M., Kumar, A. and Kumar, A. 2023. Landfill mining: A review on material recovery and its utilization challenges. *Process Safety and Environmental Protection* 169, pp. 948–958, DOI: 10.1016/j.psep.2022.11.049.

Kolesnikova et al. 2023 – Kolesnikova, I.V., Suvorov, A.S. and Bekturganova, N.Y. 2023. Analysis of prospects for the use of local raw materials for the production of self-sealing concretes in the Republic of Kazakhstan. *Bulletin of Kazakh Leading Academy of Architecture and Construction* 90(4), pp. 110––124.

Lyubchyk et al. 2015 – Lyubchyk, A., Filonovich, S.A., Mateus, T., Mendes, M.J., Vicente, A., Leitão, J.P., Falcão, B.P., Fortunato, E., Águas, H. and Martins, R. 2015. Nanocrystalline thin film silicon solar cells: A deeper look into p/i interface formation. *Thin Solid Films* 591, pp. 25–31, DOI: 10.1016/j.tsf.2015.08.016.

Mittal, N. and Anand, S. 2022. Reductive ammonia leaching process for metal recovery from polymetallic nodules: Can there be a zero waste approach? [In:] *Perspectives on Deep-Sea Mining: Sustainability, Technology, Environmental Policy and Management,* pp. 263–277, Cham: Springer, DOI: 10.1007/978-3-030-87982-2_10.

Moreno-SanSegundo et al. 2022 – Moreno-SanSegundo, J., Martín-Sómer, M. and Marugán, J. 2022. Dynamic concentration factor: A novel parameter for the rigorous evaluation of solar compound parabolic collectors. *Chemical Engineering Journal* 437, DOI: 10.1016/j.cej.2022.135360.

Nurmanova et al. 2024 – Nurmanova, S., Kolisnichenko, S., Sagmedinov, D. and Kalambayeva, G. 2024. Innovative approaches to improving the efficiency of transport engines in mobile drilling rigs in the oil and gas industry. *Bulletin of Kazakh Academy of Transport and Communications named after M. Tynyshpayev* 130(1), pp. 426–438.

Ondo Zue Abaga et al. 2023 – Ondo Zue Abaga, N., Nfoumou, V. and Makaya M'Voubou. 2023. Influence of the parent rock nature on the mineralogical and geochemical composition of ferralsols used for sedentary agriculture in the Paleoproterozoic Franceville sub-basin (Gabon). *International Journal of Biological and Chemical Sciences* 17(4), pp. 1778–1789. DOI: 10.4314/ijbcs.v17i4.38.

Ospanov et al. 2023 – Ospanov, Zh., Maydyrova, A.B. and Biryukov, V. 2023. Development trends of mining enterprises of the Republic of Kazakhstan. *Bulletin of L.N. Gumilyov Eurasian National University, Economic Series* 3, pp. 153–162.

Palianytsia et al. 2014 – Palianytsia, B., Kulik, T., Dudik, O., Cherniavska, T. and Tonkha, O. 2014. Study of the thermal decomposition of some components of biomass by desorption mass spectrometry. *Springer Proceedings in Physics* 155, pp. 19–25, DOI: 10.1007/978-3-319-05521-3_3.

Pona, Y. and Ouedrago, I. 2023. Inclusive institutions around natural resources characteristics and challenge: a case study in the central Niger delta of Mali. *International Journal of Biological and Chemical Sciences* 17(2), pp. 618–629, DOI: 10.4314/ijbcs.v17i2.26.

Rahman et al. 2022 – Rahman, M., Khan, I., Field, D.L., Techato, K. and Alameh, K. 2022. Powering agriculture: Present status, future potential, and challenges of renewable energy applications. *Renewable Energy* 188, pp. 731–749, DOI: 10.1016/j.renene.2022.02.065.

Rahman, A. and Amritphale, S. 2023. Advanced geopolymer: Utilizing industrial waste to material to achieve zero waste. [In:] *Advanced Materials from Recycled Waste,* pp. 255–272. Amsterdam: Elsevier, DOI: 10.1016/B978-0-323-85604-1.00002-0.

Sadykov et al. 2024 – Sadykov, M., Temirbaeva, N., Narymbetov, M., Toktonaliev, B. and Nariev, Z. 2024. Comparative analysis of the efficiency of hydro, wind, and solar power plants in Kyrgyzstan. *Machinery & Energetics* 15(2), pp. 106–117, DOI: 10.31548/machinery/2.2024.106.

Selvakumar et al. 2024 – Selvakumar, R.D., Wu, J. and Alkaabi, A.K. 2024. Electrohydrodynamic acceleration of charging process in a latent heat thermal energy storage module. *Applied Thermal Engineering* 242, DOI: 10.1016/j.applthermaleng.2024.122475.

Shakulikova, G.T. and Akhmetov, S.M. 2021. The role of the "green economy" in the sustainable development of ecological and economic systems of Kazakhstan. *Oil and Gas* 126(6), pp. 13–37, DOI: 10.37878/2708-0080/2021-6.01.

Soharu et al. 2021 – Soharu, A., Naveen, B.P. and Sil, A. 2021. An approach towards zero-waste building construction. [In:] *Advances in Construction Materials and Sustainable Environment*, pp. 239–257, Singapore: Springer, DOI: 10.1007/978-981-16-6557-8_19.

Syrlybayev et al. 2016 – Syrlybayev, M.K., Saimova, S.A., Tassova, A.M., Suleimenova, S.Zh., Kussainov, K.Kh., Khussainova, L.I., Zhumanova, M.K. and Askarova, A.O. 2016. Incorporation of environmental law requirements during waste management at rubbish recycling plants in the Republic of Kazakhstan. *Indian Journal of Science and Technology* 9(44), DOI: 10.17485/ijst/2016/v9i44/105473.

Taha et al. 2021 – Taha, Y., Elghali, A., Hakkou, R. and Benzaazoua, M. 2021. Towards zero solid waste in the sedimentary phosphate industry: *Challenges and opportunities. Minerals* 11(11), DOI: 10.3390/min11111250.

Vyshnevska et al. 2022 – Vyshnevska, Y., Ladychenko, V., Uliutina, O., Kanaryk, J. and Movchun, S. 2022. Regulatory and legal provision of alternative sources of energy as a component of the energy sector of the economy. *Economics and Policy of Energy and the Environment* 2022(1), pp. 119–130, DOI: 10.3280/EFE2022-001007.

Yang et al. 2022 – Yang, J., Firsbach, F. and Sohn, I. 2022. Pyrometallurgical processing of ferrous slag "co-product" zero waste full utilization: A critical review. *Resources, Conservation and Recycling* 178, DOI: 10.1016/j.resconrec.2021.106021.

Yu et al. 2023 – Yu, K., Jia, M., Yang, Y. and Liu, Y. 2023. A clean strategy of concrete curing in cold climate: Solar thermal energy storage based on phase change material. *Applied Energy* 331, DOI: 10.1016/j.apenergy.2022.120375.

Zhakupova, U.A. and Tsygulev, D.V. 2023. Environmental problems in construction: Experience in carrying out green events. [In:] Proceedings of the *International Scientific and Practical Conference: "Environmental Problems in Colleges and Schools: Experience of Green Events"*, pp. 143–147, Astana: L.N. Gumilyov Eurasian National University.

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Opracowanie bezodpadowej technologii przetwarzania wszelkiego rodzaju odpadów wapiennych przy wykorzystaniu energii słonecznej

Streszczenie

W świetle rosnących obaw o środowisko i stopniowego wyczerpywania się konwencjonalnych źródeł energii, opracowanie wydajnej technologii przetwarzania wszystkich rodzajów odpadów wapiennych przy użyciu energii słonecznej staje się kluczowym krokiem w kierunku zrównoważonego i przyjaznego dla środowiska przemysłu. Celem tego artykułu było stworzenie innowacyjnej technologii, która może skutecznie przetwarzać różne odpady wapienne przy minimalnym wpływie na środowisko i wykorzystywać energię słoneczną jako główne źródło energii. W badaniu wykorzystano dane dotyczące współrzędnych geograficznych, promieniowania słonecznego, godzin nasłonecznienia, promieniowania, klimatu i warunków oświetleniowych Republiki Kazachstanu w celu oceny potencjału energii słonecznej i jej wpływu na bilans promieniowania i warunki klimatyczne kraju. Stworzenie innowacyjnej technologii przetwarzania odpadów wapiennych w celu produkcji nowego materiału budowlanego obniży koszty wydobycia kamienia, zminimalizuje gromadzenie się odpadów i poprawi sytuację środowiskową. Osiąga się to poprzez optymalizację przetwarzania przy użyciu energii słonecznej, co przyczynia się do zrównoważenia środowiskowego produkcji i zmniejszenia zużycie paliwa i zasobów energetycznych w produkcji betonu. Badanie obejmowało zarówno teoretyczne, jak i praktyczne eksperymenty mające na celu optymalizację procesów technologicznych przetwarzania odpadów wapiennych z wykorzystaniem energii słonecznej. Ponadto przeanalizowano warunki środowiskowe kamieniołomów i zasoby energii słonecznej pod kątem zastosowania technologii słonecznej.

Słowa kluczowe: analiza zasobów, promieniowanie bezpośrednie, coquina, heliostruktury, skała