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# OPTIMISATION AND SYNTHESIS OF SINGLE BLADE VIBRATION MOTION IN AIRFLOW

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The study focuses on wind flow energy harvesting technology utilising the vibration method. The one-degree-of-freedom mathematical model comprises a flat plate connected to a foundation via an elastic element, subjected to airflow induced by the wind. Energy accumulation occurs within a generator. The braking force exerted by the generator can assume a constant, linear, or non-linear relationship with plate velocity. Oscillation motion is induced by altering the plate area within each oscillation cycle, with maximum area exposure to the windward motion and minimum during leeward movement. Control switches, functioning as level functions, facilitate motion synthesis and simulation by simplifying the description of plate area and generator switching control in the phase plane. Additionally, a control switching delay is introduced for plate area variation, described in terms of velocity and coordinate levels. The paper presents computer simulation results in the form of phase diagrams and time responses, followed by an analysis of generated power and energy extraction efficiency.

***Keywords:*** *Air flow, energy harvesting, plate vibrations, surface area control, switching delay.*

## 1. INTRODUCTION

In recent times, there has been a notable surge in interest regarding the deployment and integration of small or medium-sized wind energy harvesting equipment within urban settlements [1]. This study evaluates the performance of wind turbines and technologies that utilise micro or small wind-induced vibrations to improve their efficiency and reliability in operation. Wind energy harvesting technologies based on the use of interaction forces between air flow and moving objects through reciprocating motions demonstrate a wide range of approaches. For instance, research [2]–[7] delves into the examination of vibrations characterised by flapping or fluttering. Accordingly, investigations into the utilisation of vortices-induced vibrations can be found in studies [8]–[12], while galloping mechanisms are explored, for example, in works [13]–[17]. The analysis of these studies reveals that rotating turbines, whether vertically or horizontally oriented, generally exhibit higher power outputs compared to vibration-based technology equipment, owing to the absence of blade-stopping moments. Nevertheless, rotating turbines also present certain drawbacks [18] listed below.

- They can attain high speeds at the radial extremities, potentially posing hazards to nearby living or inanimate objects.
- High speeds may lead to increased blade vibrations and noise levels.
- Their proximity to residential structures is not always desirable.

However, vibration-based wind energy harvesting equipment also carries its own set of limitations [19] presented below.

- The energy gained during the downwind phase is reduced by the energy expanded during the upwind phase.
- Energy production levels are generally lower compared to rotor-type turbines.
- Possibility of additional high-frequency noise and vibrations.
- Sensitivity of vibration amplitudes to changes in wind speed.

To improve the efficiency of oscillatory motion technology in extracting wind energy, this study uses the principles of optimal synthesis [20], [21]. For this purpose, changing the surface area of the oscillating plate is chosen as a control action [22]. In addition, the energy storage generator control is designed with adjustable operating thresholds. Since in a real mechanism it is physically impossible to change the surface area instantly (bang-bang control), computer simulations include a delay in switching areas to simulate motion [23].

## 2. MOTION CONTROL OPTIMISATION

A model depicting the movement of a plate along the O*x* direction is shown in Fig. 1. This model comprises a plate 2, which moves along the *x*-axis and is connected to an actuator 3. A wind flow with velocity $V_0$ acts on the plate at the angle $\beta$ relative to *x* axis. The actuator 3 serves to simulate the force produced by the energy generator, as well as additional damping forces within the system. The forward motion of the system, when the relative wind velocity projections to the normal and plate are positive, is described by the following differential equation [24], [25]:

$$m\ddot{x} = A\rho(1 + C)(V_0 \cos\beta - \dot{x})^2 - F_G - F_D, \tag{1}$$

where $m$ being the mass of moving plate, kg; $x$ is a displacement of the plate, m; $C$ is a dimensionless constant; $A$ is the plate lateral surface area, m$^2$; $\rho$ is the air density, kg/m$^3$; $V_0$ is the air flow velocity, m/s; $\beta$ is the angle between airflow velocity and $x$ axis, rad; $F_G$ is the force of energy generator and $F_D$ *is* the additional damping force, N.

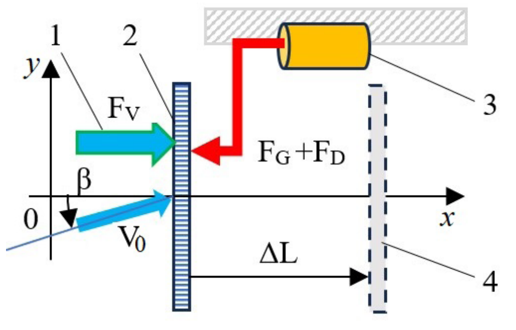


*Fig. 1.* A schematic diagram of plate rectilinear movement system: 1 – wind interaction force; 2 – a thin flat plate; 3 – an energy storage and damping actuator; 4 – end position of the plate.

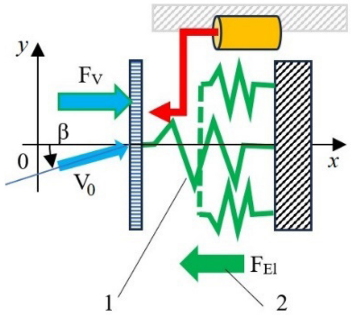


*Fig. 2.* Reciprocating vibrating system: 1 – a non-linear spring system; 2 – spring force.

The equation of motion of the reciprocating vibrating system (Fig. 2) is similar to Eq. (1), but it is supplemented with the force $F_{EL}$ of the flexible element and with the sign function (±1) switching the direction of relative velocity $(V_0 \cos\beta - \dot{x})$:

$$m\ddot{x} = A\rho(1 + C)(V_0 \cos\beta - \dot{x})^2 \cdot \mathrm{sign}(V_0 \cos\beta - \dot{x}) - F_G - F_D - F_{EL}\ . \tag{2}$$

Examining Eq. (1) through the lens of control optimisation [20], [21], it is possible to select the area $A = u_1 \cdot m[\rho(1+C)]^{-1}$ and the force $F_G = mu_2$ as control functions dependent on time $t$ and phase coordinates $x, \dot{x}$, denoted as $u_1 = u_1(t, x, \dot{x}),\ u_2 = u_2(t, x, \dot{x})$, respectively. In the scenario of unidirectional stationary motion, the criterion should reflect the energy obtained from the generator, expressed in the following form [22]:

$$J(x, \dot{x}, u_1, u_2) = \int_{t1}^{t2} u_2 \dot{x} dt, \tag{3}$$

where $t_1$ and $t_2$ are the start and end times of the movement under consideration, when the displacement $\Delta L$ is performed (Fig. 1).

The stated optimisation problem imposes a constraint on the size of the positive area $A$ with minimal $u_1^{(1)}$ and maximal $u_1^{(2)}$ values, in accordance with the following equation:

$$[u_1^{(1)}] \le u_1 \le [u_1^{(2)}]. \tag{4}$$

In terms of generator control, it is established that $u_2$>0. However, the maximum value is limited by the operational capacity of the mechanism to manoeuvre within the airflow, as outlined in the following equation:

$$0 \leq u_2 \leq [u_2^{(0)}]. \quad (5)$$

During the optimisation process of system control variables $u_1$ and $u_2$, the Pontryagin's maximum principle is applied, particularly in strongly nonlinear scenarios [22]. For this purpose, Eq. (1) is reformulated in terms of derivatives with respect to phase coordinates, including an additional function under the integral, as described in Eq. (3). As a result, the following system of equations is obtained:

$$\frac{dx_0}{dt} = u_2 x_2; \quad \frac{dx_1}{dt} = x_2; \quad \frac{dx_2}{dt} = u_1 \cdot (V_0 \cos\beta - x_2)^2 \cdot (+1) - u_2 - F_D m^{-1}, \quad (6)$$

where (+1) means that the relative velocity is positive.

According to the optimization theory [22], the Hamiltonian $H$, studied here is as follows:

$$H = \psi_0 u_2 x_2 + \psi_1 x_2 + \psi_2\{u_1(V_0 \cos\beta - x_2)^2 \cdot (+1) - u_2 - F_D m^{-1}\}. \quad (7)$$

Here the components $\psi_0$, $\psi_1$, $\psi_2$ of the related function $\psi$ are found from their derivatives by the time $t$ as follows [21], [22]:

$$\frac{d\psi_0}{dt} = -\frac{\partial H}{\partial x_0}; \ \frac{d\psi_1}{dt} = -\frac{\partial H}{\partial x_1}; \ \frac{d\psi_2}{dt} = -\frac{\partial H}{\partial x_2}, \quad (8)$$

where $\frac{\partial H}{\partial x_0}, \frac{\partial H}{\partial x_1}, \frac{\partial H}{\partial x_2}$ are the partial derivatives of $H$ by coordinates $x_0$, $x_1$, $x_2$.

According to the optimisation theory, for optimal control at any given time moment $t$, function $H$ must reach its maximum (or supremum) value subject to the constraints specified in Eqs. (4) and (5).

Analysing such a task in stationary motion with constant blade speed $V_{opt} = const$, when $F_D = 0$, the following optimal solution can be found:

$$V_{opt} = \frac{V_0 \cos\beta}{3}; \quad (9)$$

$$F_{Dopt} = A_{max} \cdot \rho(1 + C)\left[\frac{2}{3} V_0 \cos\beta\right]^2; \quad (10)$$

$$P_{opt} = A_{max} \cdot \rho(1 + C)\frac{4}{27} \cdot [V_0 \cos\beta]^3, \quad (11)$$

where $A_{max}$ is the plate maximal area, $F_{Dopt}$ is the required force from the power generator, and $P_{opt}$ is the maximum generated power in the optimisation case.

Thus, if the damping force $F_D$ is neglected, the operating force $F_G$ of the generator can be selected. Since in practice there are uncontrollable damping forces $F_D$, the generator force $F_G$ will correspondingly decrease by this amount. It should be noted that during the transition process, additional optimisation of the system is possible, for example, starting movement from a stationary position and moving to the supposed optimal position. In such scenarios, the optimisation criterion may not prioritise energy as shown in Eq. (3), but rather focus on minimising travel time *T*. Therefore, in the optimisation process, the expression in Eq. (3) should be replaced by the following expression:

$$J(x, \dot{x}, u_1, u_2) = \int_0^T 1 \cdot dt. \tag{12}$$

It is clear that in this optimal control scenario, the area *A* should be maximised ($A_{max}$), while the energy generator force must be set to zero ($u_2 = 0$). Following the attainment of the previously determined optimal stationary state, the generator should be engaged with the optimal force for mechanism synthesis. Considering the optimisation outcome obtained earlier, it can be inferred that the generator's characteristics offer a wide range of possibilities: it could function as a constant force, a linear or nonlinear function of velocity, or adopt other configurations. The application of the optimisation results discussed previously to the synthesis of wind energy harvesting mechanisms is detailed in studies [25]–[27].

Accordingly, the synthesis of the mechanism involving reciprocating vibrational motion (Fig. 2) is discussed in detail below.

## 3. MOTION MODELLING AND PARAMETER OPTIMISATION FOR OSCILLATORY SYSTEM SYNTHESIS

During the modelling and parameter optimisation, the following differential equation of motion for $\beta = 0$ was initially analysed:

$$m\ddot{x} = A\rho(1 + C)\{b_0 + b_1[0.5 \cdot \mathrm{sign}(\dot{x} - \Delta) + 0.5 \cdot \mathrm{sign}(\dot{x} + \Delta)]\} \cdot (V_0 - \dot{x})^2 \cdot \\ \cdot \mathrm{sign}(V_0 - \dot{x}) - b_2\dot{x} - cx, \tag{13}$$

where $b_0$, $b_1$, $\Delta$ are the constants of the control switching function of area *A*, $b_2$ is the linear generator parameter, *c* is the linear elasticity parameter or linear spring stiffness coefficient.

The simulation was performed with computer program MathCad under the following constant parameters: $m$ = 100 kg; $A$ = 1 m$^2$; $\rho$ = 1.25 kg/m$^3$; $C$ = 0.25; $b_0$ = 1. The remaining parameters ($V_0$, $b_1$, $\Delta$, $b_2$, $c$) were varied. The results of modelling of free oscillations (for $b_1 = 0$) are presented in Figs. 3–5.

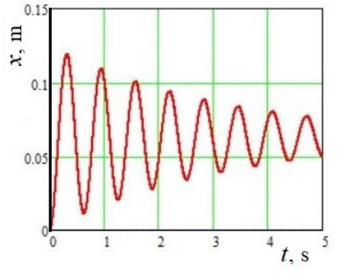


*Fig. 3.* The displacement *x* of the plate as a function of time *t* under the conditions $V_0$ = 20 m/s, $b_1 = 0$, $b_2 = 0$.

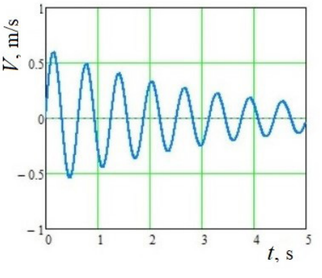


*Fig. 4.* Velocity of the plate *V* as a function of time *t* under the conditions $V_0$ = 20 m/s, $b_1 = 0$, $b_2 = 0$.

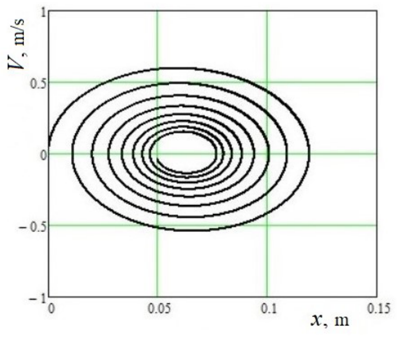


*Fig. 5.* Reciprocating motion in phase plane ($x$, $V$): $V_0 = 20$ m/s, $b_1 = b_2 = 0$.

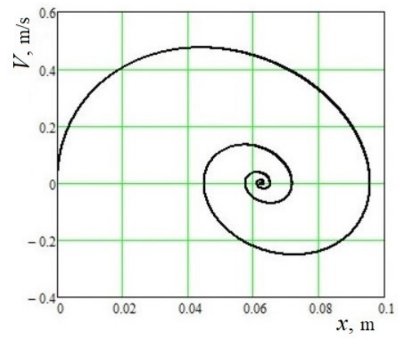


*Fig. 6.* Motion in phase plane ($x$, $V$): $V_0 = 20$ m/s, $b_1 = 0$ and $b_2 = 333.3$ kg/s.

From the graphs depicted in Figs. 3–5, it is evident that the interaction of the plate with airflow, even when the generator is inactive ($b_2 = 0$), exerts a considerable damping effect. Consequently, other drag forces can be disregarded ($F_D = 0$) for further analysis. However, in a practical scenario, the energy required for transitioning between areas should be assessed as a partial deduction from the overall energy yield (Fig. 6). Subsequent to this assessment, Figs. 7 and 8 present modelling outcomes derived from optimising the energy harvesting generator. These results pertain to a linear generator configuration under the conditions: $V_0 = 20$ m/s, $b_0 = 1$, $b_1 = 0.8$, $b_2 = 350$ kg/s, $\Delta = 0.1$.

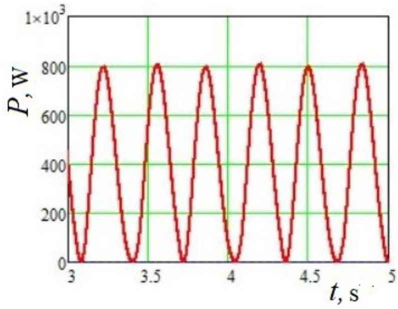


*Fig. 7.* Variation of power $P$ in time $t$.

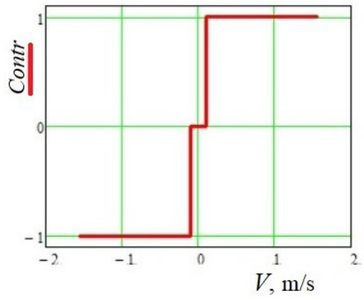


*Fig. 8.* The plate shutter switching control as a function of velocity $V$.

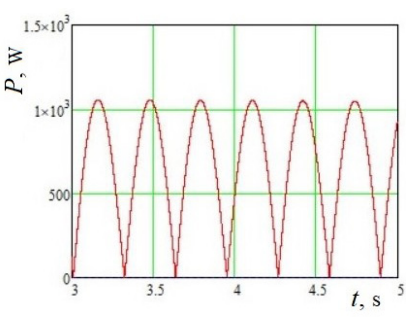


*Fig. 9.* Variation of power P in time $t$.

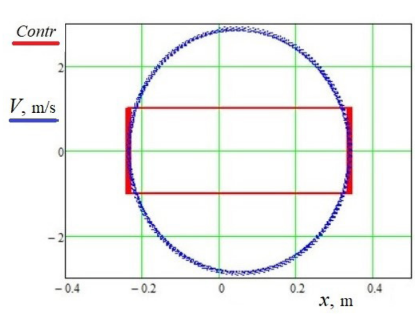


*Fig. 10.* The plate switching control in velocity $V=\dot{x}$ domain.

As follows from Fig. 7, the average power is $P_m$ = 413 W. Furthermore, the power efficiency of the process, concerning optimal rectilinear motion in accordance with Eq. (11), stands at $E_f$ = 22.32 %. However, plate shutter switching control (Fig. 8) is performed as a function of velocity in accordance with Eq. (13): $Contr = b_0 + b_1[0.5 \cdot \text{sign}(\dot{x} - \Delta) + 0.5 \cdot \text{sign}(\dot{x} + \Delta)]$.

In Figs. 9 and 10, modelling results are presented, derived from the optimisation of an energy harvesting generator configured with a nonlinear characteristic, such as dry friction $F_G = B \cdot \text{sign}(\dot{x})$. These results are obtained under the conditions: $V_0$ = 20 m/s, $b_0$ = 1, $b_1$ = 0.8, $b_2$ = 350 kg/s, $\Delta$ = 0.1, and $B$ = 370 N. The power $P$ graph (Fig. 9) indicates an average power output of 705 W. Furthermore, the power efficiency of the process, relative to the optimal rectilinear motion with Eq. (11), is calculated as $E_f$ = 38 %. However, plate switching control in velocity domain (Fig. 10) is performed with Eq. (13): $Contr = b_0 + b_1[0.5\text{sign}(\dot{x} - \Delta) + 0.5\text{sign}(\dot{x} + \Delta)]$.

Upon comparing the results obtained with both a linear and a non-linear generator, it becomes evident that in the latter case, there is a potential to elevate the average energy efficiency $E_f$ from 22 % to 38 %. The subsequent section addresses how further enhancements in energy production efficiency can be achieved by altering the operational control of the generator.

## 4. RESULTS AND DISCUSSION

It is worth mentioning that in oscillating motion with mechatronic control, it is feasible to electrically toggle the generator on or off using a "bang–bang" control approach [28]. For example, it is viable to activate periodically the generator at specific movement velocity thresholds, as described by the following equation:

$$F_G = B \cdot \text{sign}(\dot{x}) \cdot [0.5 + 0.5 \cdot \text{sign}(|\dot{x}| - \Delta_1)], \quad (14)$$

where $\Delta_1$ is a constant velocity level, m/s.

Thus, through optimisation of the parameter $\Delta_1$, an optimal value of $\Delta_1$ = 5.25 m/s was achieved, yielding a power output of 1032 W and an efficiency of $E_f$ = 55.7 %. Accompanying this optimisation, the graph depicting the control function, as per Eq. (14), is illustrated in Fig. 11. The power graph for the optimal movement scenario is presented in Fig. 12.

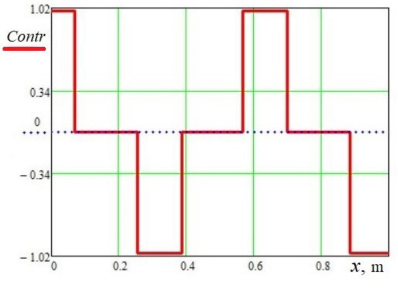


*Fig. 11.* Graph of the "bang–bang" control function as defined by Eq. (14).

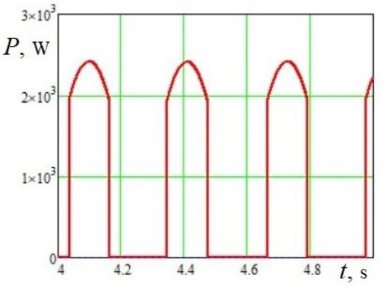


*Fig. 12.* Power graph for the optimal movement scenario: $V_0$ = 20 m/s, $b_0$ = 1, $b_1$ = 0.8, $b_2$ = 350 kg/s, $\Delta$ = 0.1, $B$ = 370 N, $\Delta_1$ = 5.25 m/s, $E_f$ = 55.7 %.

Continuing with the synthesis process of the energy harvesting system $F_G$, an analysis of the elastic force $F_{EL}$ for the cubic form was conducted, as described by the following equation:

$$F_G + F_{EL} = B\text{sign}(\dot{x}) \cdot [0.5 + 0.5 \cdot \text{sign}(\lfloor \dot{x} \rfloor - \Delta_1)] + c_1 x^3, \quad (15)$$

where $c_1$ is the nonlinear elasticity parameter, kg/s$^2$.

In this context, an illustrative example depicting movement in the phase plane from a stationary state is presented in Fig. 13. Subsequently, the power graph obtained through the "bang–bang" connection of the electric generator is shown in Fig. 14. In accordance with simulation results, a medium power output is about 1063 W and efficiency is of $E_f$ = 57.4 %.

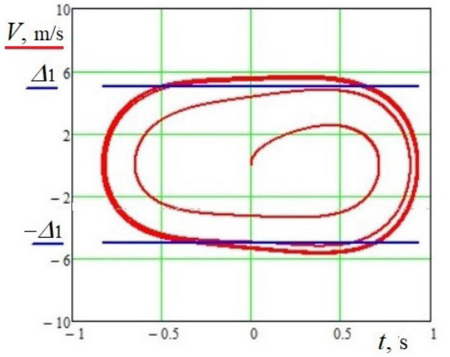


*Fig. 13.* Motion in the phase plane for the optimal movement scenario ($c_1$ = 10000 kg/s$^2$; $\Delta_1$ = 5 m/s), when: $V_0$ = 20 m/s, $b_0$ = 1, $b_1$ = 0.8, $b_2$ = 350 kg/s, $\Delta$ = 0.1, $B$ = 370 N.

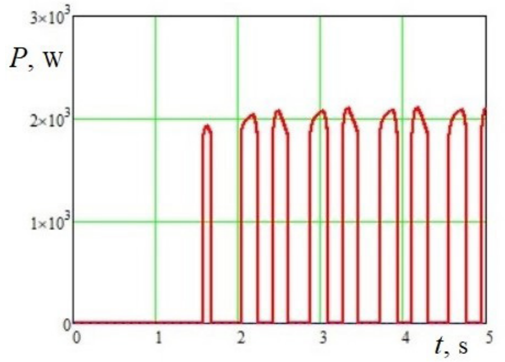


*Fig. 14.* Power graph for the optimal movement scenario with $c_1$ = 10000 kg/s$^2$ and $\Delta_1$ = 5 m/s.

In the numerical analysis, it was determined that the elastic force parameter $c_1$, within a considerable range of variations ($5 \cdot 10^3$ kg/s$^2$ < $c_1$ < $20 \cdot 10^3$ kg/s$^2$), did not exert a substantial influence on energy recovery (52 % < $E_f$ < 57 %). This is primarily attributed to the conservative nature of the suspension force. However, the investigation did not delve into the implications of a flexible nonlinear suspension in alternative scenarios.

## 5. CONCLUSIONS

As the scope of energy extraction from airflow expands, there is growing interest in optimising the operation of existing equipment and synthesising new machinery. Mechatronic control systems offer a promising avenue for achieving these goals. In the operating principles of existing systems, it is crucial to study variation in the area of interaction between the airflow and the object. Moreover, there is a need to explore control synthesis in mechatronic systems. As such, it is suggested to implement variations in the interaction area between the airflow and objects while considering control delays. Additionally, the application of bang–bang control for energy generators is under consideration. The research findings are outlined as follows:

1. optimisation of the control for varying the interaction area and managing the energy generator has been carried out.
2. during the synthesis of new equipment, it is suggested to incorporate observation of a control delay using a three-level function (+1; 0; -1) while adjusting the interaction area;
3. when synthesizing real equipment, bang–bang control is used, which increases the efficiency of the energy production system.

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# ASSESSING ENERGY POVERTY IN THE EUROPEAN UNION: INDICATORS, CHALLENGES, AND POLICY SOLUTIONS

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A sharp increase in energy prices since 2021 has had a significant impact on the European Union (EU) energy market turning the energy poverty issue into an important concern. Around 42 million EU citizens or 9.3 % of the total population in the Union faced an inability to adequately heat their homes in 2022. It is a clear call for policymakers to seriously address the energy poverty aspects eliminating the negative socio-economic impact. The research aims to analyse the energy poverty concept, its main indicators and affecting factors, identifying the possible solutions for reducing energy poverty, and paying particular attention to vulnerable users. The qualitative methods were used, i.e., the authors conducted a literature review and scrutinized scientific publications, reports and legal acts. As a result of the research, the authors have characterised the energy poverty situation in different countries, identified the main areas for solving the energy poverty challenge, as well as shared experiences of different countries on the solutions taken. The authors conclude that energy poverty has a particular impact on low-income households, children, disabled people, seniors and single mothers, who may have relatively higher energy consumption and limited resources available. In this regard, countries can benefit from such measures as setting a clear definition of energy poverty and its measurable indicators, identification of supported households, on-the-spot consultations and audits, attracting local governments, and non-governmental organisations, as well as improvement of support instruments of renewable energy sources.

***Keywords:*** *Electricity, electricity costs, energy poverty, support measures.*

## 1. INTRODUCTION

Energy poverty is a complex, multidimensional issue that is influenced by several factors. The European Union (EU) in its Energy Portal [1] points out that this phenomenon is mainly due to three primary factors: increased energy expenditure compared to the total household budget, low-income levels and lack of energy efficiency in housing and their facilities. These factors form the basis for understanding energy poverty. The situation of households is also affected by secondary factors such as geographical conditions, climatic characteristics, structural characteristics of the household, gender, health status and specific energy and transport needs [2]. The concept of energy poverty was introduced in 2009 by Directive 2009/72/EC [3] and requires appropriate solutions to protect end-users, particularly vulnerable users. In this context, each Member State should define the concept of vulnerable users, which also covers energy poverty and, inter alia, prohibits the exclusion of such users in times of crisis. Thus, one of the objectives of the Directive is to protect users by paying particular attention to low-income users. Directive 2019/944 [4] requires the EU Member States to define the concept of energy poverty. The European Pillar of Social Rights [5] and the United Nations Sustainable Development Goals [6] include energy among the basic services that have the right of access to everyone. The European Green Deal [7] points to a fair and inclusive energy transition process. The European Pillar of Social Rights states that energy is the basic service with the greatest differences in access to the EU. The Fit for 55 package [8] provides a comprehensive approach to reducing energy poverty. As Russia's invasion of Ukraine posed a security threat to the EU energy, the package was complemented by a REPowerEU plan [9] aimed at rapidly reducing the EU's dependence on Russia's energy supply through diversification, the development of renewable energy sources (RES), austerity measures, while also protecting users in the face of sharp price rises in the energy sector as seen in 2022 [10]. Policy documents contributing to a just social transition should include the Council of Europe recommendations [11], the Just Transition Fund Regulation [12], as well as several other documents specifically addressing energy poverty. Regulation 2018/1999 of the European Parliament and of the Council [13] obliges Member States to develop and publish indicators by which they identify energy poverty-stricken households, which are reflected in national energy plans and the options to mitigate them.

In Latvia in 2021, for the first time, the term "energy poverty" was strengthened in the law, and the Energy Law [14] was supplemented by stipulating that "energy poverty is the inability of a household user to maintain adequate temperature in a dwelling or to use services provided by energy supply merchants, or to pay for them due to low energy efficiency or because the charge for these services has a high proportion of household income". The definition of energy poverty as defined in the Latvian Energy Law is considerably narrower and more laconic than the European directives and recommendations mentioned suggest. The Latvian Energy Law also uses the term protected user, which provides social protection for certain groups of the population, however, it is not directly related to energy poverty.

Energy poverty rates have also been

explored in the work of various scientists, such as Buzarovsky, who defined energy poverty in 2015 as a household's inability to buy enough heat for its own needs, a problem which is linked to low-income earning and living in energy-inefficient homes [15]. In the study, "Energy Poverty and Health: Trends in the European Union before and during the Economic Crisis, 2007–2016" [16], its authors point out that people living in an environment of energy poverty are often subject to complex trade-offs between energy and healthcare pay or other essential needs. The studies carried out indicate a risk of significant exacerbation of mental and respiratory illnesses [17]. Energy poverty harms human life as it affects not only the economic aspects but also social ones and health [18]. The security of energy supply risks and costs arising from the synchronisation process, transition to RES and diversification of supply have also been analysed in other studies [2], [19]–[36].

Several projects are also devoted to energy poverty. ENPOR [37] project focuses on exploring energy poverty in the private rented sector, making it more visible and measurable and in line with the EU objectives of reducing energy poverty. The experience and current situation of Italy, Austria, the Netherlands, Germany, Greece and Croatia have been investigated. The Comact project [38] aims at improving accessibility to energy efficiency improvements for energy-saving communities living in apartment buildings. The STEP project [39] carried out in 2020–2022 is an important study. The Socialwatt project [40] was designed as a support tool for businesses and decision-makers at the local level, such as local governments, consulting companies, and builders, to effectively identify energy-poor households and develop schemes aimed at increasing the energy efficiency of their homes. The EmpowerMed project [41] focuses on the gender perspective of energy poverty policy, with particular emphasis on summer energy poverty and health. EmprowerMed has suggested that policymakers heed a whole range of recommendations, such as the health impact of energy poverty, survey visits and consultations in households affected by energy poverty, networking and training of energy consultants, including training of social services specialists, establishment of state support programmes, raising participation of citizens, gender equality issues, noting the need to balance pension income, as studies show that women receive lower pensions and are more at risk of energy poverty. The Renoverty project [42] promotes the renovation of energy and cost-efficient buildings. The project identifies barriers to reducing energy poverty: financial, awareness and access, geographic and regulatory/political. The Energy Poverty Zero project [43] focuses on deep energy renovation with scaling capabilities in poorly developed areas. The main objectives of the project include improving energy efficiency and saving energy costs for citizens through prefabricated modular systems to make deep renovation more accessible in energy-poverty-stricken, vulnerable urban areas. The objective of the JUSTEM [44] project is to help regional authorities in the EU coal energy regions assess and target equitable transition issues by introducing sustainable energy and declining the use of coal. The POWER UP project [45] supports urban efforts to plan the social role of energy market players in developing pilot schemes across Europe to combat energy poverty. Futureproof [2] is a study carried out by Latvian scientists aimed at the development and integration of Latvia's energy system in Europe to ensure a sustainable and secure energy supply in the country.

This study aims to analyse the experience of reducing energy poverty and to provide recommendations for the use of good practice. The tasks of the research are as follows:

1. to analyse energy poverty indicators in Europe and Latvia;
2. to share experience in reducing energy poverty in Europe and Latvia;
3. to formulate recommendations for the use of good practice.

The research methods used in the study are the following:

1. literature review: the study of tertiary data, including scientific literature, recommendations, policy papers, statistics and similar studies, with particular attention to the results of research projects;
2. content analysis and observation;
3. statistical analysis of secondary data, including descriptive and inferential statistics, for the processing and evaluation of quantitative data; graphical analysis to visualize trends and relationships of data.

Limitations of the research are listed below.

1. The electricity cost aspect has been considered in the context of energy poverty.
2. Energy poverty has been assessed from the perspective of households as end-users.
3. Literature in English and Latvian has been analysed in the statistical period from 2020 to the end of 2023, as a significant stage of electricity price fluctuations.
4. Options for reducing energy poverty in the EU countries have been assessed.

## 2. ANALYSIS OF ENERGY POVERTY INDICATORS

Energy poverty is closely linked to the problem of poverty, but the emphasis is on energy, as a necessity that includes the primary human needs. The sharp increase in energy prices since mid-2021 has had a significant impact on the EU energy market [23], [46]–[50]. More and more people are struggling to pay for energy, affecting not only low-income residents who previously spent much of their income on energy bills but also the middle income [51].

In line with the EU objective of achieving climate neutrality in 2050, the European Parliament resolution on a strong social Europe for a just transition [52] emphasises fairness and solidarity as key policy principles. On the other hand, the European Commission in its Recommendation 2020/1563 [53] on energy poverty calls for careful consideration to be given to the accompanying Commission Staff Working Document, which guides the identification of energy poverty. The Recommendation defines 13 energy poverty indicators divided into four groups:

1. expenditure on energy versus household income, expressed as a percentage, with the necessary threshold defined accordingly;
2. self-assessment indicators that include household answers to questions such as whether they can afford to keep the home warm enough;
3. indicators based on objective physical measurements (e.g., room temperature);
4. indirect indicators of energy poverty such as late payments, quality of housing, etc.

## 2.1. Energy Poverty Indicators in Europe

Among the key primary indicators for identifying the energy poverty problem are the inability to maintain a suitable temperature in the home, housing inadequacy, and poverty and social exclusion. Recent statistics from 2022 reveal that around 42 million EU citizens, 9.3 % of the total population in the Union, faced an inability to adequately heat their homes [54]. The figure has risen significantly compared to 2021, when 6.9 % of the population was in this situation. The increase is particularly pronounced among lower-income people. Figure 1 reflects the gravity of the situation, which is a clear call for policymakers to take action to address energy poverty factors [55].

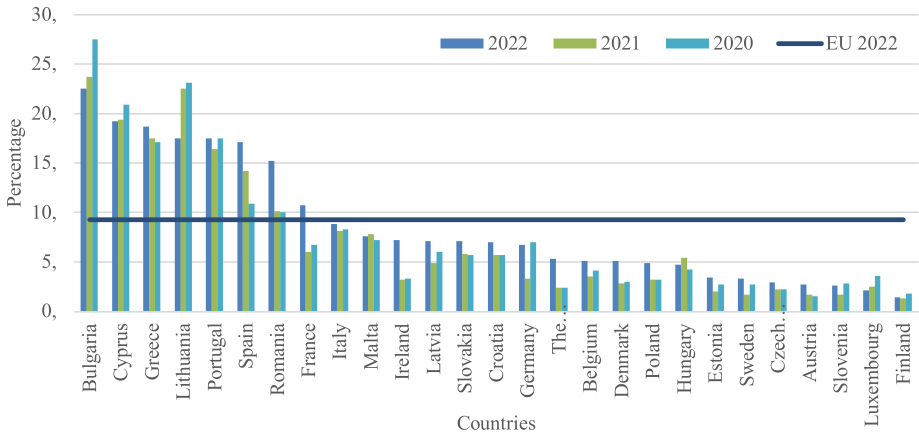


*Fig. 1.* Inability to keep home adequately warm for EU (%) 2020–2022.

As Fig. 1 shows, the highest rates in the EU are in Bulgaria (22.5 %), Cyprus (19.2 %) and Greece (18.7 %), while Sweden (1.4 %), Finland (1.3 %) and Austria (1.5 %) have the lowest rates.

Municipal bill debts are also an important indicator of energy poverty (Fig. 2). Most of these invoices are attributable to energy charges, and timely reimbursement of these invoices may indicate difficulties for households in paying for the services provided [56].

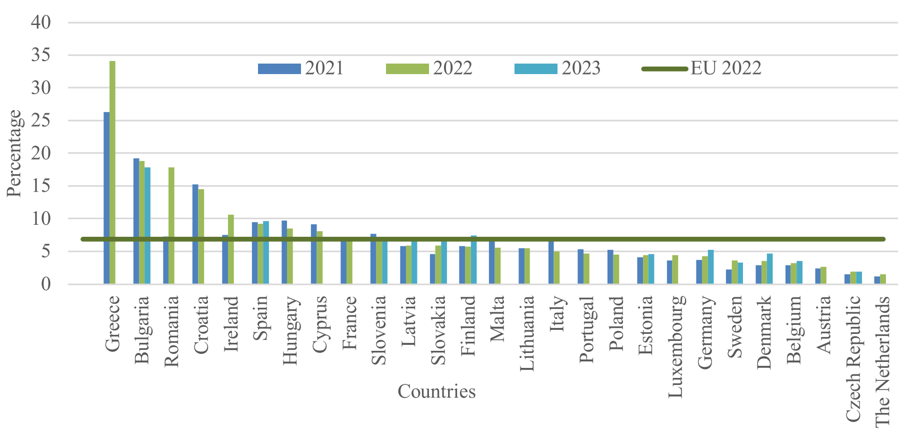


*Fig. 2.* Arrears on utility bills in the EU (%) 2021–2023.

Figure 2 shows that 6.9 % of the EU residents were in arrears for utilities in 2022, amounting to approximately 30 million households. The figure is up from 2021 (6.4 %). The highest rates are in Greece (34.1 %), Romania (17.8 %) and Bulgaria (17.8 %), while the lowest in the Netherlands (1.5 %), the Czech Republic (1.9 %) and Sweden (2.2 %). This indicator was 5.9 % for Latvia in 2022, but it reached 7 % in 2023. Municipal payments were significantly increased by the rapid increase in energy prices in 2022, when energy charges increased by more than 30 % and on average in the EU households led to a 10 % increase in municipal payments, reaching as much as 100 % in Estonia.

In 2022, 95.3 million people (Fig. 3), or 21.6 % of the EU population, were at risk of EU social exclusion and poverty. Poverty risk indicators [57] indicate the proportion of people living in households with at least one in three risks of poverty and social exclusion, which include income levels below 60 % of the median income in the country, residents who do not permit at least four out of nine basic needs and households where adults work less than 20 % of full-time working time. In 2022, the risk of poverty and social exclusion was EU higher for women than for men (22.7 % and 20.4 %) [58].

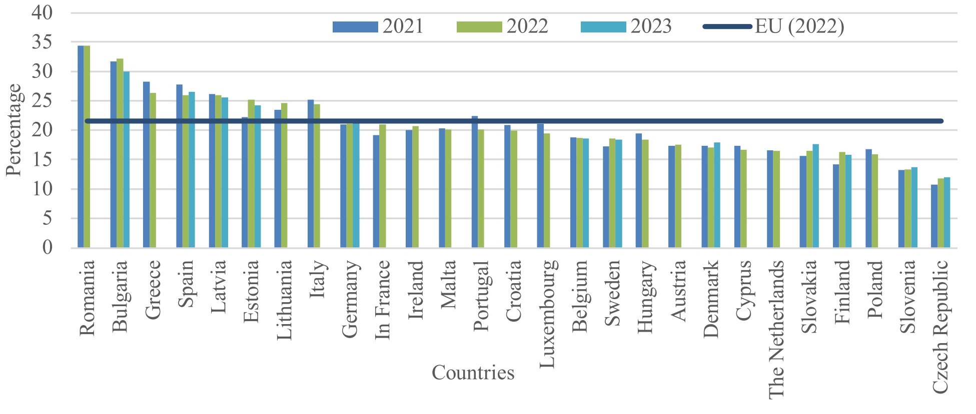


*Fig. 3.* Persons at risk of poverty or social exclusion in EU (%) 2021–2023.

According to Fig. 3, the highest risk of poverty in the EU is in Romania, Bulgaria and Greece, where it remained above 30 % in 2022. It is also relatively high in Latvia (26 %), Estonia (25.2 %) and Lithuania (24.6 %). In Germany, France, Ireland, Malta and Portugal, the risk of poverty and social exclusion stabilised around 20 % in 2022. In countries such as Austria, Belgium, Denmark, Croatia, Cyprus, Luxembourg, the Netherlands, Slovakia, Finland, Hungary, Poland and Sweden, the risk of poverty was below 20 % in 2022. The lowest risk of poverty in the EU was in Slovenia and the Czech Republic (below 15 %).

## 2.2. Energy Poverty Indicators in Latvia

Latvia's statistics measure energy poverty indicators, for example, the proportion of households who, due to lack of money, could not afford to keep their dwelling warm, etc., but they are not legally and economically further related to reducing energy poverty. Latvia is one of the EU countries with one of the lowest income levels [59].

In 2021, 418 thousand or 22.5 % of the population were at risk of poverty in Latvia [60]. The Central Statistical Bureau (CSB) also provides a detailed analysis of data on the financial capacity of different types of households to cope with expenditure. The categories are broken down by household composition and financial capacity and the figures are expressed as percentages. Indicators are divided according to the type of household and the possibilities – whether it is relatively easy for them, with little difficulty, with difficulty, with great difficulty, whether it is easy or very easy to deal with expenditure. In 2023, for example, one person (65 years and over), one adult with children, one person (16–64 years), a couple without children, and a couple with three or more children could pay the costs with great difficulty or difficulty. Regarding the measurement of energy poverty indicators, although Latvian legislation restricts the way energy poverty and household support measures are detected, the Latvian NECP for 2021–2030 is intended to reduce it to European averages [61]. According to the NECP, the primary indicator of energy poverty is the provision of heat housing. In contrast, in the context of Section 120 of the Energy Act, a household affected by energy poverty is one registered as in need or deprived of renting a social apartment. Latvia states in the NECP that in the period up to 2030, the proportion of households deprived of sufficient heat in the dwelling will be reduced below the EU average. Consequently, the 2030 target is for this indicator to be less than 7.5 % in Latvia (in 2022 it was 8.6 % on average in Latvia). Latvian statistics record, but do not apply, energy poverty support solutions to households that could not afford to keep their home warm due to a lack of funds (Fig. 4) [62].

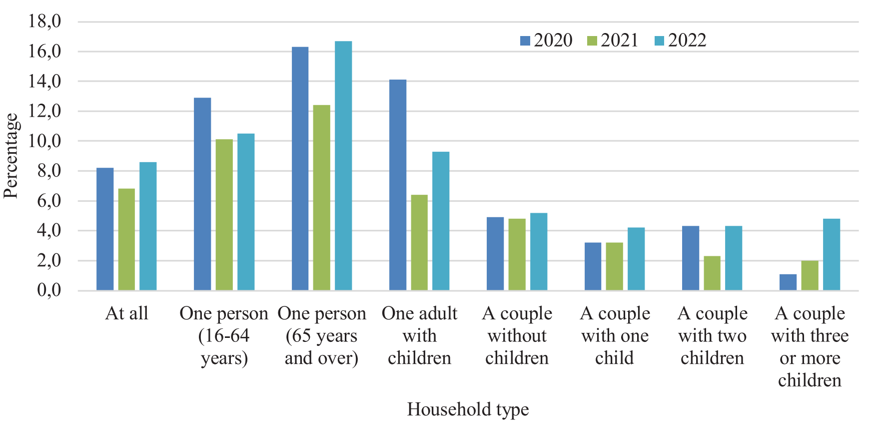


*Fig. 4.* Proportion of households unable to afford to keep their home warm due to a lack of money in Latvia (%), 2020–2022.

Figure 4 shows that in 2022 there were 8.6 % of such households in Latvia, but in some household groups this figure reached 16.7 % (one person over the age of 65). Overall, the proportion of households unable to keep their home warm rose by 27 % in 2022 compared to 2021. Although Latvia's average is lower than the EU (9.3 %), the indicators are significantly higher in some socially vulnerable household groups. One person over the age of 65 is most affected by this problem. In 2022, 16.7 % of households in this group were unable to afford to keep the home warm, up to 34 % in 2021. In 2022, 4.3 % and 4.8 % of couples with two and three or more children were unable to provide sufficient heating, compared to 2.3 % and 2.0 % in 2021.

Regarding another indicator recommended by the EU, which is also registered in Latvia, it should be noted that on average in Latvia this indicator was 7.0 % in 2023, which is slightly above the EU average (6.9 %). This figure has increased since 2021 (5.8 %) (Fig. 5) [63].

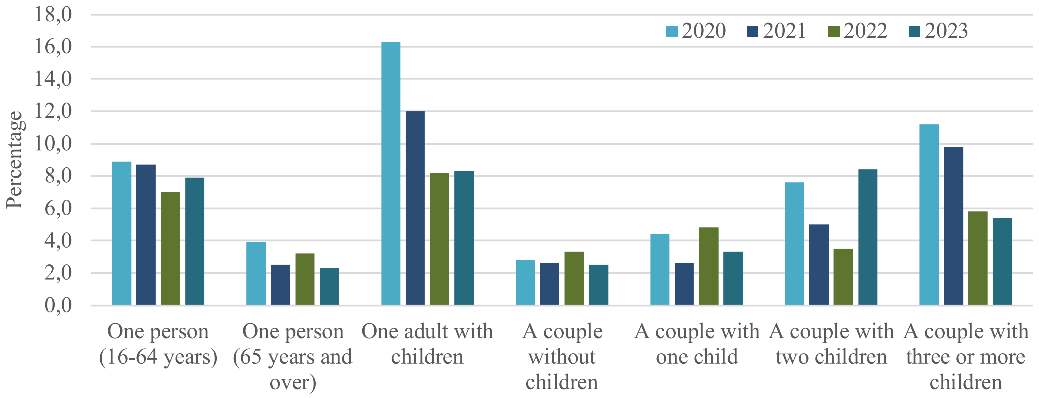


*Fig. 5.* Arrears on utility bills in Latvia (%), 2020–2023.

According to Fig. 5, the proportion of households with arrears for different payments due to a lack of money is seen to have fallen in 2023 compared to 2020. One adult with children (8.3 %) and a couple with two children (8.4 %) have the most arrears. Conversely, the couple without children (2.5 %) and one person over 65 (2.3 %) have the lowest arrears. This shows that the most vulnerable household is one person with children. However, the existence of utility arrears only partly reflects the existence of energy poverty, which also depends on spending priorities. The interviews show that elderly people pay communal payments very disciplined and fear the consequences of not paying them.

The proportion of people at risk of poverty or social exclusion (Fig. 6) [64] is another important indicator that the EU attributes to the detection of energy poverty, which is also used in Latvia.

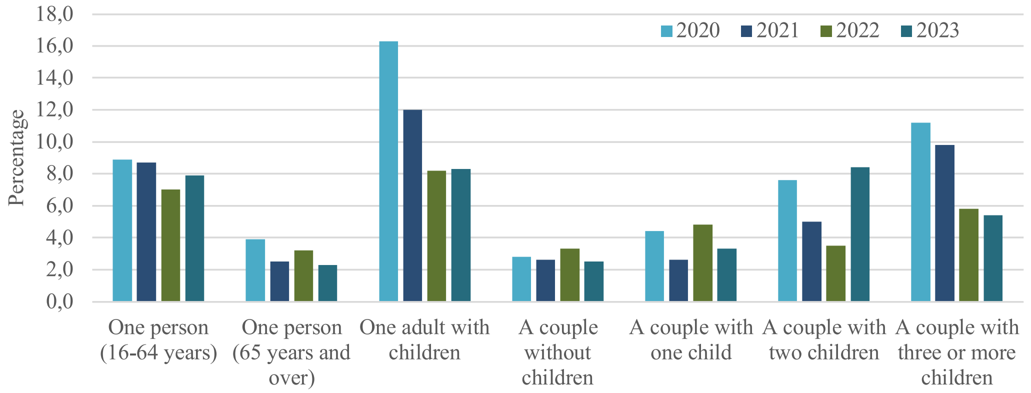


*Fig. 6.* Persons at risk of poverty or social exclusion in Latvia (%), 2021–2022.

Figure 6 shows that in the period of 2021–2022 the proportion of people at risk of poverty or social exclusion was particularly high among the unemployed (62.7 %), pensioners (47.9 %) and non-employed (47.1 %). The rate is also high among the self-employed (25.7 %) and even workers (10.2 %).

## 3. EXPERIENCE OF REDUCING ENERGY POVERTY

The section explores the experience of several EU Member States to make recommendations on good practice.

### 3.1. Reducing Energy Poverty in Europe

The Polish Energy Act [65] defined energy poverty by including three criteria in 2022: low income, high-energy costs and low-energy housing. However, there are difficulties with methodologies that prevent full support. There is no coordinated and uniform policy in the country to alleviate energy poverty. Poland is subject to a social tariff on electricity for the disadvantaged. Energy allowance and housing support, which are paid to low-income households monthly, are also envisaged. In Poland, a pre-paid electricity meter is installed free of charge, enabling the household to control energy consumption in the interests of both the household itself and the electricity trader, thus avoiding unforeseen costs. The Energy Efficiency Law of Poland sets energy efficiency targets and binding requirements in Poland, including elements such as certification of new heating systems [66]. By 2027, remote heat and water consumption measurement systems must be installed on apartment buildings. Energy supply companies are obliged by law to carry out energy efficiency projects for end-users and to provide confirmation of a specific saving. Given the use of coal, support for RES is offered in Poland, as regards heating and replacement of old heating systems under the Clean Air programme [67]. The programme provides financial support for at least 30 % of investments in heat pumps and PV systems for households with an annual income of up to PLN 100,000 (EUR 22,000).

Germany [68] is characterised by a multifaceted approach to tackling energy poverty, especially for people with disabilities. National policies include regional initiatives as well as the non-governmental sector. Energy poverty is recognised as a social problem linked to poverty reduction and social inclusion. Affordable energy is one of the central objectives of Germany's energy transition strategy. The state is helping to cover outstanding energy bills. Consultation support is provided without social support. Local initiatives are common in Germany, with several programmes providing for free or subsidised energy audits, often carried out by volunteers and trained professionals. The country also has a social tariff in place for certain vulnerable user groups. In some cities, households receive benefits for renting more energy-efficient housing. To limit user disconnection from the network, smart meters are tried to limit energy consumption. The StromSparCheck project [69] is a nationwide power-saving support platform that helps local governments and organisations create their own energy audit programmes. The project is based on giving free advice to low-income households about energy saving and choosing services. More than 500,000 people have received energy-saving advice, with an average savings per household of about 0.6 t/year in $CO_2$. In Germany, households have access to programmes that facilitate the installation of small solar PV systems. For example, the KfW programme offers loans of up to EUR 100,000 at an interest rate of 0.35 % per annum and a maturity of up to 20 years.

Bulgaria [70] is one of the most affected countries by energy poverty and has received increased attention recently. The concept of energy poverty is not defined here, the problem is being addressed as part of a broader social policy towards vulnerable users. Nationally, most of the solutions focus on improving housing, such as homes with energy classes E, F, and G receive 100 % of the cost of energy efficiency improvement projects. Bulgaria has introduced social tariffs on electricity for low-income residents, as well as defining other categories of households for whom such a tariff is provided. Social tariffs in Bulgaria are a successful way to alleviate energy poverty for vulnerable households, particularly in the context of the liberalisation of the electricity market and the abolition of regulated tariffs. The solution was to introduce a compensation mechanism covering up to 70 % of the share of the electricity tariff for deprived households with electricity consumption below 100 kWh per month for elderly people over 70 living alone, disabled people, families with a disabled child and those receiving targeted heating benefits. Individual counselling and education for citizens are available in Bulgaria. For defined categories of low-income groups, a heating benefit is available during the winter months, as well as emergency benefits are paid to them once a year, including for compensation of electricity charges. On 30 June 2023, the Energy and Water Regulatory Commission set the renewed feed-in tariffs for electricity produced from renewable energy sources, including biomass, guaranteeing a fixed duty rate per unit of electricity produced [71]. In addition to the feed-in tariff, the Commission shall fix the premiums that energy producers receive from a fund, which serves as a supplement to the feed-in tariff in question. These premiums are based on the reference price set by the Commission as the expected market price, for example, for PV energy producers this price is set at 128.09 EUR/MWh.

In Lithuania, the definition of energy poverty has not been strengthened in legislation, but the methodology recommended by the EU is used in statistics and calculations. In 2021, Lithuania carried out a project "Namų ukiai energetikos transformacijos kotexe" [72], which launched a targeted fight against energy poverty in Lithuania. The project included data mining and analysis to create a system to measure energy poverty in the country and increase the country's effectiveness in reducing it. This resulted in two indicators for measuring energy poverty: household indicator, with a proportionally high share of income for energy and the number of households with no means of adequately heating the dwelling. These data are then used to develop targeted policies to reduce poverty. Since 2005, the government has been carrying out a residential renovation programme that includes building insulation and renovation of heating systems. In Lithuania, energy efficiency obligations have been imposed on energy traders by a special contract to conduct consumer education. In 2020, a programme was opened in Lithuania to support Lithuanian households in switching to PV panels (30 %) and heat pumps (40 %).

The Cypriot Ministry of Economics, with the participation of municipalities and the non-governmental sector, is implementing a 2021 to 2026 project "Tackle Energy

Poverty in Households with Disabled People and Support Social Integration" [24], aimed at achieving the country's NECP objectives and reducing energy poverty by preventing social exclusion in the transition to a climate neutral economy. Within the framework of the project, it is planned to change roof insulation, lighting, and specialised equipment, and purchase energy-efficient household appliances. Subsidies amount to 80 %. The project aims to reduce household energy consumption by at least 35 % in the long term, from 3,900 MWh to 2,535 MWh, saving 1193 t $CO_2$ emissions.

In Spain, the project "Apoyo a las familias en riesgo de exclusión social por parte de las administraciones regionales y locales de La Rioja" [73] aims to mitigate the impact of energy poverty. The uniqueness of the project is that this municipal-funded project involves identifying poor families helping through non-governmental organisations and strengthening cooperation between state and local governments. Energy audits have been carried out within the framework of the project, consultations have been provided, as well as financial support has been provided. Amendments to regional legislation have been developed and made within the framework of cooperation to ensure rapid provision of assistance to the target audience.

The Czech Government is implementing a programme to reduce energy poverty in New Green Savings Light [74]. The programme offers support to households receiving an old-age pension, a third-grade disability pension or housing benefit. For small-scale energy-saving measures such as roof insulation, floor insulation, window replacement and exterior door replacement, applicants receive up to 150,000 Czech crowns (around EUR 6,394). Importantly, funding is already available at the start of the project. As of April 2023, applicants also received a subsidy of 90,000 Czech crowns (approximately EUR 3,835) for PV systems. The programme also includes free counselling options. Good national practices are summarised in Table 1.

**Table 1.** An Overview of Experiences from Other Countries

| **Country** | **Good practice** |
|---|---|
| Poland | Social tariff on electricity, energy benefits and housing support for low-income households. The Clean Air programme provides financial support for heat pumps and PV systems. |
| Germany | A multi-faceted approach, including national and regional initiatives, the non-governmental sector. Free or subsidised energy audits and consultancy. The StromSparCheck project is about saving power. |
| Bulgaria | Social tariffs on electricity for low-income households. 100 % support for energy efficiency improvement projects for low-energy homes. Personal consultancy and heating benefits during winter months. |
| Lithuania | Residential renovation programme. Imposing energy efficiency obligations on energy traders. Grant programe for transition to PV panels and heat pumps. |
| Cyprus | Project Tackle Energy Poverty in Households with Disabled People and Support Social Integration. Replacement of roof insulation, lighting, and specialised equipment with an 80 % subsidy. |
| Spain | The Apoyo a las familias en riesgo de exclusión social project includes energy audits, advice and financial support. Cooperation with non-governmental organisations and amendments to regional legislation. |
| Czech Republic | New Green Savings Light programme with support for old-age pension, disability pension and housing benefit recipients. Subsidies for RES systems and free counselling. |

As Table 1 shows, the most common best practices in reducing energy poverty include introducing social tariffs and energy benefits for low-income households, energy efficiency improvement programmes, and providing free or subsidised energy audits and advice. Support for the use of renewable energy technologies and targeted programmes for vulnerable groups are also essential. The combination of these measures helps ensure a sustainable energy supply and reduce energy poverty across different groups of society.

### 3.2. Experience of Latvia

Latvia's National Development Plan 2021–2027 [75], and Latvia's Sustainable Development Strategy until 2030 [76] determine important areas for further development of the country, which are the reduction of social exclusion and poverty, improvement of energy efficiency, the introduction of renewable energy resources, as well as areas for improvement of housing quality. These documents specify the responsible institutions and the areas of their activities in achieving the objectives. The relevant decisions are enshrined in the Latvian legislation, such as the Energy Efficiency Law [77], and the Construction Law [78], which lays down principles and objectives of energy efficiency policy, and energy efficiency requirements for buildings, heating and cooling systems. Several social support instruments have been introduced in Latvia, which have an indirect impact on reducing energy poverty, for example, the Law on Measures for the Reduction of Exceptional Increase in Energy Resource Prices [79] provides for reducing the negative socio-economic impact of the increase in energy prices on low- and medium-low-income households by granting aid in the form of a reduction in the fee for the natural gas, thermal energy, electricity and decentralised fuel consumed. These measures were implemented in 2022 to protect households from the sharp rise in energy carrier prices.

The Latvian legislation also provides for social support for various vulnerable groups, such as the Law on Social Services and Social Assistance [80], the Cabinet Regulation Regarding the Assessment of the Material Situation of a Household and Receipt of Social Assistance [81], which provides support for persons and low-income families to ensure that their basic needs are met. At the same time, Latvian municipalities are entitled to decide on the aid to be granted and the amount thereof to vulnerable households by striking regulations. Services and discounts for protected users are an important social support tool to offset energy charges. The Electricity Market Law stipulates that a protected user is a poor or low-income family (person), multi-child family or family (person) in the care of whom there is a disabled child or a person with disability group I who uses electricity in their household for their own needs (final consumption) [82]. As regards the protected user, the law provides several reliefs, which affect discounts not only in the application of tariffs but also in the provision of connection and the prohibition of disconnecting them from the energy supply. The amendments made to Cabinet Regulation No. 345 "Regulations Regarding the Trade Service of a Protected Customer" strengthened their protection from 12 December 2023, because they obliged all electricity traders to provide the protected User Service regardless of the number of subscribers. From 1 January 2024 [83], the aid intensity of the protected user was also increased by setting it at EUR 25 for a multi-child family and EUR 20 for needy/low-income households (persons), families in the care of a disabled child, a person with disability group I or its trustee instead of the previous EUR 15. In May 2022, protected users included persons with disability group I and children with disabilities (34,954), needy or low-income families (45,318), multi-child families (83,827). As of June 2022, there were 164,099 protected users in the country, but only 90,358, or 55 %, received support. The service did not apply to 11,110 persons on the maintenance debtor register.

Development Financial institution Altum JSC shall provide a support programme to owners of one apartment house, by Cabinet Regulation No. 103 of 11 February 2021 "Regulations Regarding the Support Program for the Renovation and Energy Efficiency Improvement of Single-Apartment and Two-Apartment Residential Houses", for purchasing of new electricity production equipment and improvement of energy efficiency for families with children in the form of a guarantee, support and/or grant. Aid intensity is up to EUR 4,000 for solar and wind power plants, and up to EUR 5,000 for energy efficiency. 80 % of the annual electricity production must be used for own consumption. The aim was to achieve a reduction in primary energy consumption of at least 20 %. It is not permitted to be used in economic activities. At present, new applications have been suspended [84].

The Central Finance and Contracting Agency provides a support programme for apartment homeowners, in line with the specific support objective to improve nature conservation and biodiversity, and green infrastructure by improving household heating systems. The programme provides support for connection to district heating systems, as well as for the purchase and installation of thermal energy sources, including heat pumps, pellet boilers, biomass boilers and electric heating systems. The costs covered by the aid may amount to up to EUR 4400 per declared population, with a maximum aid intensity of up to 95 % depending on the type of solution. Self-consumption must use at least 80 % of the annual electricity production. An economic activity may be carried out under the conditions of de minimis aid [85]. The amendments to the Electricity Market Law [82] provide that from 1 May 2024 the new net settlement system, which is used by users who have not joined the old accounting system, and which provides for a system of mutual settlement not according to quantity but price, became operational.

## 4. CONCLUSION

Energy poverty is a multidimensional issue, affected by high energy expenditure relative to the total household budget, low-income levels and insufficient energy efficiency in housing and equipment. Energy poverty has a particular impact on low-income households, children, disabled people, seniors and single mothers, who may have relatively higher energy consumption and limited resources available. As a result, these groups are exposed to higher energy poverty. At the EU level, solutions are being taken to improve energy efficiency and reduce energy costs, for example, through the Social Climate Fund and the Just Transition Fund. In Latvia, the NECP envisages a goal to reduce energy poverty by improving the indicator of users' inability to maintain adequate temperature in a dwelling to 7.5 %. The EU looks at different indicators of energy poverty, such as the inability to maintain a suitable temperature in a dwelling, quality of housing, debts of municipal bills, and persons subject to social exclusion. For example, the highest risk of social exclusion in the EU is in Romania, Bulgaria and Greece, where it remained above 30 % in 2022. It is also relatively high in Latvia (26 %), Estonia (25.2 %) and Lithuania (24.6 %). Energy poverty indicators in Latvia include income level and poor or low-income status. Statistics show that 22.5 % of Latvia's population was at risk of poverty in 2021. The proportion of households unable to keep their home warm rose by 27 % in 2022 compared to 2021. Other countries have different experiences in solving the problem of energy poverty, from which Latvia should use the definition of energy poverty and its measurable indicators, identification of supported households, on-the-spot consultations and audits, attracting local governments, and non-governmental organisations, as well as improvement of RES support instruments.


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# MOULD RESISTANCE OF PAPER PLASTER MADE FROM CELLULOSE-CONTAINING WASTE

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The objective of this study was to determine mould resistance of the plaster made from waste paper. To study the plaster quality, two laboratory tests were conducted. First, mould resistance of a dry plaster was studied, and second, mould resistance of a wet plaster was tested. Since wet plaster mix must be used for plastering, the resulting surfaces are extremely wet. The plaster placed on the wall would dry for at least two weeks under favourable conditions (sufficient ventilation and temperature). During this period, there is a great risk that the plaster might become mouldy. Another risk of becoming mouldy occurs when an already plastered wall receives moisture (e.g., water damage). The experiments carried out under laboratory conditions showed that in an environment with high relative humidity the plaster did not become mouldy.

***Keywords***: *Mould resistance, paper plaster, waste recycling.*

## 1. INTRODUCTION

Paper plaster has a very good moisture buffering capacity, which means that the plaster is porous, absorbs moisture readily, and emits it to the surrounding environment. Previous laboratory studies confirm that paper plaster is an outstanding water buffering material belonging to the moisture buffering class presented by Nordtest method as “excellent” [1].

The impact of various additives (clay, chalk, and lignin) and different technologies on the moisture and properties of plaster has been reflected in several research papers [2]-[6]. A large amount of wastewater is generated during the production of paper plaster. The effect of the adhesives used in the fabrication of paper plaster on the hygroscopic properties of the plaster has been studied by Nutt et al. [5], as has the impact of colouring on the hygroscopic properties of the plaster [4]. Although a lot of attention has been paid to different properties of paper plaster in recent years, the mould resistance of paper plaster has not been studied in detail.

Indoor dampness is a considerable problem in European countries [7]-[10]. Haverinen-Shaughnessy has found that mould is present in more than 10 % of European houses [11]. Several hundreds of bacterial and fungal species can be found from indoor environment [12]. Mould can cause damage to a building and initiate chemical emissions from building materials, which are prone to microbial growth and health hazards for the residents [13]-[15]. Most commonly the moulds found in homes belong to the species *Penicillium*, *Cladosporium*, *Aspergillus* [16]; [17], *Alternaria*, *Fusarium*, and *Trichoderma* [18].

An environment supporting fungal growth is created when even some of the listed prerequisites are met: wet-to-moist area is present, provided that the right temperature ranges, micro- and macronutrients are available [19]. Certain organic substances are broken down and absorbed by mould fungus [20]. When the temperature is between 0 and 50 °C and the relative humidity (RH) is more than 65 %, fungal growth usually takes place [21]. The conditions of 20 to 35 °C, a stagnant environment, and a relative humidity of greater than 95 % are ideal for the fastest growth [20]; [22].

## 2. MATERIALS AND METHODS

### 2.1. Specimens

The mould resistance of nine different paper plaster mixes was studied. The mixtures were made from three components: newsprint, glue, and water. Crumpled newspaper was placed into tap water (room temperature) for 24 hours.

The mixture was then stirred until the paper was disintegrated and a uniform mass was formed. Excess water was drained from the mixture by pressing on a sieve, after which the adhesive mixture was added. In order to prepare the glue, the Metylan Universal Premium wallpaper adhesive made from potato starch (Amylum Solani) ($C_6H_{10}O_5$), methylcellulose ($C_6H_7O_2(OH)_x(OCH_3)_y$), and methylcellulose ($C_6H_7O_2(OH)_x(OCH_3)_y$) were used.

**Table 1.** Composition of Paper Plaster Mixtures, Paper Type: Newspaper; Paper Weight: 500 g

| Mixture code | Paper type | Glue type | Notes |
|---|---|---|---|
| A-T100 | Newspaper | potato starch | *Amylum Solani* $C_6H_{10}O_5$ |
| A-T50 | Newspaper | potato starch | *Amylum Solani* $C_6H_{10}O_5$ |
| A-T20 | Newspaper | potato starch | *Amylum Solani* $C_6H_{10}O_5$ |
| A-H30 | Newspaper | Metylan Universal Premium | modified starch, chemically introduced antifungal additives |
| A-H20 | Newspaper | Metylan Universal Premium | |
| A-M20 | Newspaper | methylcellulose | $(C_6H_7O_2(OH)_x(OCH_3)_y)$ |
| A-M10 | Newspaper | methylcellulose | $(C_6H_7O_2(OH)_x(OCH_3)_y)$ |
| A-M5 | Newspaper | methylcellulose | $(C_6H_7O_2(OH)_x(OCH_3)_y)$ |

All the specimens with certain composition were prepared and tested in triplicate. The first group of test specimens were dry, prepared 2.5 years before the start of the experiment, and stored indoors at room temperature in plastic containers where they were exposed to airborne mould spores. The second group of test specimens was prepared directly before the start of the experiment and was not dried. The test specimens had a diameter of 9.0 cm and a height of 2.5 cm.

### 2.2. Method and Equipment

The experiments were carried out in full accordance with the ASTM standard method D3273-00 "Standard Test Method for Resistance to Growth of Mould on the Surface of Interior Coatings in an Environmental Chamber" [23]. This standard uses qualitative rating scale based on visual examination and describes the test environment and its operating conditions to assess indoor mould growth over a 4-week period. The work was performed in the RUMED 4101 climate chamber, where the relative humidity could be adjusted between 20 % and 95 % (accuracy ± 2−3 %) and the temperature between 0 °C and 60 °C (accuracy ±0.5 °C). A Kern PLT 1200-3A digital scale with a measurement range of 0 to 1200 g and an accuracy of 0.001 g was used to prepare the mixtures.

In the first test, the mould resistance of the dry test specimens (group 1) was studied. The surface of the test specimens was visually evaluated every two days. The test specimens were hung in the climate chamber in such a way that their contact with each other was excluded and that, in the presence of mould, the mould could not be transferred to the other test specimen because of contact. The experiments were started at 75 % RH, and its value was increased by 5% each week. The temperature was 22 °C ± 0.5 °C during the experiment. At the end of the experiment, the air humidity in the climate chamber was 95 %. Test specimens were made in 3 parallels.

In the second experiment, the mould resistance of the wet test specimens (group 2) was studied. The test specimens were placed in the climate chamber immediately after their preparation. The tests were started at 95 % relative humidity, and the humidity was decreased by 5 % each week. The temperature was stable during the experiment (22 °C ± 0.5 °C). At the end of the experiment, the air humidity in the climate chamber was 75 %. The surface of the test specimens was visually evaluated every two days.

## 3. RESULTS AND DISCUSSION

The following mould species: *Aspergillus spp., Alternaria spp., Penicillium spp., Cladosporium spp., Fusarium spp., Trichoderma spp.* were tested during the five-week experiment, when the dry test specimens (group 1) and the wet test specimens (group 2) were kept in an environment favourable for mould growth (RH = 75–95 %, temperature 22 °C). No mould was detected by visual inspection. The test specimens of the second experiment in the fifth week of the experiment are shown in Fig. 1.

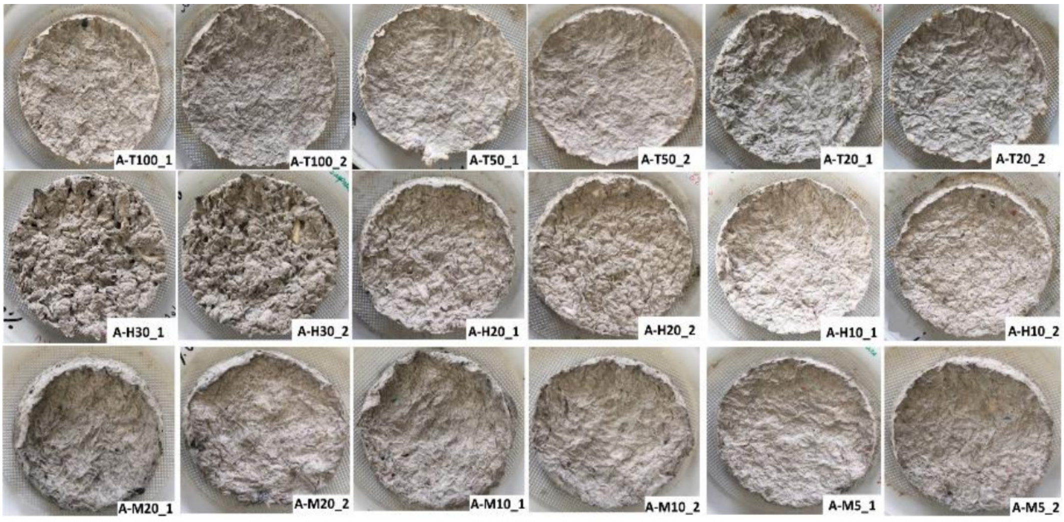


*Fig. 1.* Test specimens of the second experiment on the fifth week.

The results of the tests conducted show that paper plaster is not an interior finishing material that readily becomes mouldy, both when the plaster in the wall gets wet and when the wet plaster dries after installation. Mould grows in the pH range of 3.5 to 8 [24].

In general, moulds require an acidic environment (pH<7) to grow [25]. The more basic the environment, the less chance there is for mould growth. However, some species of fungi can also grow under slightly alkaline conditions [26].

For the moulds *Aspergillus spp. and Trichoderma spp*., the favourable growth conditions require pH level of 4 as a minimum (Sing and Desrosier, 2024). The maximum pH level that favours growth is 7.5 for *Aspergillus spp.* at 30 °C and a pH level of 6 for the temperature range between 25 °C and 30°C in the case of *Trichoderma spp*. [27]. For *Alternaria spp*., pH from 6 to 7 and temperature between 30 °C to 40 °C are favourable growth ranges.

*Penicillium spp*. has the widest favourable pH growth range of the selected moulds in the sample (from 3.9 to 9.1) [28]; [29]. *Cladosporium spp.* is the fungus present in the sample with the lowest growth-promoting pH level and temperature [29]. The pH that favours the mould growth is between 3.5 and 6.7, and the temperature is between 15 °C and 35 °C [30]. In contrast to *Penicillium spp., Fusarium spp*. has the narrowest favourable pH range of 6.7 to 7.2 between 24 °C and 26 °C [31]. The optimum temperature for *Penicillium spp*. growth is 25 °C [31].

While methyl cellulose or Metylan universal premium is mixed to make paper plaster, they create an alkaline environment (pH=7.8 or 9.8) that most mould species cannot grow in. The only exception in this case is *Penicillium spp*., whose maximum growth-promoting pH is 9.1. Since the temperature in the climate chamber was established at 22 °C ± 0.5 °C and the growth of the fungus was promoted with 25 °C temperature, this three-degree temperature difference could have affected the growth of moulds on the test specimens, as temperature is known as one of the abiotic factors that can affect mould growth [31]. The pH level of the test specimens, which were prepared using potato starch as an adhesive, was 6.7 and did not change during the experiment.

This given pH level was suitable for almost all mould species, except for *Trichoderma spp*. [24]; [27]. Also, the obtained pH was quite close to the upper limit of the pH level which favoured the growth of mould *Cladosporium spp*. [24]; [27]. In the case of mixtures made with potato starch, the main reason for the non-appearance of mould could have been the potato starch itself being used as an adhesive. The temperature in the climate chamber was not conducive to growth, still moulds grow at 22 °C, although more slowly [31].

Organic substances are added to paper plaster to change the colour or properties of the paper plaster [3]. As a result of adding various organic substances to paper plaster, the mixture can become more acidic, providing a greater chance of mould growth. Moulds prefer pH level 3−7, but most mould requires slightly acidic conditions [32]. Alternatively, organic additions may initiate the opposite reaction, and the mixture becomes more alkaline, inhibiting the formation of moulds. There is also a risk that the organic matter used as an additive has mould spores on it.

## 4. CONCLUSION

The mould resistance of nine different paper plaster mixes made from three components − newsprint, glue, and water − was studied. The results of the tests conducted showed that paper plaster was successfully applicable as an interior finishing material as it did not become mouldy in the environment favourable to moulds: both in the case when the plaster got wet or during the period when the wet plaster dehydrated after installation.

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# REGULATION AND ORGANISATION OF HOUSING MANAGEMENT ACTIVITIES IN GERMANY, POLAND AND LATVIA

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Multi-dwelling buildings are one of the essential infrastructural elements of a residential area. Therefore, qualitative and professional management of such real estate is of importance. The insufficient investment into maintenance and improvement of housing is stated in Latvian policy planning documents as one of the most significant problems, causing risks for achieving the goal of compliance of the housing fund with energy efficiency, construction, safety and amenity standards.

The article examines the main aspects of management of residential buildings, identifies the related risks and offers solutions for their prevention. The article aims at emphasising the significance of building maintenance and exploring management processes of residential buildings in Latvia, Poland and Germany, making a comparison that helps to understand the housing management regulation and organisational approach in each country and identify their common and differing features.

In the course of the research, the authors of the article review the sources on management activities of residential buildings, identify and assess the management process risks and make a comparative analysis of housing management processes in Latvia, Poland and Germany.

Information regarding the housing management field of the countries examined in the article has been obtained by summarising and analysing the policy documents and regulatory enactments, as well as by interviewing Latvian, Polish and German experts.

When analysing the obtained results, conclusions have been made with regards to political responsibility, legal regulation and professional competence requirements in the field of housing management.

***Keywords:*** *Housing management, housing policy, multi-dwelling buildings, residential buildings.*

## 1. INTRODUCTION

The economic growth of residential areas depends largely on its infrastructure, which is formed by a number of different elements. Multi-dwelling buildings are one of the essential infrastructural elements of a residential area which depreciate with time. Therefore, qualitative and professional management of such real estate is of importance. By not performing the due maintenance and timely restoration of some elements of the infrastructure, deterioration of their technical condition and transformation into slum is inevitably approached.

Latvian policy planning documents stipulate that it is required to ensure the development of all types of infrastructure and improvement of its quality, availability of basic services and qualitative housing. National Development Plan of Latvia for 2021–2027 sets goals for compliance of the housing fund to the energy efficiency, construction, safety and amenity standards [1]. Housing Availability Guidelines for 2023–2027 stipulate that insufficient investment into maintenance and improvement of housing is one of the most significant problems [2].

One of the main obligations of owners of residential buildings is to ensure housing management, which also includes decision-taking related to their building management and conclusion of transactions. If the owners do not ensure the housing management themselves, such activity is assigned to a professional manager.

To ensure professional and sustainable management, the manager should inform the owners on the content of services, technical features of the administered facility, opportunities for improvement, maintenance costs and other factors related to the management process. Rights and obligations of the manager should be considered in connection with the assigned volume of the management task, which is stated in writing in the concluded management authorisation agreement.

Management of multi-dwelling buildings is a functional process of mutual interaction, which is ensured by observing the continuity principle in order to implement a set of organisational, economic, engineering, legal, political, social, technological and informative activities aimed at effective management, which is performed in order to achieve extension of the housing life cycle, safe operation of the residential building, observation of human health and environmental safety principles in the context of the housing sustainable preservation [3]. The priority accorded the issue of housing in emerging markets is immense; to most governments, the availability of sufficient but basic housing for all is often stated as a priority for enhancing the social needs of society [4].

Currently, there are no uniform requirements in the European Union regarding the housing management process and the managers as such. Each member state has a different practice in regulation of the housing management process, determining the limits of responsibility between the parties involved in the process, requirements to their education and qualification, and support mechanisms. However, there is one common goal – to ensure the appropriate maintenance of the housing fund, enabling to maximally extend the housing life cycle. Buildings have been amongst the most valuable assets of any nation in the sense that they provide people with shelter and facilities for work and leisure. It is known that the specific perspective of building maintenance still does not receive the attention it should [5], [6].

In many cases, especially in Western Europe, owners of multi-dwelling buildings delegate their housing maintenance to a professional management enterprise. Whereas the characteristic situation for Eastern Europe is when owners of multi-dwelling buildings are natural persons, who live in the apartments owned by them [7].

The article examines main aspects of management of residential buildings, identifies the related risks and offers solutions for their elimination. The authors analyse activities related to housing management in Latvia, Poland and Germany, making a comparison regarding the political responsibility, legal regulation and the professional competence requirements in this field.

## 2. METHODOLOGICAL APPROACHES

The article aims at emphasising the significance of building maintenance and exploring management processes of residential buildings in Latvia, Poland and Germany, making a comparison in order to understand the housing management regulation and organisational approach in each country, common and different features, as well as evaluating which of the activities could be taken into consideration and included in implementation of the national housing management process.

In the course of the research, the authors of the article:

- review the sources on management activities of residential buildings,
- identify and assess risks when organising the housing management process,
- make a comparative analysis of housing management processes in Latvia, Poland and Germany.

To make the comparison, indicators such as the requirements to education of real estate managers, training opportunities, the manager's role in the real estate administration and chief management activities have been used.

The authors of the research have identified the criteria for evaluating the opportunities to improve training of managers of multi-dwelling buildings and to include topical themes in the study process. It has been clarified in the course of the research what skills need to be developed or studied more profoundly during the training, for example, a more profound understanding of climate change issues and increasing energy efficiency of buildings, as well as of digitalisation issues.

Information regarding the housing management field of the countries examined in the article has been obtained by summarising and analysing the policy documents and regulatory enactments, as well as by interviewing Latvian, Polish and German experts. Identification and analysis of the main management activities is based on regulatory enactments. The article uses materials from the European Climate Initiative – EUKI[1] project "CLI-MA (From Housing Manager to CLImate MAnager)".

## 3. MANAGEMENT OF RESIDENTIAL BUILDINGS IN LATVIA

Management of residential buildings is a long-term process, where the decisions taken affect the situation in the future. In total, about a half of the European Union residents (46.4 % in 2021) live in multi-dwelling buildings [8]. Thus, the issue of management of residential buildings and its optimal organisation is very topical.

Well-being of any resident of an apartment depends on the way the management process is organised; therefore, owners have to take a decision regarding who will provide management of the residential building. Efficient and qualitative management of residential buildings promotes a more active involvement of house residents in organising the management process, which, in its turn, makes the manager's work transparent and facilitates its quality control, as well as the efficient usage of financial resources. The type of apartment ownership is closely related to the remaining residential property of a particular building. To ensure the harmonious development of residential property, the apartment owners, on the basis of the existing laws and regulations, as well as mutual decisions, jointly agree on further maintenance, development of the building, efficient use of resources and management [9].

### 3.1. Management Activities in Latvia

One of the most important directions of management of residential buildings in Latvia and other Eastern European countries is their maintenance and sanitary cleaning, which are performed for the purpose of supporting the respective aesthetic place of residence and environment. Technical support includes maintenance, repairs, fast response in the event of detecting defects, as well as technical inspections, in order to avoid premature damage of the facility and its engineering systems, organisation of repairs [10]. Sanitary cleaning and improvements in a residential building is a service that ensures cleanliness in the building and its entire territory by tidying and cleaning internal premises in accordance with the requirements of the owners and users [11].

Types and strategies of technical support or maintenance can be classified as follows:

- Preventive maintenance, which is performed at certain previously set time periods or in accordance with the previously set criteria and intended to reduce the possibility of errors or deterioration of the object functioning,
- Maintenance based on the actual technical condition, which is performed based on the prophylactic technical inspection and observing the dynamics and/or parameters and the following activities.

[1] EUKI (Die Europäische Klimaschutzinitiative) is a project financing instrument formerly provided by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) and today managed by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

Repairs or maintenance are performed when a deficiency is revealed and the unit is to be renovated, in order to restore the required performance.

Housing management includes a range of routine activities:

- Organisation of public utilities, e.g., water, electricity, heating and waste removal,
- Planning and ensuring performance of maintenance, repairs and sanitary cleaning,
- Management of financial resources, including development and administration of the housing budget, collection of payments from owners and preparation of reports on expenses,
- Communication with owners and other involved parties, e.g., municipality and service providers.

Housing management encompassing activities are illustrated in Fig. 1.

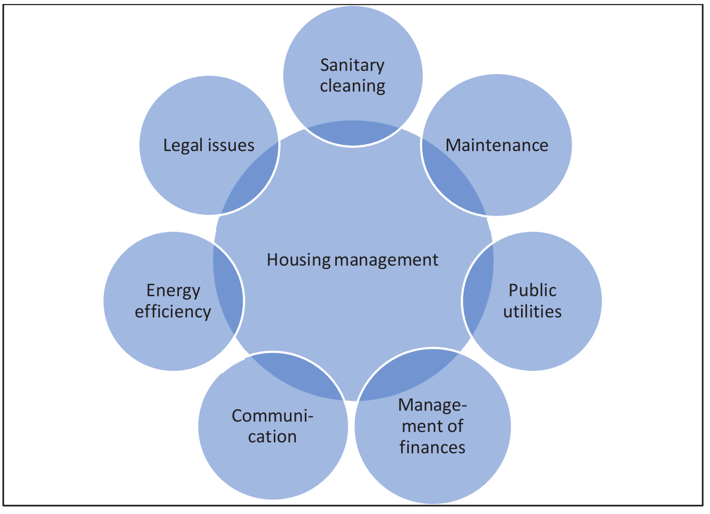


*Fig. 1.* Housing management activities

Housing management encompasses a number of categories, including technical management (maintenance, renovation, etc.), financial management (housing financing, housing policy) and operational (daily) and strategic housing management activities. It encompasses short-term decisions and activities such as response to routine problems, as well as mid- and long-term management policy [12].

Management of residential buildings includes services such as supervision of agreements, organisation of repairs and renovations, preparation of reports on lease activities and their administration, representation of the owner at court, filing of all technical and legal documentation of the house, as well as consulting owners on real estate strategic management.

Housing management encompasses not only ensuring of the general technical condition of the building, but also improvement of its energy efficiency. The housing manager should ideally be capable of stimulating owners to implement projects to increase energy efficiency of the building.

Stability of the place of residence is directly connected to safety of the building, which means ensuring that strangers do not get into the building and the property is not damaged as a result of unforeseen accidents. Also, the arrangement of lease relations in the respective country is vital here [13].

## 3.2. Management Process Organisation in Latvia

Housing management can be organised both by societies established by residents (owners of apartments) and owners, and by professional managers. In view of the aforementioned, it can be concluded that the following consecutive steps have to be observed in assigning the management order binding for the parties:

- A society of apartment owners of the residential building has to take a decision on choosing the management form and the draft agreement provisions,
- If it has been chosen to assign the housing management to a company or a professional manager, a management agreement has to be concluded between apartment owners and the manager on fulfilment of the management assignment,
- If it has been chosen to ensure management without an intermediary, owners agree between themselves on the duties to be taken and the provision of financial resources.

Each management form is characterised by different types of risks, for example, lack of professional skills, lack of capacity (capacity includes increase of work quality and efficiency of managers, improvement of development and introduction of the policy of actions, improvement of cooperation and coordination between all parties involved in the management process), non-professional accounting of the budget, lack of cash resources, etc. Possible risks in-line with bad management are comprehensively described in Table 1.

**Table 1.** Housing Management Risks for Residential Buildings

<table>
<tr><th>Apartment Owners</th><th>Society of Apartment Owners</th><th>Professional Manager</th></tr>
<tr><td colspan="3">Lack of professional skills</td></tr>
<tr><td>Performance of unnecessary repairs (funds are invested in improving visual appearance of the building but not in improving safety of the building structures or energy-efficiency increase)</td><td>No skills in taking professional decisions and determining priorities when making repairs</td><td rowspan="2">Weak theoretical knowledge but practical skills available. Thus, an erroneous decision can be taken, not observing requirements of regulatory enactments and standards.<br>Poor or no skills in applying theoretical knowledge and regulatory requirements in practice.</td></tr>
<tr><td colspan="2">Insufficient knowledge regarding regulatory requirements<br>Lack of technical knowledge<br>Lack of skills in organising the management process<br>Errors in work with documents</td></tr>
<tr><td colspan="3">Lack of knowledge of climate change issues and energy efficiency in general</td></tr>
<tr><td>Lack of knowledge in final benefits from introducing energy efficiency measures. Do not believe in the human effects on climate changes.</td><td>Weak knowledge on measures and actions in order to improve the capability to adjust and facilitate stability regarding climate change and its consequences.</td><td>There are theoretical but no practical skills regarding measures and actions in order to improve the capability to adjust and facilitate stability regarding climate change and its consequences.<br>Very general approach to implementation of energy efficiency measures and the subsequent maintenance of the building.</td></tr>
<tr><td colspan="2">Insufficient knowledge regarding the impact of climate change on different industries of the national economy and the society in general.</td><td></td></tr>
<tr><td></td><td colspan="2">No skills to develop a long-term energy efficiency strategy for the building.</td></tr>
<tr><td colspan="3">Lack of capacity</td></tr>
</table>

<table>
<tr><th>Apartment Owners</th><th>Society of Apartment Owners</th><th>Professional Manager</th></tr>
<tr><td>Insufficient resources to perform the required works, for example, regular repairs and prevention of accidents.<br>Only few owners are involved in the management process.</td><td>Lack of professionals, resulting in errors in budget planning (insufficient funds for management and repairs).<br>Non-professionally concluded contracts on repair, renovation and other works.</td><td>Insufficient planning and organisational capacity; it is not possible to organise fast emergency works.<br>Insufficient knowledge on specific technical activities, materials, equipment, etc.</td></tr>
<tr><td colspan="3">Non-professional accounting of the budget</td></tr>
<tr><td colspan="2">During the management process, accounting reports are not prepared with due quality and are not submitted within the deadlines set in the regulatory enactments, the cash flow (incomes and expenses) is not accounted precisely.</td><td>Due to lack of professionals, accountants are employed, who are not familiar with the housing management specifics and make errors in the accounting files.</td></tr>
<tr><td colspan="3">Lack of cash resources</td></tr>
<tr><td></td><td colspan="2">There is a lack of financial resources to pay the employees.</td></tr>
<tr><td colspan="3">Accruals are not made, there is shortage of cash flow and lack of cash for the planned works.<br>If owners of the residential building do not pay for services in due time, penalties may be calculated and/or provision of services may be terminated.</td></tr>
</table>

To prevent the aforementioned risks in the course of the management process, it is required to select responsible people and employees with professional knowledge in the respective field. If employees have insufficient professional skills, it is possible to improve these, e.g., by providing and participating in trainings, seminars, etc. It is also possible to attract professionals in the respective filed pursuant to an agreement. Whereas, if a risk has already turned into a problem, knowledgeable people or experts have to be sought to evaluate the situation and provide proposals for a solution of the situation.

Where knowledge regarding energy efficiency issues and climate change is insufficient, general or mostly theoretical, it is required to plan professionally and determine the specific directions of activities, in order to adjust to climate change more successfully. In such a case, professional competence and skills to attract appropriate specialists are significant.

To prevent the capacity risks, already during the planning process, it is necessary to analyse different situations regarding the performance of work, providing specific solutions. It is also recommended to conclude agreements with the required service provider, who will be involved in solving an occurring problem when needed. For example, repairs are started, which have to be finished until a certain deadline, but there is insufficient labour force to complete the work – additional workers have to be sought and contracted.

To avoid non-professional budget accounting, the solution is to employ professional accountants, as well as to observe the so-called “four eyes” principle, so that, when organising financial accounting, a minimum of two employees participate in performing the specific functions.

To prevent lack of cash resources, it is required to form cash accruals, to perform the result-focused reminder or warning process regarding non-payers, as well as to start the debt collection process against them. It is possible to borrow lacking financial resources at credit institutions (in such a case, loan interest has to be taken into account as additional expenses).

The identified risks and solutions for their prevention indicate to the importance of competence, qualification and training of persons who ensure management activities.

## 4. COMPARISON OF HOUSING MANAGEMENT IN GERMANY, POLAND AND LATVIA

### 4.1. General Comparison

Management of residential buildings requires increasingly more complex knowledge, skills and competences. Within the framework of the research, to obtain an idea about the approach of different countries, housing management conditions in Germany, Poland and Latvia have been compared regarding both, general issues (political responsibility, formal and informal education) and specifically renovation of buildings and energy efficiency increase issues. Information on general housing management conditions is summarised in Table 2 and text of this subchapter [14], [15], [16].

**Table 2.** Comparison of General Housing Management Conditions in Germany, Poland and Latvia

| Germany | Poland | Latvia |
|---|---|---|
| **Who is politically responsible for housing management?** | | |
| Ministry of Justice<br>Ministry of the Interior and Community<br>Ministry for Economic Affairs and Climate Action | Ministry of Development and Technology<br>Ministry of Infrastructure<br>Ministry of Internal Affairs and Administration | Ministry of Economics |
| **Is the certification of the housing managers compulsory?** | | |
| No[2] | No | Yes |
| **Is any non-compulsory training available?** | | |
| Yes | Yes | Yes |
| **Are the housing managers represented by a central or regional association?** | | |
| The Association of Real Estate Managers Germany (VDIV) with 10 regional associations,<br>The Federal Association of Real Estate Managers (BVI)<br>Membership is voluntary | Over 20 local associations and 4 Federations of associations<br>Membership is voluntary | The Association of Management and Administration of Latvian Housing (AMALH)<br>Membership is voluntary |

With regards to political responsibility, regulation and responsibility (property rights, construction requirements, different support mechanisms) of housing management aspects in Germany and Poland are divided between different ministries. For example, in Germany, the Ministry of Justice is engaged in issues of property rights, the Ministry of the Interior in construction issues and the Ministry for Economic

2 Latest amendments to the Act on the Ownership of Apartments anticipate starting certification of housing managers at the end of 2023 (at the earliest).

Affairs and Climate Action in housing subsidies and climate issues.

A similar system exists in Poland. Regulations concerning technical requirements of the building and its energy efficiency are included in the Ordinance of the Ministry of Infrastructure Technical conditions to be met by buildings and their location. The Ministry of Development and Technology is responsible for territorial planning and real estate management. The Ministry of Internal Affairs and Administration is engaged in EU funds support mechanisms.

In Latvia, both, construction and housing industries are under the supervision of the Ministry of Economics. Construction in the competence of the ministry encompasses the development of the industry policy and improvement of the system of regulatory enactments. The aim of the housing policy is defined as promotion of the housing quality and accessibility, developing the appropriate regulatory base for efficient management of residential buildings and supporting energy efficiency measures there.

To jointly solve the respective sector's problems, housing managers in all three countries are united in different associations:

- The Association of Real Estate Managers in Germany (*Verband der Immobilienverwalter Deutschland/VDIV*) is the largest industry association representing the interests of property managers at the national level. The Association unites more than 3,600 members, who administer about 8.2 million apartments. The VDIV Germany is supported by 10 regional associations.
- Poland has more than 20 regional associations and four federations of associations (*Polska Federacja Stowarzyszeń Zawodów Nieruchomościowych/Polish Federation of Real Estate Associations, Polska Federacja Rynku Nieruchomości/Polish Real Estate Federation, Polska Federacja Organizacji Zarządców, Administratorów i Właścicieli Nieruchomości/Polish Federation of Real Estate Managers, Administrators and Owners, Federacja Porozumienie Polskiego Rynku Nieruchomości/ Federation of the Polish Real Estate Market*).
- The Association of Management and Administration of Latvian Housing (AMALH) is a public organisation that unites natural and legal persons in Latvia having interest in reaching joint objectives as for management and administration of real estate. The Association unites more than 40 legal persons engaged in real estate management.

In Germany, ownership and all relations within this context are regulated by the Act on the Ownership of Apartments (*Wohnungseigentumsgesetz/WEG*). This regulatory enactment provides also the management (administration) regulation. In accordance with latest amendments to the law, starting from 1 December 2023, apartment owners can request the appointment of a certified manager. The certification is no obligation in appointing a certified administrator. The certification is the means for increasing the quality of property management companies and, hence, also professional skills of the property manager. Property managers do not need to have a special education/ certificate to start their business, but they are obliged to have a certain number of hours of advanced training/further education (*Weiterbildung*) to be allowed to continue their activities. In Germany, the Act on the Ownership of Apartments does not provide a definition of the housing manager's profile, but the law stipulates that the manager represents the Homeowners' association. Management activities in the real estate field mean technical, financial, legal and organisational tasks to be solved in the course of the facility administration. The specific tasks of the manager are set by owners (homeowners' association/HOA) of the administered facility.

In Poland, the real estate industry is regulated by the Real Estate Management Act. From late 1990s until 2013, the profession of property manager required a state professional license. Following amendment of the law in 2013, licencing is no more required, and the scope of real estate management must be specified in a real estate management contract signed by the owners, a housing association or another person holding the right to the real estate. According to the Polish classification of activities, a real estate administrator is defined as a natural person who takes responsibility for the maintenance of a given real estate. The Real Estate Management Act defines a real estate manager as an entrepreneur who conducts business in the field of real estate management. Real estate management consists of making decisions and performing activities whose goal is ensuring real estate management.

In Latvia, administrative activities, obligations, as well as education and vocational qualification requirements for housing managers are determined in the Law on Administration of Residential Buildings. The manager/administrator in Latvia is defined as an adult natural person or a legal person with the capacity to act, who on the basis of an administration contract performs the administrative activities assigned by the owner/s of a residential building.

For the management of multi-apartment buildings in Latvia, vocational education is necessary and a document certifying at least a fifth level of vocational qualification is obligatory. In some cases, a fourth level vocational qualification is sufficient (e.g. housing manager is an owner, who is personally managing a residential building belonging to him or her; or an owner, who has been authorised to perform management activities by the other residential building owners).

It can be concluded that all three countries have legal regulations for housing managers and the field of their operation. In Germany and Poland, such requirements of a comparatively general kind and are more specifically determined by apartment owners who assign and contract the manager. In Latvia, the activities, tasks, competences and responsibility of housing managers, as well as their qualification requirements, are stipulated more comprehensively. Currently, the Ministry of Economics of the Republic of Latvia drafting a new law for management of residential buildings, anticipating significant changes in the authority of housing managers. It is planned to strengthen the role of the housing manager as a qualified expert, who will be capable of providing apartment owners with information on works to be performed in order to meet the requirements set by regulatory enactments with regard to construction and energy efficiency.

In Germany, as mentioned before, property managers do not need to have a special education to start their business, but In order to become a certified administrator, a person must pass an examination at the Chamber of Industry and Commerce (*Industrie- und Handelskammer*) to confirm that the potential housing manager has the necessary legal, technical and economic/financial knowledge. Also, a person, who has completed vocational training as a real estate agent or as a merchant in the real estate and housing industry, who has a recognized qualification as a certified real estate specialist, or who has a university degree with a focus on real estate, can be acknowledged as a certified administrator.

In Poland, there are no requirements regarding education, experience and qualifications confirmed by an exam to act as a professional manager. Only few chapters in the Real Estate Management Act refer to the professional requirements for the job as housing managers. The database of managers is maintained by the Polish Real Estate Federation. About 2,350 managers with valid licenses are registered there. There is also the Polish nationwide Register of Property Managers of the Federation "Polish Real Estate Market Agreement". It is a register of natural persons who obtained an optional and voluntary license of this federation. About 3,000 managers are registered there.

In Latvia, a fifth level vocational qualification is obtained after four years of studies at the Bachelor level, which covers 160–180 credit points (1 Latvian credit point corresponds to 1.5 ECTS). To obtain a fourth level vocational qualification, it is required to graduate the programme with a volume of not less than 960 hours. Housing manager is included in the list of mandatory applicable occupational standards. Housing managers must register in the Register of Residential Building Managers of the Building Information System (BIS). Currently (as of 7 February 2024), 1,219 managers are registered in the BIS. The BIS is under the supervision of the State Construction Control Bureau of Latvia and, hence, the Ministry of Economics.

In all three countries, building managers have the opportunity to upgrade their competences by attending different courses and trainings. Having reviewed opportunities for additional education, a high activity is detected in Poland. Associations of building managers provide basic vocational training for managers. For example, a person who completes the course and passes the test exam receives the License of the Property Manager of the Polish Federation of Real Estate Market and is registered in the Central Register of Managers run by the Polish Federation of Real Estate Market. The syllabus is based on that of the European Real Estate Council course. The course is organised in the form of four weekend seminars (60 academic hours). It covers the following themes:

- Property management as a professional activity,
- Legal elements in real estate management,
- Technical aspects of real estate management,
- Economic and financial basics in real estate management,
- Residential property management,
- Management of non-residential real estate,
- Sources of information about real estate,
- Interpersonal communication in the profession of a real estate manager,
- Local inspections of the property.

Other associations in Poland also offer training courses that help raise the qualification levels of its members. Mostly, these are online trainings lasting from 4 to 8 hours. In Latvia and Germany, associations of housing managers also offer courses of different length (mostly between 4 to 20 hours) on specific topics, e.g., finances, support mechanisms, accounting, technical inspection, etc.

Having evaluated the qualification requirements of housing managers, it can be concluded that the highest professional qualification requirements to managers of residential buildings are in Latvia, as a certain professional qualification level is required, which can be obtained only upon completion of a full Bachelor programme, respectively by studying for four years. In Germany, qualification requirements for housing managers are being developed but are not (yet) mandatory. In Poland, there are no mandatory requirements to the education of housing managers.

Role of Housing Manager in Increasing Energy Efficiency

Having researched the policy guidelines, legal regulation and requirements to professional qualification of housing managers, it can be concluded that in all three countries the housing policy and legal enactments determine orientation towards the necessity of increasing energy efficiency of buildings. With regards to duties of the housing manager, up to now the emphasis has been on maintaining the technical condition, sanitary cleaning, ensuring public utilities, management budget planning and financial accounting. However, recently, the situation has changed. For example, in Latvia, the occupational standard was developed and adopted in 2021, where one of the main duties of the housing manager is ensuring fulfilment of the requirements set for energy efficiency of the building – she or he is to perform tasks like ensuring measures to meet minimum energy efficiency requirements of the building and the increase of its energy efficiency, supervision of heating and ventilation systems of the building and coordination of the energy certification process of the building.

To perform these duties validly and to achieve the goals set in Latvian development planning documents regarding energy efficiency of buildings, duly educated housing managers are required with competences in energy efficiency and climate change issues, who can organise the implementation of energy efficiency measures and appropriate maintenance of buildings afterwards [17]. At the same time, knowledge in Latvia regarding climate change and energy efficiency in general is assessed as weak (cf. Table 1) and considered one of the risk factors in building management. This can be explained by the fact that previously trainings were more focused on management activities and less on energy efficiency measures.

Polish experts indicate that in order for the manager to be the initiator of modernisation activities in the building, she/he should have knowledge comparable with that of the energy auditor, i.e., knowledge of technical solutions that can be used in the building, be able to assess their energy and economic efficiency, as well as the impact on the quality of life of residents in terms of improving the internal climate. Certainly, one has to keep in mind that the manager can only suggest to the owners the renovation activities needed; the decision is always taken by the owners. Polish experts note that trainings organised by different associations do not or very rarely include the aspect of increasing energy efficiency of buildings. If related issues are examined, it is done in the context of applicable regulations and requirements and not stressing the necessity to take measures for reducing the energy demand [14], [18].

*Verband Immobilienverwalter Deutschland (VDIV)* in Germany developed a study course *Klimaverwalter* (Climate Administrator) for housing managers to improve their knowledge in energy efficiency measures. German experts emphasise that housing managers must have technical, commercial and legal expertise, as well as key skills on project management, meeting management, facilitation and collaboration. Managers have the responsibility to involve various stakeholders in energy renovation processes and in the decision-making process at an early stage. It is recommended that property managers have extensive technical and methodological knowledge in order to be able to accompany and support decision-making processes of a homeowners' association. Good networking with energy and funding consultants is also helpful.

In view of the provisions laid down in the legislation, it can be concluded that a competent housing manager can to a large extent influence the decision for building renovation, as well as organise the related processes. Whereas a decision on renovation is taken by the building owners, construction and the required preparatory work and services are performed by respective construction specialists (see Table 3).

**Table 3.** Opportunities of the Housing Manager to Involve in the Building Renovation Process

| Housing managers can: | Housing managers cannot: |
|---|---|
| • inform the building owners on the necessity of measures to increase energy efficiency;<br>• indicate to positive aspects of increasing energy efficiency;<br>• organise technical inspection, energy audit, energy certification;<br>• organise the process of applying for and receiving financing;<br>• organise the construction process for renovating the building. | • take a decision on energy efficiency measures and the application for financing (competence of the building owners);<br>• perform technical inspection, energy audit, energy certification himself/herself (performed by certified specialists);<br>• select the specific technical solutions (performed by construction specialists and agreed with the owners);<br>• perform construction and construction supervision (performed by construction specialists). |

When implementing the CLI-MA (From Housing Manager to CLImate MAnager) project, experience and knowledge from Germany VDIV study course *Klimaverwalter* (Climate Administrator) was transferred to Poland and Latvia. In Latvia, the housing manager study programmes "Real Estate Management" and "Civil Construction and Real Estate Management" have been improved, supplementing several study courses with additional materials on different energy efficiency aspects. In Poland, a special study course has been developed available to housing managers in a stationary form and for purchase on an e-learning platform.

## 5. CONCLUSIONS

The obligation of apartment owners of residential buildings is to ensure the management of commonly owned parts of the building. A professionally organised and implemented housing management process, in general, successfully ensures long-lasting and qualitative operation of the residential complex, which makes it possible not only to maintain the value of the property, but also to increase it.

When administering a real estate, it is required to know the regulatory basis, be competent in engineering, accounting and record keeping, taxes, business planning, fire safety and labour protection issues, as well as in the legal, organisational and communication fields. For managing residential buildings, the state as the legislator, the owners and the housing manager have to develop a sustainable long-term strategy of the building management, including three pillars: economy, urban environment and community. A systemic approach of economic analysis has to be applied in planning, evaluating strengths and weaknesses of different measures and their alternatives, in order to achieve significant benefits with the smallest resources (investments) possible in the field of building management, education of the involved parties, climate change and introduction of energy efficiency measures.

All three countries have legal regulations in place regarding housing managers and their operation field. In Germany and Poland, these are at a relatively general level and the specific activities are determined by the apartment owners contracting the housing manager. In Latvia, management activities, tasks, competences, responsibilities and qualification requirements are stipulated more comprehensively. Having evaluated the qualification requirements of housing managers, it can be concluded that Latvia has the highest professional qualification requirements to housing managers, as a certain level of professional qualification is required to work as housing manager.

Having researched the policy guidelines, legal regulations and requirements to the professional qualification of housing managers, it can be concluded that in Latvia and Eastern European countries, the housing policy and regulatory enactments are geared towards increasing the energy efficiency of buildings. Recently, the connection of these issues with housing management has become more topical. Up to now, the emphasis in housing management has been on maintaining the technical condition, sanitary cleaning, ensuring public utilities and financial issues. However, the actual situation shows that housing managers are required to also have competences in energy efficiency and climate change issues and be able to organise the implementation of energy efficiency measures. On the other hand, quite often, a lack of such skills and competences negatively affects the living conditions of residents.

The housing manager's skills to administer buildings and communicate with apartment owners play an important role in improving the general condition of the building and its energy efficiency. A competent housing manager is a person who can inform, promote and organise the initiation and implementation of projects to increase the energy efficiency of buildings. The decision to renovate the building is taken by the building owners, while construction and the required preparatory work is performed by respective construction specialists. Coordinated and transparent division and delimitation of tasks and responsibilities is the key.

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# COMPARISON OF RADIATION LEVELS IN THE SOIL AND ROCKS IN THE AREAS SURROUNDING OLD PHOSPHATE MINE, RUSSAIFA, JORDAN

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The activity concentrations of the terrestrial naturally occurring radionuclides $^{214}$Pb, $^{214}$Bi (from $^{238}$U series), and $^{228}$Ac (from $^{232}$Th series) and $^{40}$K were measured in soil and rock samples obtained from three sites of the Russaifa mine and its surrounding in the Russaifa region using an HPGe-detector of 20 % relative efficiency. While the soil activity (in Bq/kg) was found to be: 408.63 ± 26, 383.9 ± 4.7, and 383.0 ± 4.0 for $^{238}$U, $^{214}$Bi, and $^{214}$Pb, respectively. The rock activity was found to be 225.4 ± 19, 180.36 ± 3.9, and 179.47 ± 3.1 for $^{238}$U, $^{214}$Bi, and $^{214}$Pb, respectively. Our results reveal that the average activity concentrations in the mine (site 1) are higher than worldwide average values [6] for $^{238}$U, $^{214}$Pb, and $^{214}$Bi. In contrast, the results show that the average absorbed dose rates in the other sites 2 and site 3 are lower than the world average for all radionuclides measured in this study. Also, the average activity concentrations in soil samples $^{238}$U, $^{214}$Pb, and $^{214}$Bi are higher than the average activity concentrations in rock samples in all sites. Furthermore, the average absorbed dose rate (in nGy h$^{-1}$) was found to be 265.3 for $^{238}$U, 233.3 for $^{214}$Bi, and 13.3 for $^{214}$Pb, respectively, and the average absorbed dose rates for both $^{228}$Ac and $^{40}$K were below the minimum detectable activity (MDA). Moreover, the average annual effective dose rates in soil and rock samples were estimated. While it is found to be 366.90 µSv for $^{238}$U, 306.84 µSv for $^{214}$Bi, and 37.58 µSv for lead in soil samples, for the rock samples it is found to be 163.75 µSv for $^{238}$U, 105.83 µSv for $^{214}$Bi, 13.05 µSv for lead. However, the average annual effective dose rates for $^{214}$Bi and $^{40}$K in soil and rock samples are below the minimum detectable activity (MDA). The results display that the average outdoor annual effective doses for both $^{238}$U and $^{214}$Bi are higher than the world average and the average outdoor annual effective dose equivalents for the other radionuclides are lower than the world average. They also show that the average outdoor annual effective doses in soil samples for $^{238}$U, $^{214}$Pb, and $^{214}$Bi are higher than the average outdoor annual effective doses in rock samples.

***Keywords:*** *Absorbed dose, activity concentrations, affective dose, Jordan, mine,* $^{238}$*U.*

## 1. INTRODUCTION

Exposure to high levels of radiation can cause acute health effects. It can also result in long-term health effects such as cancer and cardiovascular disease. The natural radiation sources include cosmic radiation and the radiation arising from the decay of naturally occurring radioactive sources like gamma rays released from the radionuclides of $^{238}$U, $^{232}$Th, and $^{40}$K through decay series present in the soil, rock, and water [2]–[5]. The radiation exposures depend on many parameters. One of these parameters is the geological and radiochemical characteristics of the area [1], [6]. The radiation studies showed that there were regions with considerably high natural background radiation while most places were classified as low to medium levels. This encourages us in Jordan to perform radioactivity monitoring and wide surveys of radiation exposure. Such studies and surveys will allow us to have an assessment of the current public radiation protection as well as create a baseline for the future assessments. Moreover, the establishment of baseline data of high quality and with efficient measurements will support our efforts to protect our public health and our environment.

Many radioactivity studies have focused on the natural background radiation from primordial radionuclides including $^{238}$U, $^{232}$Th, and $^{40}$K found in the soil, and rock since they make up about 80 % of the total radiation dose that an individual receives annually [7]. Because of its role in the transit of radionuclides to biological systems, the soil is one of these factors that significantly influences radioactive pollution in the environment [8]. Additionally, soil radioactivity is widely utilised to create a benchmark for upcoming radiation risk assessment, nuclear safety, and exploration [9].

It is well known that the earth's crust contains radioactive nuclides with variable concentrations in the uranium and thorium decay chains. While uranium ($^{238}$U) decays to produce radioactive nuclides like radium ($^{226}$Ra), radon ($^{222}$Rn), and bismuth ($^{214}$Bi), the decay of the thorium element ($^{232}$Th) will lead to other radioactive nuclides including actinium ($^{228}$Ac), bismuth ($^{212}$Bi), and lead ($^{212}$Pb). Most gamma rays come from the decaying of $^{228}$Ac, $^{208}$Tl, and $^{212}$Pb.

Since one of the most important pathways for exposure to naturally occurring radioactive materials (NORM) is mining [1], in this study we will focus on the investigation of the radioactivity in the Russaifa Mine and the surrounding area. The activity concentration of the naturally occurring radionuclides ($^{214}$Pb, $^{214}$Bi (from $^{238}$U series), and $^{228}$Ac (from $^{232}$Th series) and $^{40}$K) in soil and rock samples obtained from three sectors in and around the Russaifa Mine in Zarqa city will be measured. Each of these naturally occurring elements has isotopes that are radioactive and may increase the amount of exposure received by the populations living in the vicinity of the Russaifa Mine. Thus, the measurements will enable us to assess the baseline radioactivity levels from natural sources of rocks and soil close to a phosphate mine, compare them with the global average of these radioactivity levels, and with other regions far from phosphate mines. Moreover, the values of radiation emitted from the rocks will be compared with those emitted from the soil. The activity concentration, the absorbed dose rate, and the annual effective dose of the naturally occurring radionuclides $^{214}$Pb, $^{214}$Bi (from $^{238}$U series), and $^{228}$Ac (from $^{232}$Th series) and $^{40}$K in soil and rock will be determined.

## 2. MATERIALS AND METHODS

### 2.1 Study Area and Sample Collection

Over 60 % of the land in Jordan is covered in phosphate deposits, according to the Jordan Phosphate Mines Company (JPMC). Russaifa Mine, Al-Hassa and Al-Abiad Mine, and Eshidiya Mine are the three principal phosphate mines constructed in the country [10]. JPMC commenced its phosphate mining activities in 1935 in the Russaifa phosphate mine. In 1985, the JPMC closed the old phosphate mine at Russaifa because its production was reduced to low levels. However, there is still a significant natural radiation background in the Russaifa phosphate mine and its surroundings. Therefore, environmental studies to measure radiation levels from natural sources in this area are crucial. In our study, six soil and rock samples were collected from three separate locations. While two samples (soil and rock) were obtained from the mine (labelled: Site 1) and the other four were collected from the mine's surrounding area. The four mine's surrounding area samples consist of two samples (soil and rock) obtained from the area near the Amman-Zarqa highway (labelled Site 2) north-east the mine and the other two samples (soil and rock) collected from the AL-Tatweer area (labelled Site 3) south-west the mine shown in the region map presented in Fig. 1.

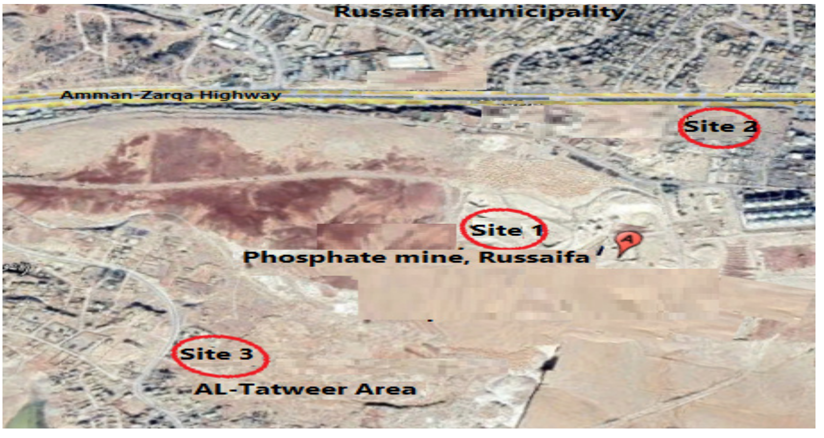


*Fig. 1.* A map of the study area indicating sampling sectors.

### 2.2. Physical Preparation

The sample's physical preparation steps are presented in Fig. 2. All samples were agglomerated in the laboratory, dried in an oven at 105 °C for 24 h, and sieved through a 0.2 mm sieve to remove any larger objects present. A massive piece of machinery called a jaw crusher was used to break rocks. Then a disc mill crusher was used to grind the samples. Furthermore, ball mills were frequently employed for material crushing and grinding to produce ultra-fine powders. Before counting, each sieved sample was weighed, meticulously sealed, and kept for at least 4 weeks to give $^{238}U$ and $^{232}Th$ time to attain equilibrium with their respective progeny.

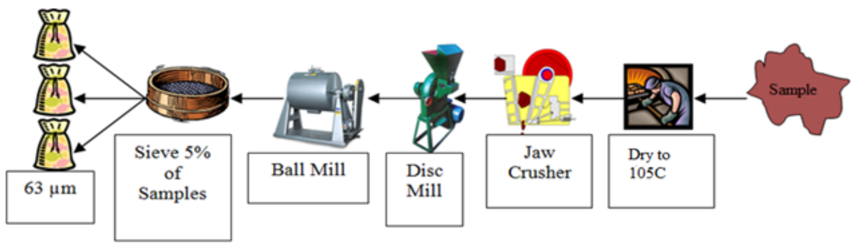


*Fig. 2.* Physical preparation steps for samples.

## 2.3 Gamma-Ray Detection System

The radioactivity of these samples was measured using a low-level counting system consisting of a high-purity Ge detector installed at the Jordan Atomic Energy Commission (JAEC) Laboratory for physical and chemical analysis. This high-purity germanium detector has Model No. GC1518 (CANBERRA multi-input Genie2k gamma spectrometry system). The detector was protected by a huge cylindrical shield made of a 1.6 mm high purity low background copper liner, 9.5 mm low carbon steel outer jacket, 15 cm thick low background lead bulk shield, and 1 mm low background tin liner. The shield effectively suppresses the background gamma radiation present at the lab.

# 3. RESULTS AND DISCUSSION

Direct calculations were performed using the concentration-to-dose conversion coefficients recommended by MCNP [11] to determine dry air external exposure dose rates (EEDR) at 1 m above the ground surface due to radiation released from natural radionuclides at the considered areas according to the following equation:

$$D = A \times C_F, \quad (1)$$

where A is radionuclide activity concentration in Bq/kg; and $C_F$ is dose rate conversion factor in nGy/h per Bq/kg [11]. The dose rates in Table 2 were then converted to the annual effective dose rate ($H_E$) (in µSv/y) listed in Table 3 using the following equation:

$$H_E = D \times T \times F, \quad (2)$$

where D is the absorbed dose rate (nGy/h), T is the annual time outdoors (2920 h/y) and F is the public absorbed-to-effective dose conversion factor ($0.8\times10^{-6}$ mSv/nGy).

The activity concentrations of $^{40}$K, $^{238}$U, $^{228}$Ac, $^{214}$Bi, and $^{214}$Pb computed in Bqkg$^{-1}$ for all samples are presented in Table 1. $^{238}$U activity concentrations ranged from 127.6 ± 13.2 to 963±38.0 Bqkg$^{-1}$ (soil samples) with an average activity of 317.02± 22.5 Bqkg$^{-1}$ and from 115.5 ± 12.9 to 429.8± 24.9 Bqkg$^{-1}$ (rock samples) with an average activity of 225.4 ± 19 Bqkg$^{-1}$. Among $^{238}$U series, $^{214}$Bi and $^{214}$Pb show also the highest values of activity concentration. While the activity concentrations for $^{214}$Pb ranged from 113.7 ± 3.3 to 905.6 ± 6.4 Bqkg$^{-1}$ (soil samples) with an average activity of 383.0 ± 4.0 Bqkg$^{-1}$ and from 119.5 ± 2.8 to 314.4±3.9 Bqkg$^{-1}$ (rock samples) with an average activity of 179.47 ± 3.1 Bqkg$^{-1}$ , the activity concentrations for $^{214}$Bi ranged from

124.6 ± 3.0 $Bqkg^{-1}$ to 907.8 ± 8.2 $Bqkg^{-1}$ (soil samples) with an average activity of 383.9 ± 4.7 $Bqkg^{-1}$ and from 118.5 ± 3.6 $Bqkg^{-1}$to 313.1 ± 5.0 (rock samples) $Bqkg^{-1}$ with an average activity 180.36 ± 3.9 $Bqkg^{-1}$ (Table 1). We also observed that the activity concentrations of $^{40}K$ ranged from MDA to 153.9± 12.0 $Bqkg^{-1}$ (soil samples) with an average activity of 131.05 ± 10.4 $Bqkg^{-1}$ and from MDA to 201.2± 13.2 $Bqkg^{-1}$ (rock samples) with an average activity of 175.7± 11.9 $Bqkg^{-1}$, and the activity concentrations of $^{228}Ac$ ranged from MDA to 15.9± 2.4 $Bqkg^{-1}$ (soil samples) with an average activity of 15.85± 3.5 and from MDA to 27.3± 2.9 $Bqkg^{-1}$ (rock samples) with an average activity of 23± 2.3 $Bqkg^{-1}$ (MDA: minimum detectable activity, where the MDA for $^{40}K$ is 65 $Bqkg^{-1}$ and the MDA for $^{228}Ac$ is 4.5 $Bqkg^{-1}$). The higher concentrations of $^{238}U$, $^{214}Bi$, and $^{214}Pb$ are found in the soil samples.

The total average of activity concentrations for $^{238}U$, $^{214}Bi$ and $^{214}Pb$ are 408.63 ± 26 $Bqkg^{-1}$, 383.9 ± 4.7 $Bqkg^{-1}$, and 383.0 ± 4.0$Bqkg^{-1}$, respectively. By comparing these concentrations with the world average, we found that the mean values of activity concentrations of $^{238}U$ from soil samples and the rock samples in this study were higher than the world average [6]. Also, the total average activity concentration for $^{238}U$, $^{214}Bi$, and $^{214}Pb$ were higher than the world average. The (±) values shown are due to the 1σ variation because of counting errors.

Table 2 shows the absorbed dose rate measured in air at 1 m above the ground in the three selected sites. The absorbed dose rates in the air outdoors are found for $^{238}U$ to be in the range of 48.6156–366.903 nGy $h^{-1}$ with an average value of 155.69nGy $h^{-1}$ (soil samples) and from 44.0055–163.7538 nGy $h^{-1}$ with an average value 85.89 nGy $h^{-1}$ (rock samples). The average of these absorbed dose rates for the $^{238}U$ series ($^{214}Bi$ and $^{214}Pb$) were also calculated. While for $^{214}Bi$, it is found 129.8 $nGyh^{-1}$ for the soil samples and 60.96 nGy $h^{-1}$ for the rock samples, the average absorbed dose rates for the $^{214}Pb$ are 15.64 nGy $h^{-1}$ and 7.4 nGy $h^{-1}$ for the soil and rock samples, respectively. The average of absorbed dose rates for $^{40}K$ is found to be 4.95 $nGyh^{-1}$ for the soil samples and 6.641 for the rock samples. This indicates that the rate of absorbed dose for both soil and rock samples for $^{238}U$ and $^{214}Bi$ from terrestrial radiation in the outside air in the studied area was higher than the limit allowed by UNSCEAR-2000 and ICRP–1990 [19], [20] (18-93 nGy $h^{-1}$). The average value of the absorbed dose rate of $^{214}Pb$ was slightly less than the worldwide median value recommended by ICPR 60–1990, and UNSCEAR–2000 [11], [12].

The calculated annual effective doses (mSv/y) are listed in Table 3. The annual effective doses (mSv/y) in air outdoors are found for $^{238}U$ to be in the range of 113.566–857.0854 mSv/y with an average value of 363.69 mSv/y (soil samples) and from 102.7968–382.5289 mSv/y with an average value 200.63 mSv/y (rock samples). For the $^{238}U$ series ($^{214}Bi$ and $^{214}Pb$) the average annual effective doses for the $^{214}Bi$ are 303.14 mSv/y and 142.41 mSv/y for the soil and rock samples, receptively. The average of the annual effective doses for $^{40}K$ is found to be11.57 mSv/y (soil samples) and 15.51 for the rock. Also, the average of the annual effective doses for $^{228}Ac$ is found to be 14.11 mSv/y (soil samples) and 20.47 for the rock. This indicates that the annual effective dose for both soil and rock samples for these radionuclides from terrestrial radiation in the outside air in the studied area was lower than the limit allowed by UNSCEAR-2000 and ICRP–1990 [19], [20] (300–600 mSv/y). At Site 1, the values of activity concentration, dose rate, and annual effective dose are higher than that of other sites.

**Table 1.** Activity Concentrations (Bq kg$^{-1}$) of Natural Radionuclides in Soil Samples from Different Regions in Jordan Compared to those of the Present Study

| Site | sample type | $^{40}$K | $^{232}$Th series | $^{238}$U | $^{238}$U series | |
|---|---|---|---|---|---|---|
| | | | $^{228}$Ac | | $^{214}$Bi | $^{214}$Pb |
| Site 1 | rock | MDA | MDA | 429.8± 24.9 | 313.1 ± 5.0 | 314.4±3.9 |
| | soil | MDA | MDA | 963±38.0 | 907.8 ± 8.2 | 905.6 ± 6.4 |
| Site 2 | rock | 201.2± 13.2 | 27.3± 2.9 | 131 ± 15.6 | 109.5 ± 3.0 | 104.5 ± 2.7 |
| | soil | 108.2± 8.8 | 15.9± 2.4 | 135.3 ± 18.2 | 119.4 ± 3.1 | 129.7 ± 2.4 |
| Site 3 | rock | 150.2± 10.6 | 18.7± 3.2 | 115.5 ± 12.9 | 118.5 ± 3.6 | 119.5 ± 2.8 |
| | soil | 153.9± 12.0 | 15.8± 2.1 | 127.6 ± 13.2 | 124.6 ± 3.0 | 113.7 ± 3.3 |
| Average (soil) | | 131.5± 10.4 | 15.85±3.5 | 408.63 ± 26 | 383.9 ± 4.7 | 383.0 ± 4.0 |
| Average (rock) | | 175.7± 11.9 | 23± 2.3 | 225.4 ± 19 | 180.36 ± 3.9 | 179.47 ± 3.1 |
| Total Average | | 153.6±7.0 | 19.4±2.7 | 317.02± 22.5 | 282.13 ± 4.3 | 281.24 ± 3.6 |
| World average (UNSCEAR 2000)[6] | | 400 | 30 | 35 | 35 | 35 |
| * MDA: minimum detectable activity | | | | | | |

**Table 2.** Average Absorbed Dose Rate (nGy h-1) in the Air at 1 m above Sampling Points in the Study Areas and Calculated Annual Effective Dose

| Site | sample type | $^{40}$K | $^{238}$U | $^{228}$Ac | $^{214}$Bi | $^{214}$Pb |
|---|---|---|---|---|---|---|
| Site 1 | rock | MDA | 163.75 | MDA | 105.83 | 13.05 |
| | soil | MDA | 366.90 | MDA | 306.84 | 37.58 |
| Site 2 | rock | 7.61 | 49.91 | 10.4013 | 37.01 | 4.34 |
| | soil | 4.09 | 51.55 | 6.0579 | 40.36 | 5.17 |
| Site 3 | rock | 5.68 | 44.01 | 7.1247 | 40.05 | 4.96 |
| | soil | 5.82 | 48.62 | 6.0198 | 42.11 | 4.72 |
| Average (rock) | | 6.641 | 85.89 | 8.76 | 60.96 | 7.4 |
| Average (soil) | | 4.95 | 155.69 | 6.04 | 129.8 | 15.64 |
| Average | | 5.79 | 120.79 | 7.4 | 95.3 | 11.5 |
| World range (UNSCEAR 2000)[6] | 18 -93 | | | | | |

**Table 3.** Annual Effective Dose (μSv/y) Based on the Current Study

| Site | sample type | $^{40}K$ | $^{238}U$ | $^{228}Ac$ | $^{214}Bi$ | $^{214}Pb$ |
|---|---|---|---|---|---|---|
| Site 1 | rock | MDA | 382.52 | MDA | 247.21 | 30.48 |
| | soil | MDA | 857.09 | MDA | 716.80 | 87.79 |
| Site 2 | rock | 17.77 | 116.59 | 24.30 | 86.46 | 10.13 |
| | soil | 9.55 | 120.42 | 14.15 | 94.27 | 12.08 |
| Site 3 | rock | 13.26 | 102.80 | 16.64 | 93.56 | 11.58 |
| | soil | 13.59 | 113.57 | 14.06 | 98.38 | 11.02 |
| Average (rock) | | 15.51 | 200.63 | 20.47 | 142.41 | 17.56 |
| Average (soil) | | 11.57 | 363.69 | 14.11 | 303.14 | 36.96 |
| Average | | 13.54 | 282.16 | 17.29 | 222.78 | 27.26 |
| World average (UNSCEAR 2000) | 70 | | | | | |

**Table 4.** Reported Values of Gamma Activity in Soil (Activity Bq kg$^{-1}$), from Work Conducted Worldwide

| Region | $^{40}K$ | $^{238}U$ | $^{228}Ac$ | $^{214}Bi$ | $^{214}Pb$ | Reference |
|---|---|---|---|---|---|---|
| Southern Lebanon | 1.2–15.7 | | BDL–1.8 | 10.7–15.2 | | [13] |
| Areas near to old phosphate mine, Russaifa, Jordan | 44 - 307 | 48.3 - 523:2 | | | | [10] |
| Central Ashanti Gold Mine, Ghana | 1895.4 (soil) 642.4 (rock) 214.8–2170.4 | 52.4 (soil) 9.7 (rock) 9.7–124.9 | | | | [14] |
| Northeast Bangladesh | 884 (average) | | | | | [15] |
| South Sinai, Egypt | 1186.45 | 46.39 | | | | [16] |
| Jaduguda uranium mines in the shear zone. Eastern India | BDL | 123 - 40858 | | | | [17] |
| Southern Egypt | 292.81 – 695.57 | 5-23.60 | 1.92 – 13.2 | 2.01 – 26.12 | 2.97 – 28.91 | [18] |
| Antalya in Turkey | 148.45 | | 28.05 | 16.21 | 18.25 | [19] |
| Douala city, Cameroon | 125 - 410 | 18 - 45 | | | | [20] |
| Surface Soil of Old Phosphate Mine in Russaifa of Jordan | BDL – 2.40 | 27.35-420.19 | | | | [21] |

## 4. CONCLUSIONS

In conclusion, the activity concentrations of the terrestrial naturally occurring radionuclides $^{214}Pb$, $^{214}Bi$ (from $^{238}U$ series), and $^{228}Ac$ (from $^{232}Th$ series) and $^{40}K$ were measured in soil and rock samples obtained from three sites of the Russaifa mine and its surrounding in the Russaifa region using an HPGe-detector of 20 % relative efficiency. The average activity concentrations in Bq/kg were found to be: 696.4± 31.5 for $^{238}U$, 610.5±6.6 for $^{214}Bi$, 610±10.3 for $^{214}Pb$ and MDA (minimum detectable activity) for both $^{40}K$ and $^{228}Ac$ in the mine (Site 1), 133.2±16.9 for $^{238}U$,114.4±3.0 for $^{214}Bi$ 117.1±2.6 for $^{214}Pb$, 21.6±2.7 for $^{228}Ac$ and 154.7±11 near Amman-Zarqa Highway (Site 2), 121.6±13.1 for $^{238}U$ 121.5±3.3 for $^{214}Bi$ 116.6±3.0 for $^{214}Pb$, 17.3±2.7 for $^{228}Ac$ and 152.1±11.2 for $^{40}K$, in AL-Tatweer area (Site 3). While the soil activity (in Bq/kg) was found to be 408.63 ± 26, 383.9 ± 4.7, and 383.0 ± 4.0 for $^{238}U$, $^{214}Bi$, and $^{214}Pb$, respectively. The rock activity was found to be 225.4 ± 19, 180.36 ± 3.9, and 179.47 ± 3.1 for $^{238}U$, $^{214}Bi$, and $^{214}Pb$, respectively. Our results reveal that the average activity concentrations in the mine (Site 1) are higher than worldwide average values [6] for $^{238}U$, $^{214}Pb$, and $^{214}Bi$.

In contrast, the results show that the average absorbed dose rates in Sites 2 and 3 are lower than the world average for all radionuclides measured in this study. Also, the average activity concentrations in soil samples $^{238}U$, $^{214}Pb$, and $^{214}Bi$ are higher than the average activity concentrations in rock samples in all sites. Furthermore, the average absorbed dose rate (in nGy $h^{-1}$) was found to be 265.3 for $^{238}U$, 233.3 for $^{214}Bi$, and 13.3 for $^{214}Pb$, respectively, and the average absorbed dose rates for both $^{228}Ac$ and $^{40}K$ were below the minimum detectable activity (MDA). Moreover, the average annual effective dose rates in soil and rock samples were estimated. While it was found to be 366.90 µSv for $^{238}U$, 306.84 µSv for $^{214}Bi$, and 37.58 µSv for lead in soil samples, for the rock samples it was found to be 163.75 µSv for $^{238}U$, 105.83 µSv for $^{214}Bi$, 13.05 µSv for lead. However, the average annual effective dose rates for $^{214}Bi$ and $^{40}K$ in soil and rock samples were below the minimum detectable activity (MDA). The results display that the average outdoor annual effective doses for both $^{238}U$ and $^{214}Bi$ are higher than the world average, and the average outdoor annual effective dose equivalents for the other radionuclides are lower than the world average. They also show that the average outdoor annual effective doses in soil samples for $^{238}U$, $^{214}Pb$, and $^{214}Bi$ are higher than the average outdoor annual effective doses in rock samples.

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# MANUFACTURABILITY AND PERFORMANCE STUDY OF TRIPLY PERIODIC MINIMAL SURFACE AIR-TO-AIR HEAT EXCHANGER

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The study tests 3D printability, heat transfer characteristics and pressure drop of two types of triply periodic minimal surface heat exchanger in order to develop new flow principles for compact heat exchanger design. Various generic plate heat exchanger designs are also tested to compare to the printed alternatives. Geometry variations for heat exchangers and laboratory testing air recuperators are modelled in SolidWorks software and manufactured mostly by UV LCD and FDM additive manufacturing methods.

Digital light processing printing method has been found to be most successful in printing the TPMS structures, while using photopolymer materials. Literature studies conclude that the most promising structures are Schoen's gyroid and Schwarz-diamond surfaces, which have been modelled and tested in several variations. Using these results, full size gyroid and Schwarz-D structure heat exchangers have been modelled, manufactured and tested. The results are compared and analysed to study the effect of advanced surface designs in heat transfer efficiency.

The obtained results can be used in compact air-to-air thermal recuperator development as well as other low pressure heat exchanger applications, as the printed TPME heat exchangers outperform the plate heat exchangers in similar dimensions.

***Keywords:*** *Additive manufacturing, gyroid, heat transfer, Schwarz-diamond, thermal recuperator.*

## 1. INTRODUCTION

Ventilation is one of the key factors in ensuring energy efficiency, as heat loss from a residential building ventilation system in much of Northern Europe can be up to 35–40 kWh/m2, and 60–95 % of ventilation heat loss can be recovered by heat recovery system [1].

With the rise of additive manufacturing in recent years, higher energy efficiency and materials saving can be achieved by using 3D printing methods in heat exchanger manufacturing. At fixed pressure drop requirements, triply periodic minimal surfaces, such as Schwarz-diamond surface, heat exchangers can achieve the same heat transfer performance in an order of magnitude smaller volume than tubular exchangers. This is especially advantageous in applications where space or weight limitations are strict [2].

Residential ventilation is traditionally provided through ventilation openings or open windows in buildings, and in recent years, mechanical ventilation systems in newly developed buildings. While this method provides effective ventilation, it also results in significant heat loss. This issue can be largely mitigated by equipping the ventilation system with a heat recovery system. The use of such a system allows up to 85 % of the heat lost through ventilation to be reused for reheating incoming air. In much of Northern Europe, buildings are still not equipped with heat-recovery ventilation systems. This is primarily due to the high cost, relative complexity, and in some cases, the impracticality of installing such systems [3].

To bypass previously mentioned issues, compact heat recovery systems for single rooms could be more affordable and easier to implement. Such a system should provide enough ventilation for a single room accommodating up to two individuals, and requires air exchange rate that can ensure adequate CO2 levels, not exceeding 1000 ppm [4]. According to ISO and EN standards, the minimum required air flow rate should never be below 4 l/s per person, which results in 8 l/s minimum requirement for a 2-person bedroom, which is around 28.8 $m^3/h$ [5]. This value of flow rate will be used as reference in the following study.

In similar studies, through the investigation of experimental data regarding the heat transfer rate and pressure drop, it is concluded that the TPMS based compact heat exchangers achieve significantly higher heat transfer efficiency, which results from the high surface area per unit of volume and their three-dimensionally continuous and completely interconnected flow channel structure [6]. This means that innovative compact heat exchanger designs based on TPMS structures can create very efficient ventilation devices, while maintaining low pressure drop in the system from the heat exchanger itself. As the goal is to study very compact air-to-air heat exchanger designs for heat recovery, TPMS structures are chosen as the most promising design choices for the heat exchanger core. Some of the most used and validated types of such structures in other studies are Schoen's gyroid and Schwarz-Diamond [7], which is why these will be used in further testing of printing methods, materials and heat exchanger performance.

## 2. METHODOLOGY

In order to create a full scale triply periodic minimal surface (TPMS) heat exchanger 3D model, base models of single TPMS surface cells were designed using SolidWorks 2020 CAD software (see Fig. 1). The designed gyroid and Schwarz-diamond surfaces can be described using equations of spatial coordinates of x, y, z [8]:

Schwarz-d:

$$\cos(x)\cos(y)\cos(z) - \sin(x)\sin(y)\sin(z) = 0. \quad (1)$$

Gyroid:

$$\sin(x)\cos(y) + \sin(y)\cos(z) + \sin(z)\cos(x) = 0. \quad (2)$$

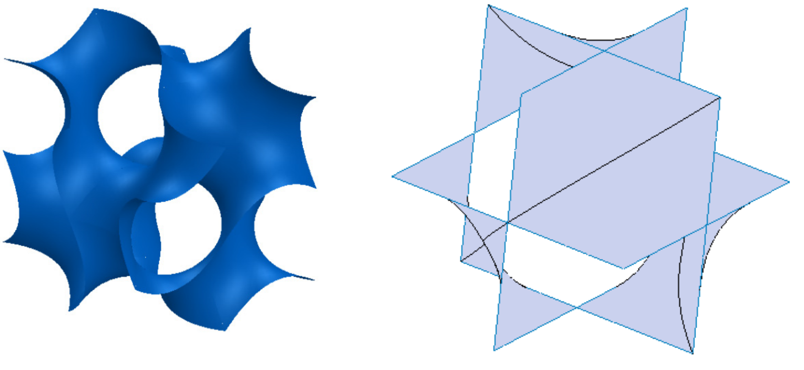

*Fig. 1.* Gyroid (left) and Schwarz-diamond (right) surface cells.

Since SolidWorks CAD software does not have a built-in function for modelling TPMS surfaces, and their further processing is also difficult, modelling the Gyroid and schwarz-D structures takes longer than expected. For such designs, specialised software is available, such as N-Topology, but it will not be reviewed in this study. To obtain a full-scale model of the heat exchanger, the resulting single-cell surfaces are patterned in all directions. The surface thickness (wall thickness) is assigned to the surface model obtained, the exterior walls of the casing and the intake and exhaust manifolds are modelled. For the compact thermal recuperator study, heat exchanger prototype dimensions (for plate, gyroid and schwarz-d heat exchangers) of 200x180x120 mm were selected (see Fig. 2 below).

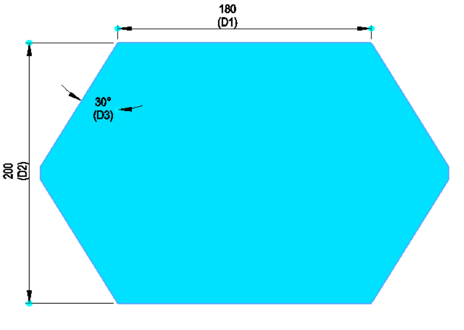


*Fig. 2.* Overall dimensions of the heat exchanger (height: 120 mm).

Using thin wall thicknesses in air-to-air application, the heat transfer coefficient of the heat exchanger material does not play a big role in the overall efficiency (assuming that the walls can be printed in thicknesses below 0.5 mm), as in such a case the convective heat transfer coefficient impacts the overall heat transfer (Eq. (3)). Therefore, it was decided to use a widely available and cheap printing material, and to model the wall thickness of the TPMS structure as small as possible to reduce the effect of the thermal conductivity of the material on the thermal efficiency.

$$\frac{1}{U} = \frac{1}{h_{ci}} + \Sigma(\frac{s_n}{k_n}) + \frac{1}{h_{co}}, \quad (3)$$

where U – overall heat transfer coefficient, W/($m^2$*K);

$h_{ci,o}$ – a convective heat transfer coefficient for fluid inside and outside the wall, W/m*K (air – 10–100 W/m*K);

$s_n$ – n wall thickness, m;

$k_n$ – n wall material heat transfer coefficient, W/m*K [9].

To compare a gyroid cell size effect on heat transfer and pressure drop, three different TPMS structure variants were created, changing the size of the single cells (Fig. 1) in each iteration, but keeping the overall model dimensions and wall thickness (0.32–0.35 mm). Porosity was determined by SolidWorks mass properties tool (ratio of volume of flow channels for fluid flow to total volume of structure).

**Table 1.** TPMS Geometric Parameters Used in Heat Exchanger Designs

| Heat exchanger structure | Wall thickness [mm] | Porosity | Cell size, LxWxH [mm] |
|---|---|---|---|
| Gyroid | 0.35 | 94.6 % | 20x20x20 |
| Schwarz-D V1 | 0.32 | 93.9 % | 20x20x20 |
| Schwarz-D V2 | 0.32 | 93.5 % | 20x18x18 |

To separate the warm and cold air channels, opposite flow openings are filled in the inlet and outlet. The resulting file is exported in STL format for printing (see Fig. 3). By blocking the correct inlet and outlet channels, cross flow setup for the heat exchanger is achieved.

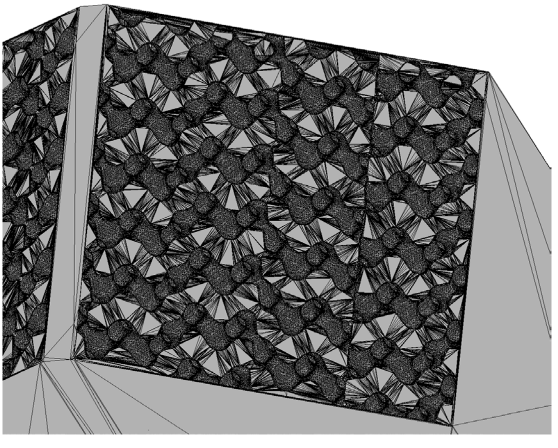

*Fig. 3*. Inlet/outlet channels of Schwarz-d heat exchanger.

In order to fit more easily into the maximum printing dimensions of the Creality Halot Mage Pro printer (228x128x230 mm), the heat exchanger models were split in half for partial printing. 3D printing programs were prepared in Chitubox Pro software, where the necessary printing parameters were set and printing support structures were added (see Fig. 4).

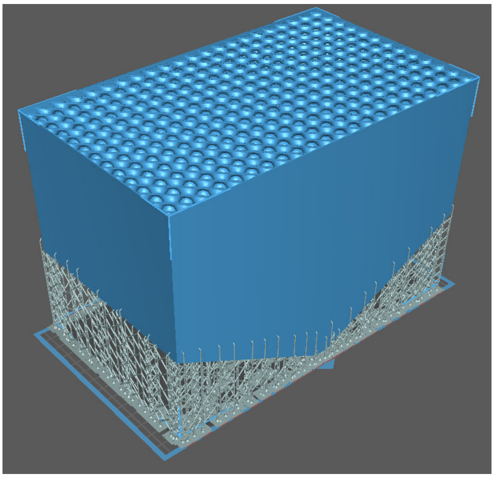

*Fig. 4*. Sliced heat exchanger model in Chitubox Pro 3D program.

The printing method and parameters for heat exchanger structure printing were tested to achieve optimal surface quality for heat exchangers with the thinnest possible wall thickness. Printing was performed using the parameters that yielded the best surface quality while minimising wall thickness.

**Table 2.** Parameters of the 3D Printing Material Used [10]

| | | |
|---|---|---|
| Creality Standard resin | | |
| Density | 1.14 | g/cm$^3$ |
| Tensile strength | 60–68 | MPa |
| Surface hardness | 85–90D | Shore D |
| Heat transfer coefficient | 0.18 | W/m*K |

**Table 3.** Printing Parameters Used

| | | |
|---|---|---|
| Layer height | 0.05 | mm |
| Bottom layer count | 6 | |
| Exposure time | 1.6 | s |
| Bottom exposure time | 45 | s |
| Light-off delay | 6 | s |
| Lifting distance | 8 | mm |
| Lifting speed | 300 | mm/min |
| Printing resolution | 7680x4320 | px |

Heat exchanger parts and their inlet/outlet manifolds printed by the UV LCD method were glued together using UV curing polymer (which is the same printing material). Since small wall thicknesses are not required outside the heat exchanger, the fan housing, connecting pipes and sensor mounts were printed with a Prusa MK3S FDM printer, with standard printing parameters.

*Fig. 5*. Heat exchangers printed by UV LCD method.

During printing, it was observed that the amount of photopolymer consumed is about 30 % higher than calculated in the 3D printing program. When measuring the wall thicknesses in the heat exchangers, it was concluded that the actual wall thicknesses are in the range of 0.40–0.60 mm, not 0.32–0.35 mm, as defined in the model. Therefore, it is likely that slightly lower porosity, heat exchanger efficiency and higher back pressure will be obtained than expected, which should be taken into account for further development.

For comparison, plate heat exchangers of a similar design were made, where the flow channels were separated by parallel flat aluminium plates with a thickness of 0.5 mm, a gap between the plates of 2.0–3.0 mm and a heat transfer coefficient of the material ~237W/m*K.

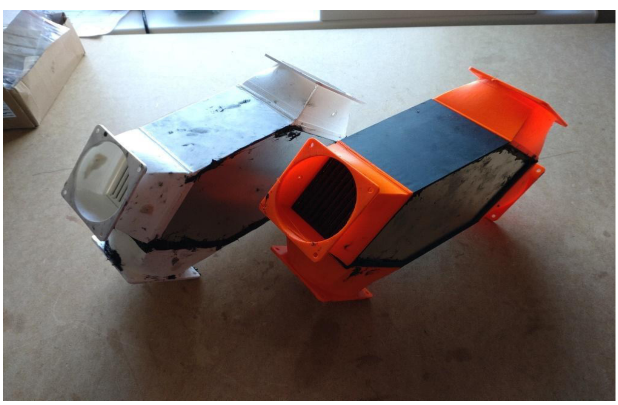

*Fig. 6.* Plate heat exchangers.

For laboratory testing and measurements of temperature in each channel, flow rate and back pressure, a test rig with PMB-1212PLB2-A radial fans, Honeywell ABP2 pressure sensors, UT-363 anemometer, AM2302 temperature and humidity sensors, power supply unit for fan speed control and ESP32 microcontroller for recording results were used (see Fig. 7).

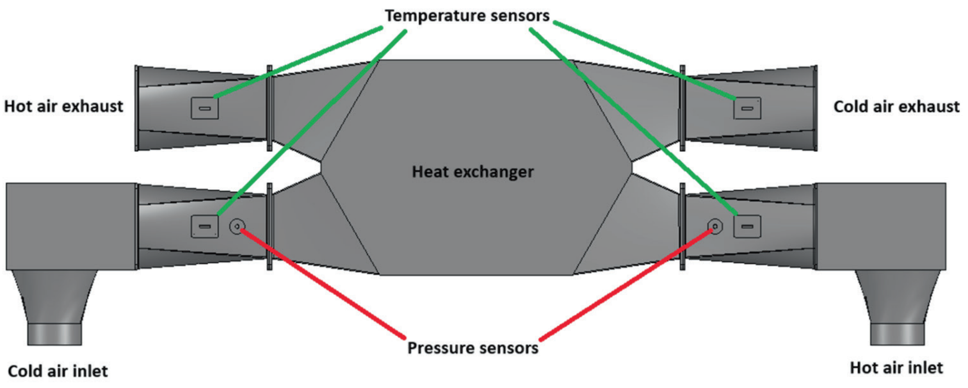


*Fig. 7.* Laboratory testing recuperator.

To mitigate the surrounding environment effect on the results of temperature measurements, the testing equipment was placed in a foam housing that served as a thermal insulator.

*Fig. 8.* Insulated testing stand.

## 3. RESULTS AND DISCUSSION

Plate heat exchangers are currently the most common type of heat exchangers in building air thermal recovery equipment. However, the size of the equipment available on the market for this type of high-efficiency recuperators is much larger than that envisaged in this project [11]. In order to clarify the possible flow volumes and efficiency, and to compare them with TPMS recuperators, several tests of plate heat exchangers at different flow rates were performed. Air gap sizes were determined experimentally – reducing the gap below 2 mm resulted in high flow resistance, and larger and louder fans were needed to achieve the required flow speeds. The same testing setup and equipment were used in both TPMS and plate heat exchanger tests.

The advantage of such heat exchangers is easier production in large volumes –

comparatively, the production of one full-size TPMS heat exchanger can take up to 12 printing hours of one UV LCD printer. Alternatively, plate heat exchanger parts are easily mass-produced, and the most time-consuming step is the assembly of the heat exchanger.

Thermal efficiency is calculated as the ratio of actual temperature difference between the same flow inlet and outlet to the maximum possible temperature difference achievable (temperature difference between the inlets) [9]. Both supply (IN) and exhaust (OUT) side thermal efficiency is used to calculate the average heat exchanger efficiency. The stale room air from the room is defined as "Hot" and the fresh outside air is defined as "Cold" in this study.

Testing of plate heat exchangers was carried out using cold outside air as ColdIN and warm room air as HotIN. Measurements were made at different flow rates, recording the relevant results as the temperature stabilised in all the channels. The results are summarised in Table 4.

**Table 4.** Plate Heat Exchanger Testing Results

| Air gap, mm | Flowrate, m3/h | HotIN, °C | HotOUT, °C | ColdIN, °C | ColdOUT, °C | Efficiency IN | Efficiency OUT | AVG efficiency |
|---|---|---|---|---|---|---|---|---|
| 3.0 | 15.4 | 21.7 | 16.7 | 11.3 | 18.2 | 48.1 % | 66.3 % | 57.2 % |
| 3.0 | 7.8 | 21 | 15.7 | 11.6 | 18.5 | 56.4 % | 73.4 % | 64.9 % |
| 3.0 | 6.4 | 21.9 | 17 | 13.2 | 19.9 | 56.3 % | 77.0 % | 66.7 % |
| 3.0 | 16.2 | 20.1 | 11.5 | 1.8 | 12.8 | 49.7 % | 60.1 % | 54.9 % |
| 3.0 | 20.5 | 20.6 | 11 | 1.3 | 13.4 | 49.7 % | 62.7 % | 56.2 % |
| 3.0 | 33.9 | 21.4 | 12.3 | -0.5 | 12.5 | 41.6 % | 59.4 % | 50.5 % |
| 3.0 | 35.3 | 23.1 | 15.3 | 7.7 | 12.6 | 50.6 % | 31.8 % | 41.2 % |
| 2.0 | 30.4 | 22.9 | 10 | 3.5 | 14.1 | 66.5 % | 54.6 % | 60.6 % |
| 2.0 | 30.4 | 22.9 | 10 | 3.5 | 14.1 | 66.5 % | 54.6 % | 60.6 % |
| 2.0 | 13.7 | 21.9 | 5.9 | -3.3 | 16.5 | 63.5 % | 78.6 % | 71.0 % |
| 2.0 | 3.4 | 20.3 | 7.2 | -0.1 | 15.4 | 64.2 % | 76.0 % | 70.1 % |

It can be concluded that at the planned heat exchanger flow rate (around 30 m 3/h), plate heat exchangers only reach 41.2–60.6 % average efficiency, 2.0 mm slot heat exchangers being more efficient. At lower productivity modes, the efficiency reaches up to 71.0 %.

The TPMS heat exchangers, manufactured by additive manufacturing methods, were tested similarly, using the same testing setup. To achieve similar temperature ranges in all tests, artificially heated air was used for HotIN, and room temperature air was used for ColdIN. In all of the gyroid and Schwarz-diamond heat exchangers some temperature inertia can be noticed.

At the beginning of testing, warm air inlet heating was started and measurements were continued until the warm air inlet temperature was around 40 °C and the temperature of all channels stabilised. In the case below (see Fig. 9), it was assumed that the values were stable between 400 s and 450 s. Average temperature values during this period were used for further calculations. Similar methodology was used for all heat exchanger tests.

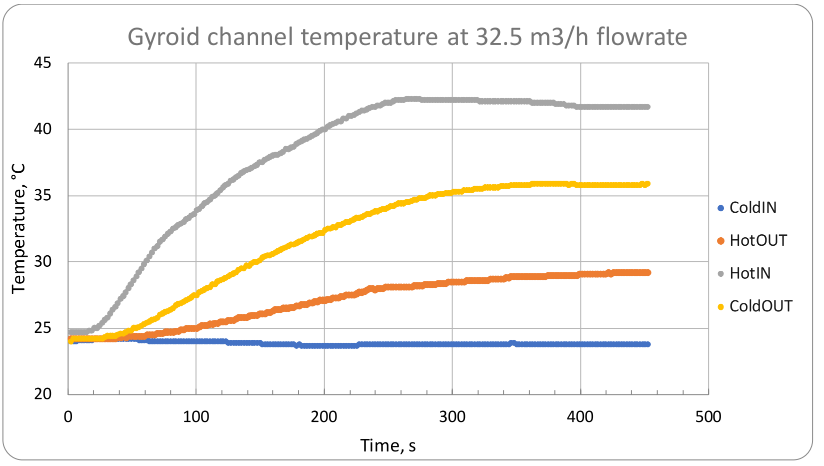


*Fig. 9.* Gyroid heat exchanger temperature study at a flow rate of 32.5 m3/h.

In the pressure drop data, it can be observed that there have been pronounced fluctuations in the measurements, which could have arisen as a result of the turbulent flow regime. It was concluded that for testing, as well as for the control of the device prototype, it would be necessary to create a measurement filter in the software, which would record the results more evenly.

The results of the measurements were fluctuating, but there was no observable trend of changes in the graph, and there were a lot of data points; therefore, in order to determine the flow back pressure in the heat exchanger, the average value was extracted from all measurements. Since the back pressure at a flow rate of 32.5 $m^3$/h was very low (on average 17.2 Pa in the warm and cold air intake manifold), a testing was also carried out at higher flow rates (65 m3/h), with the aim of comparing the drop in efficiency and the increase in back pressure, from which it could be concluded about the possibilities of making an even smaller size heat exchangers of similar designs.

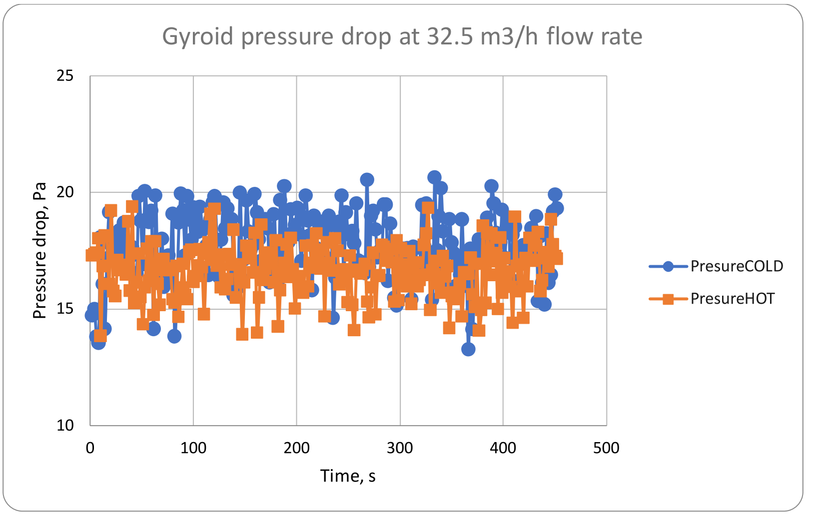


*Fig. 10.* Gyroid heat exchanger pressure loss at a flow rate of 32.5 m3/h.

Testing was conducted with all heat exchanger designs analogous to the previous measurement, a time period with stable temperature values was chosen and average values of the time period were used in efficiency calculation.

**Table 5.** TPME Heat Exchanger Measurements

| | **Flowrate, m3/h** | **HotIN, °C** | **HotOUT, °C** | **ColdIN, °C** | **ColdOUT, °C** | **Efficiency IN** | **Efficiency OUT** | **AVG efficiency** | **Pressure, Pa** |
|---|---|---|---|---|---|---|---|---|---|
| Gyroid | 20.1 | 42.1 | 28.9 | 24.0 | 36.7 | 72.9 % | 70.2 % | 72 % | 7.1 |
| Gyroid | 32.5 | 41.8 | 28.7 | 23.8 | 36.4 | 69.8 % | 67.6 % | 69 % | 17.2 |
| Gyroid | 65 | 39.1 | 29.2 | 23.5 | 33.0 | 63.5 % | 60.9 % | 62 % | 58.5 |
| Schwarz-D v1 | 21.9 | 42.5 | 28.7 | 24.05 | 37.6 | 74,3 % | 73,4 % | 74 % | 9.1 |
| Schwarz-D v1 | 32.5 | 44 | 29.8 | 24.1 | 38.7 | 71.4 % | 73.4 % | 72 % | 20.7 |
| Schwarz-D v1 | 57.2 | 38.3 | 29.1 | 24 | 35.2 | 64.3 % | 78.3 % | 71 % | 60.1 |
| Schwarz-D v2 | 20.5 | 44.7 | 30.2 | 26.2 | 39.4 | 78.4 % | 71.4 % | 75 % | 8.4 |
| Schwarz-D v2 | 30 | 43.85 | 30.15 | 26.3 | 38.75 | 78.1 % | 70.9 % | 75 % | 20.8 |
| Schwarz-D v2 | 57 | 42.9 | 29.0 | 24.1 | 37.45 | 73.9 % | 71.1 % | 72.0 % | 68.8 |

For the gyroid structure heat exchanger, as in the previous test, no trend of change could be observed in back pressure measurements at any testing attempts, so the average pressure value was calculated from all the data for each flow rate. By increasing the flow rate two times, the back pressure value increased 3.4 times, but the efficiency of the heat exchanger decreased by only 7 % from thermal efficiency of 69 % at a flow rate of 32.5 $m^3/h$. The achieved results agree with previous studies, implying higher heat transfer efficiency compared to conventional heat exchanger designs and relatively higher pressure loss at high flow rates [12]. The stable efficiency might suggest that adjustments in cell geometry could allow for more compact designs of heat exchangers, while maintaining low pressure loss at low to medium flow rates and achieving similar stable performance. At lower flow rates, an increase in slight efficiency can be noticed (3 %), and pressure loss decreases by approximately 2.4 times.

Like the gyroid heat exchanger, both Schwarz-D heat exchangers were tested with similar air flow and temperature values through the cold and warm air ducts. The Schwarz-D v1 heat exchanger achieved efficiency of 72 % (at a flow rate of 32.5 $m^3/h$), but the Schwarz-D v2 achieved thermal efficiency of 75 % (at a flow rate of 30 $m^3/h$). The average back pressure value for v1 inlet channels at 32.5 m3/h was 20.7 Pa. It was concluded that for the Schwarz-D v2 heat exchanger it was possible to obtain high efficiency (75 %) at a very low pressure drop (20.8 Pa) even without further optimising the heat exchanger and inlet geometry. This could create opportunities to design compact and quiet heat recovery devices, as a relatively low pressure loss had to be overcome to achieve the required flow rate. Likewise, just as for gyroid samples, further overall size decrease and geometric variations should be tested.

By increasing the flow rate to 57.2 $m^3/h$ in the v1 heat exchanger, a slight decrease in thermal efficiency (1 %) was observed, and the back pressure increases by ~2.9 times (60.1 Pa). When reducing the flow volume to 21.9 m3/h, the efficiency was slightly higher (increase by 2 %), and the back pressure decreased by about 2.3 times (9.1 Pa). It can be assumed that the flow rate in these structures does not significantly affect the heat exchange (even more so that the gyroid structures), but it has a great impact on the back pressure. Based on these findings, an improved laboratory prototype should be designed and tested, having smaller cell sizes and disproportionate cells in the flow direction. There is reason to believe that in this way higher efficiency will be achieved at similar flow rates without increasing the back pressure values.

The Schwarz-D v2 has stable thermal efficiency at a flow rate from 20.5 to 30 $m^3/h$, but it decreases slightly (by 3 %) when increased to 57 $m^3/h$. The trends in pressure loss at different flow rates are similar to that of the v1 study.

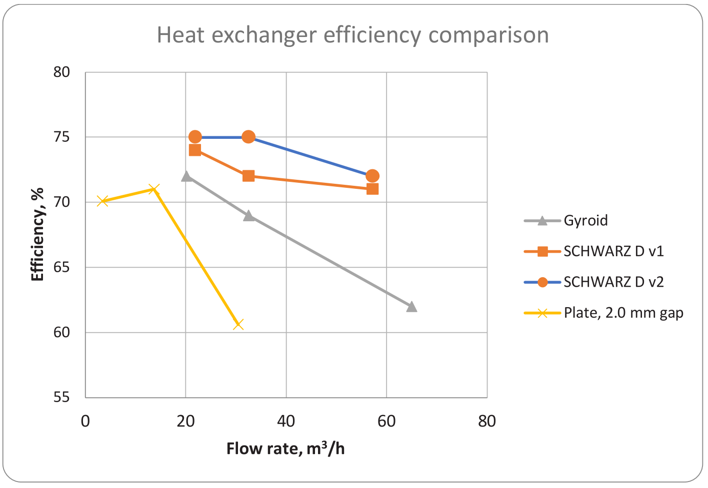


*Fig. 11.* Heat exchanger efficiency comparison.

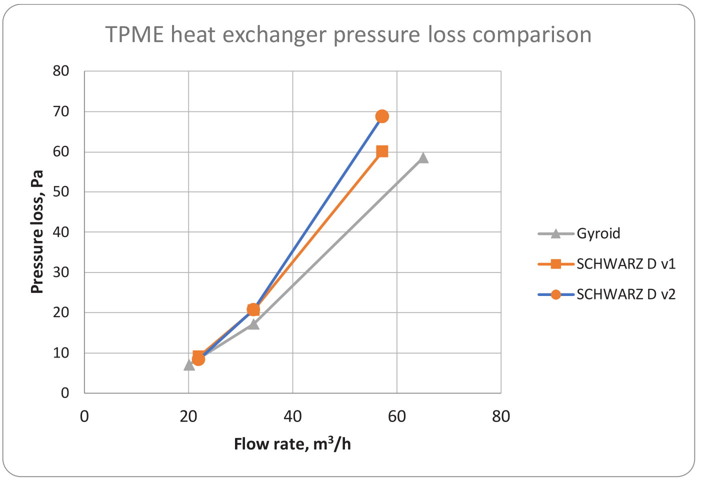


*Fig. 12.* Heat exchanger pressure loss comparison.

## 3. CONCLUSIONS

In this paper, the ability to print air tight, thin walled triply periodic minimal surfaces was confirmed, by using UV LCD printing method. Such heat exchanger structures can be used in low pressure and temperature systems, such as single room residential ventilation air recuperators due to their light weight, compact size and relatively low chance of fouling, compared to more traditional types of heat exchangers. The actual wall thicknesses of the TPMS heat exchangers were greater than those modelled. This likely results in slightly lower porosity, reduced efficiency, and higher back pressure than anticipated, which must be considered when developing further prototypes. Improving printing parameters to achieve thinner walls should also be explored.

During the laboratory tests, it was concluded that printed plastic heat exchangers have better heat exchange efficiency at similar flow rates and back pressure in the inlet channels, compared to similar sized metal plate heat exchangers. In a compact recuperator design that has been chosen, only Schwarz-D v2 structure heat exchangers reach thermal efficiency of ~75 %, while maintaining around 30 m3/h flow rate, that is the minimum required for 2-person bedroom ventilation, and the low back pressure might imply that further optimisation of geometry can lead to increased efficiency. The relatively low back pressure measurements (~20 Pa) indicate that even smaller size systems could be achievable for single room ventilation, depending on other ventilation unit requirements and performance.

All the printed heat exchangers (Schwarz-D and gyroid) performed with relatively stable efficiency at different flow rates, with maximum change in thermal efficiency being 10 % for gyroid heat exchanger. As the flow rate increases, the back pressure in the inlet channels increases rapidly for all TPME designs.

The low noise level and back pressure at the inlet (~20 Pa) at the average planned flow volume can make it possible to use smaller and more quiet ventilators that could reduce the whole system dimensions for a thermal recuperator. This coupled with the low weight, low cost and corrosion resistance, compared to conventional metal plate heat exchangers could be advantageous in compact systems.

In order to use such designs in residential ventilation, further studies are required to assess cost-performance, production scalability, heat exchanger fouling, frosting, environmental impacts, and other relevant properties. Additionally, there are numerous approaches to geometrically optimise the heat exchanger for improved efficiency or reduced pressure drop.

## ACKNOWLEDGEMENTS

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# INFLUENCE OF IRON(III) OXIDE NANORODS ON THE MECHANICAL AND THERMAL PROPERTIES OF PAN NANOFIBER MATS

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This study delves into the integration of iron (III) oxide ($Fe_2O_3$) nanorods into orientated polyacrylonitrile (PAN) nanofiber mats, a topic of considerable interest in applications such as water treatment and environmental remediation. Focussing on the modification of PAN nanofibers, the research investigates the impact of varying concentrations (1 %, 3 % and 5 %) of $Fe_2O_3$ nanorods on the mechanical and thermal properties of the nanofiber mats. Mechanical strength was evaluated by tensile testing, while thermal stability was evaluated by thermogravimetric analysis (TGA). The results indicate a notable improvement in the mechanical strength of the nanofiber mats, with an increase of up to 24 % observed at the highest nanorod concentration of 5 %. However, the thermal stability of the mats showed a decrease of approximately 12 % as per the TGA results. This research provides new insights into the effect of $Fe_2O_3$ nanorod reinforcement on PAN nanofibers, highlighting the trade-offs between mechanical enhancement and thermal stability.

***Keywords:*** *$Fe_2O_3$, nanocomposite, nanorod, PAN nanofibers, tensile test, thermogravimetry (TGA).*

## 1. INTRODUCTION

The escalation of heavy metal pollution, a by-product of relentless industrialisation and urbanisation, poses a serious threat to environmental integrity and human health. The contamination of natural potable water with heavy metals, such as arsenic (As), lead (Pb), cadmium (Cd), and mercury (Hg), frequently exceeds the permissible limits established by the World Health Organisation (WHO) and other environmental authorities. Consequently, the removal of heavy metal ions from contaminated wastewater has become a critical concern in water management and environmental remediation [1].

Electrospinning, a cost-effective method to produce nanofibers [2], has shown promise in the development of filtration [3], [4], antibacterial textiles [5]–[7] and drug delivery materials [8]–[10]. Typically, these nanofibers exhibit a lower mechanical strength. To address this issue, $Fe_2O_3$-reinforced nanofibers have been used to filter heavy metals and pollutants from air and water [11].

Conventionally, polymers are reinforced with high-strength materials to enhance their mechanical properties [12]. However, the impact of reinforcing $Fe_2O_3$ nanorods on the mechanical and thermal stability of nanofibers has not been adequately explored. Understanding the influence of $Fe_2O_3$ content on the mechanical and thermal properties of nanofiber mats is crucial, given their exposure to external forces and varying temperatures in practical applications.

This research article presents the production of high-strength, orientated polyacrylonitrile (PAN) nanofiber mats, reinforced with 1 %, 3 %, and 5 % $Fe_2O_3$ nanorods. We have conducted a comprehensive investigation into their mechanical properties through tensile testing and compared them with an analytical model to determine their statistical significance. Furthermore, the thermal stability of these nanofiber mats was evaluated using thermogravimetric analysis (TGA). This study aims to elucidate the mechanical and thermal behaviour of $Fe_2O_3$-reinforced PAN nanofiber mats, thus contributing to the advancement of filtration technology in environmental applications.

## 2. MATERIALS AND METHODOLOGY

The aim of the research is to study the influence of nanorods and their volume fraction on the thermal and mechanical properties of electrospun nanofibers. Using polyacrylonitrile (PAN) as the base material, we produced the nanofibers through an electrospinning process employing PAN powder and N,N-dimethylformamide (DMF) as the solvent. Polyacrylonitrile (average molecular weight: 150,000 (typical); CAS number: 25014-41-9) and N,N-dimethylformamide (DMF; ACS reagent, ≥99.8 % purity; CAS number: 68-12-2) were procured from Sigma-Aldrich Chemicals (Merck KGaA, Darmstadt, Germany). Iron oxide ($Fe_2O_3$) nanorods (CAS number: 1309-37-1), also sourced from Sigma-Aldrich Chemicals, were integrated with PAN to fabricate the nanofiber mats.

The PAN nanofibers were synthesised using an established electrospinning setup and parameters, as previously documented by the authors [13]–[15]. The primary modification involved the addition of 1 %, 3 %, and 5 % (wt./wt.) $Fe_2O_3$ nanorods to DMF. These nanorods underwent ultrasonic treatment to ensure dispersion and separation. Subsequently, PAN powder was added, followed by eight hours of magnetic stirring. The complete nanofiber mat fabrication process is illustrated in Fig. 1.

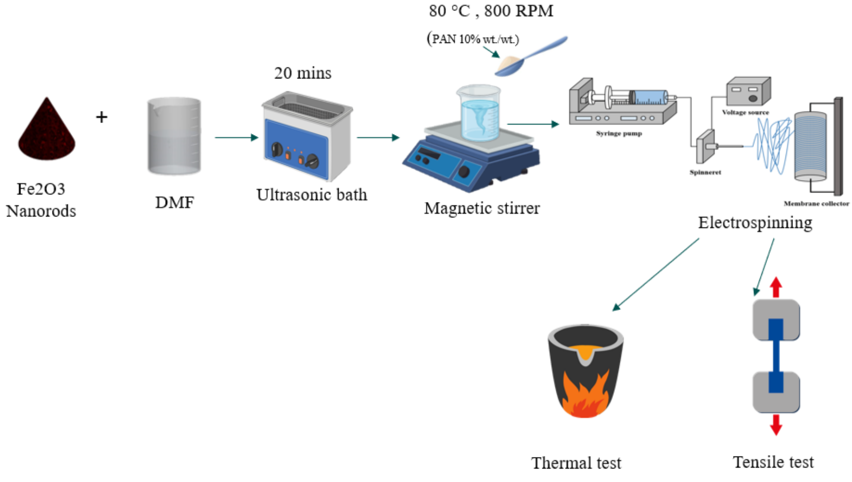


*Fig.1.* Schematic representation of the nanofibre mat fabrication process incorporating $Fe_2O_3$ nanorods.

The samples were denoted as E0, E1, E3, and E5, representing the elastic modulus of the nanofiber mats with 0 %, 1 %, 3 %, and 5 % $Fe_2O_3$ nanorods, respectively.

Scanning electron microscopy (SEM) analysis employed a Hitachi TM3000 tabletop SEM. The parameters included a magnification of 1500x, a vacuum of $10^{-2}$ Torr, ion coating at 6 mA, a gold (Au) sputter coating, and a coating thickness of 150. The contrast in the SEM images was enhanced for clearer observation.

Tensile properties were measured using a Mecmesin Multi-Test 2.5-i tensile testing machine with a 25-N sensor (PPT Group UK Ltd., UK). Sample preparation adhered to ISO 139:1973 "Standard Environments for Conditioning and Testing", specifying a temperature of 21 °C ± 1 °C, relative air humidity of 60 %, and atmospheric pressure of 760 mm Hg. The sample dimensions were conformed to ASTM D882-18, with a size of 50 mm × 10 mm (length × width). Four measurements per sample were made. The thickness of the nanofiber mat was measured using a Digimatic micrometre (range: 0–25 mm; Digimatic micrometre, MDC-25PX, code No. 293-240-30, serial No. 71912410, Mitutoyo, Japan). Specimens were cut parallel to the nanofiber orientation, attached to a paper template, and then mounted on the tensile testing machine. The preparation method is detailed further in [14].

The statistical significance of the experimental results was assessed by comparison with the Rule of Mixtures (ROM) and Halpin-Tsai micromechanical model, as delineated in Eqs. (1) and (2).

$$E_c = V_{Fe}.E_{Fe} + V_{pan}.E_{pan}; \quad (1)$$

$$E_c = \frac{E_{Fe}(1 + \zeta\ \eta\ V_{pan})}{1 - \eta\ V_{pan}}; \quad (2)$$

$$\eta = \frac{E_{pan} - E_{Fe}}{E_{pan} + \zeta E_{Fe}}, \quad (3)$$

where

$E_C$ is the elastic modulus of the composite material, MPa;

$V_{Fe}$ is the volume fraction of $Fe_2O_3$ nanorods in the composite;

$E_{Fe}$ is the elastic modulus of the $Fe_2O_3$ nanorods, MPa;

$V_{PAN}$ is the volume fraction of the PAN in the composite;

$E_{PAN}$ is the elastic modulus of the PAN nanofiber mat, MPa.

η is a function and ζ denotes an empirical parameter or a curve-fitting parameter that is used to calculate the value that matches the experimental data. In this study, the empirical parameter ζ = 1 was selected as mentioned in [13].

The Rule of Mixtures is a simplistic yet effective approach, primarily used to predict the properties of composite materials. It operates on the premise that the overall property of a composite can be approximated as a weighted average of the properties of its constituents, proportional to their respective volume fractions. On the other hand, the Halpin-Tsai model offers a more nuanced approach. It is particularly adept at predicting the elastic properties of composite materials with dispersed phase inclusions, such as fibres or particles. This model accounts for the geometry and distribution of the inclusions and the interface effects between the matrix and the inclusions, thereby providing a more detailed understanding of the mechanical behaviour. Both models are integral to our study, as they offer theoretical benchmarks against which the experimental results of the Fe2O3 reinforced PAN nanofiber mats can be rigorously evaluated.

Thermogravimetric analysis was performed using a TG 209 F1 Libra® thermomicrobalance (NETZSCH, Germany). The samples, weighing 5–6 mg, were heated in $Al_2O_3$ crucibles from 20 °C to 900 °C at a rate of 10 °C/min, in an inert nitrogen atmosphere with a flow rate of 30 ml/min.

## 3. RESULTS AND DISCUSSION

The SEM image depicted in Fig. 2 provides a detailed visual representation of the PAN nanofiber matrix reinforced with $Fe_2O_3$ nanorods. These nanorods, measuring approximately 50 nm in length and 10 nm in diameter, are uniformly distributed and well integrated within the nanofibers, a critical factor for achieving desired mechanical enhancements. The presence of bubble-shaped formations in the nanofiber matrix, as observed in the SEM image, is a notable feature. This morphology is likely a consequence of the high voltage applied during the electrospinning process, which influences the fibre formation and can lead to such unique structural characteristics.

Figure 3 presents the mechanical response under tensile loading for each nanofiber mat sample, which includes pure PAN and PAN reinforced with 1 %, 3 % and 5 % $Fe_2O_3$ nanorods.

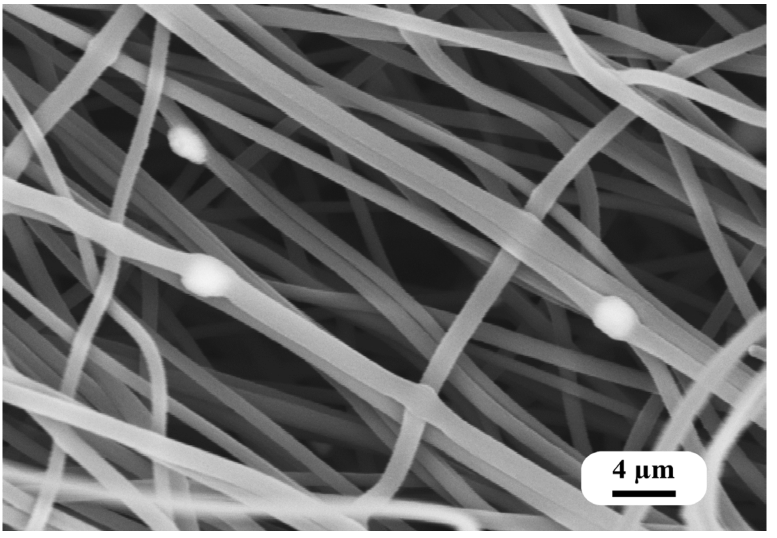


*Fig. 2.* SEM image of the nanofiber reinforced with nanorods.

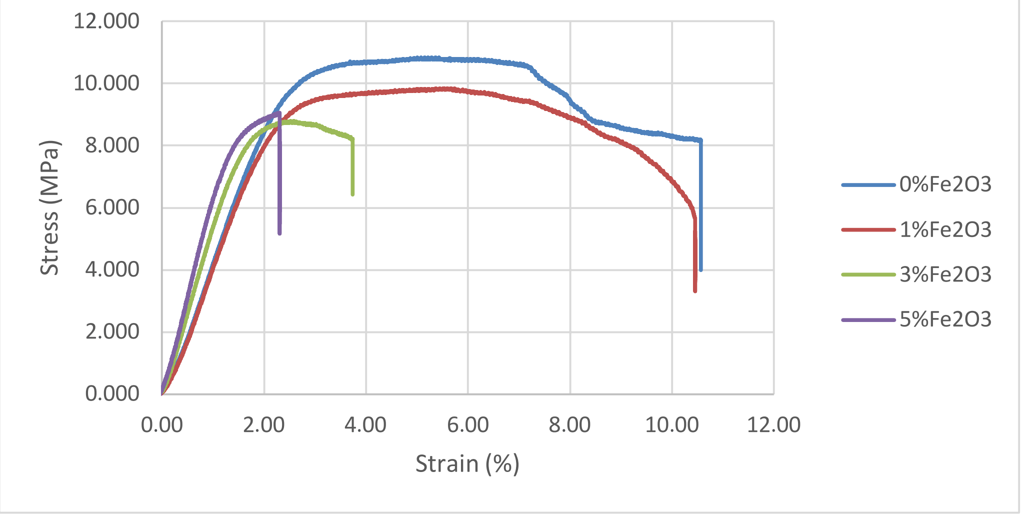


*Fig. 3.* Representative stress-strain curves for all sample variants.

In the context of ultimate tensile strength, the pure PAN nanofiber mat exhibited a value of 11.32 ± 1 MPa. Upon incorporation of $Fe_2O_3$ nanorods, a discernible alteration in strength was observed. Specifically, for nanofiber mats with 1 %, 3 % and 5 % $Fe_2O_3$, the ultimate tensile strengths were recorded as 10.36 ± 2 MPa 9.5 ± 2 MPa, and 9.13 ± 1 MPa, respectively. These data indicate an initial increase in strength with the addition of nanorods of up to 3 %, followed by a slight decrease with reinforcement at 5 % reinforcement.

The elastic modulus, a measure of material stiffness, was found for the pure PAN nanofiber mat to be 471.2 ± 10 MPa. In contrast, the addition of 1 %, 3 %, and 5 % $Fe_2O_3$ nanorods resulted in elastic moduli of 480.2 ± 10 MPa, 545.21 ± 10 MPa, and 586.63 ± 10 MPa, respectively. These results demonstrate a consistent increase in stiffness with the increasing percentage of $Fe_2O_3$ nanorods.

A notable decrease in the elongation at break was observed as a consequence of nanorod reinforcement. The break elongation of the pure PAN nanofiber mat was measured at 9.86 ± 2 %. For mats reinforced with 1 %, 3 % and 5 % $Fe_2O_3$, the values were 8.69 ± 2 %, 4.84 ± 1 %, and 2.63 ± 1 %, respectively (Table 1). This trend highlights the increased brittleness and reduced ductility of nanofiber mats with higher $Fe_2O_3$ content, a common trade-off observed in reinforced composites where increased strength and stiffness often come at the expense of ductility.

**Table 1.** Summary of Mechanical Properties

| Materials | Ultimate tensile strength, σ (MPa) | Young's modulus, E (MPa) | Elongation at break (%) |
|---|---|---|---|
| PAN nanofiber mat | 11.32 ± 1 | 471.2 ± 10 | 9.86 ± 2 |
| PAN & 1 % $Fe_2O_3$ | 10.36 ± 2 | 480.2 ± 10 | 8.69 ± 2 |
| PAN & 3 % $Fe_2O_3$ | 9.5 ± 2 | 545.21 ± 10 | 4.84 ± 1 |
| PAN & 5 % $Fe_2O_3$ | 9.13 ± 1 | 586.63 ± 10 | 2.63 ± 1 |

The observed enhancements in mechanical properties are attributable to the precise and uniform reinforcement of $Fe_2O_3$ nanorods. The gradual increase in tensile strength and Young's modulus with increasing $Fe_2O_3$ content evidence the effectiveness of nanorod reinforcement in improving material strength and rigidity. The slight reduction in elongation at break with a higher $Fe_2O_3$ content suggests a corresponding increase in material stiffness.

The results of Table 2 reveal a notable correlation between the experimental data and the theoretical predictions, especially in the context of the Halpin-Tsai model.

**Table 2.** Experimentally and Analytically Calculated Values of Elastic Modulus of Nanofiber Mats

| | E value for PAN (MPa) | E value for 1% of $Fe_2O_3$ (MPa) | E value for 3% of $Fe_2O_3$ (MPa) | E value for 5% of $Fe_2O_3$ (MPa) |
|---|---|---|---|---|
| Experimental result | 471.2 | 480.2 | 545.21 | 586.63 |
| ROM method | - | 516.496 | 607.088 | 697.68 |
| Halpin-Tsai method | - | 496.095 | 546.571 | 597.982 |

The experimental values for the elastic modulus exhibit an incremental increase with a higher $Fe_2O_3$ content, a trend captured well by the Halpin-Tsai model. The closer alignment with experimental results, compared to the ROM model, could be attributed to its more comprehensive approach in considering the impact of particle geometry and distribution within the matrix. The slight discrepancies observed with the ROM model may be due to its relatively simplistic approach, which may not fully encapsulate the intricacies of nanoscale interactions and the resultant mechanical properties.

Figure 4 presents the TGA of PAN nanofiber mats reinforced with 1 %, 3 % and 5 % $Fe_2O_3$. The TGA curves reveal critical insights into the thermal degradation behaviour of these nanocomposites. A notable feature in all samples is the sharp decrease in weight at approximately 280 °C, indicative of the rapid degradation of PAN within the crucible. Specifically, the first degradation onset temperatures for the 1 %, 3 % and

5 % $Fe_2O_3$ nanofiber mats were observed at 280 °C, 285 °C, and 29  °C, respectively. This trend suggests an incremental delay in the onset of degradation with increasing $Fe_2O_3$ content. After degradation, mass loss increased in proportion to the increment of the reinforced nanoparticles. However, at 900 °C the remaining mass was 12 % less in the 5 % $Fe_2O_3$ compared to the samples with 1 % $Fe_2O_3$.

Furthermore, a uniform weight loss was observed around 100 °C in all samples, likely attributable to the evaporation of the solvent used in the fabrication process. This solvent evaporation began at 100 ºC and continued up to 120 °C. At the post-phase, a stable mass was maintained until the onset of complete degradation of the nanofiber mats.

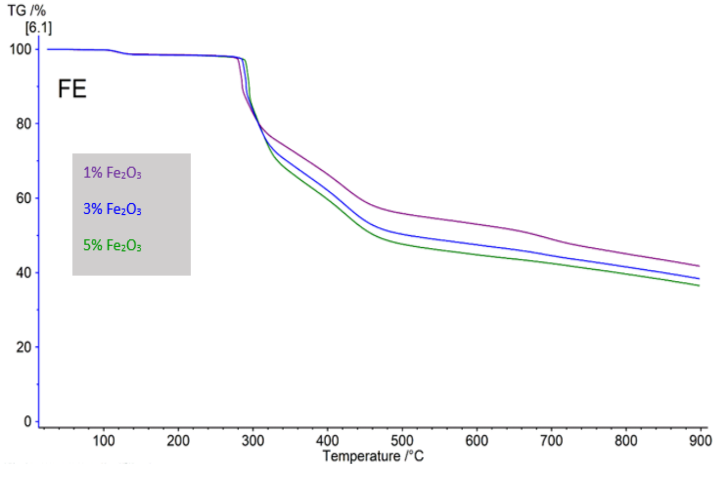


*Fig. 4.* TGA graph of all nanocomposites.

The observed increase in thermal degradation temperature with a higher $Fe_2O_3$ content can be attributed to the enhanced thermal conductivity imparted by the metallic nanoparticles. As the percentage of $Fe_2O_3$ nanorods in the nanofiber mats increases, so does the thermal conductivity, which in turn influences the thermal stability of the composite material. This higher thermal conductivity of the metallic particles likely contributes to a more efficient heat dissipation throughout the matrix, thereby increasing the temperature required to initiate degradation. This phenomenon underscores the effectiveness of $Fe_2O_3$ nanorods in enhancing the thermal stability of PAN nanofiber mats, an attribute that could be highly beneficial in applications where thermal resilience is a critical factor.

## 4. CONCLUSIONS

The comprehensive study conducted on the influence of $Fe_2O_3$ nanoparticles on the mechanical and thermal properties of PAN nanofiber mats has yielded several insightful findings. Integrating $Fe_2O_3$ nanorods into the PAN matrix significantly alters both the mechanical and thermal behaviour of the resultant nanocomposites.

Mechanically, the incorporation of $Fe_2O_3$ nanorods leads to a notable increase in both the ultimate tensile strength and the elastic modulus of the nanofiber mats. This enhancement in mechanical properties is observed to be up to 24 % at a 5 % $Fe_2O_3$ content. The increase in stiffness and strength can be directly attributed to the reinforcing effect of the uniformly distributed $Fe_2O_3$ nanorods. However, this reinforcement comes with a trade-off in ductility, as evidenced by the decrease in elongation at break with higher $Fe_2O_3$ content. These findings are consistent with the principles of composite materials, where the addition of reinforcing phases typically enhances strength and stiffness but reduces ductility.

From a thermal perspective, the TGA analysis reveals an increase in thermal stability with the addition of $Fe_2O_3$ nanoparticles. The degradation temperature of the nanofiber mats decreases progressively with higher concentrations of $Fe_2O_3$, suggesting a decrease in thermal resistance. This improved thermal stability can be attributed to the higher thermal conductivity of the metallic $Fe_2O_3$ nanoparticles, which facilitates a more efficient heat distribution and delays the appearance of thermal degradation.

In conclusion, the study underscores the efficacy of $Fe_2O_3$ nanoparticles as a reinforcing agent in enhancing the mechanical and thermal properties of PAN nanofiber mats. The findings of this research not only contribute to the existing body of knowledge on nanocomposite materials but also open up new avenues for the application of these materials in areas requiring enhanced mechanical strength and thermal stability. Future research could explore the scalability of this approach and investigate the long-term durability and environmental impact of such nanocomposite materials in real-world applications.

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# OPTIMISATION OF SOLAR TRIGENERATION SYSTEM

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The development of a solar trigeneration system for households is a complex and difficult task. The development of a rational system requires a multifaceted and balanced solution. Energy technology should be capable of independently and fully satisfying consumer demand and compatible with today's widely used engineering systems. To ensure broad application and use of the system, it must be sufficiently compact, cost-effective, and easy to install and repair.

***Keywords:*** *Heating, PV, solar cooling, solar trigeneration.*

## 1. INTRODUCTION

The information available on solar trigeneration systems for households is limited. A significant number of technical data mainly relate to large-scale photovoltaic solar air conditioning systems [1]–[6]. Reliable information on the amount of energy produced by such systems has only been obtained over the recent years, but it often remains inaccessible for the public, although there is strong interest in this type of technology on the part of solar energy researchers and engineers. This study examines solar trigeneration technology, which uses low-power equipment applicable to single-family homes. Such a system includes a solar PV electrically operated compressor cooler with cold energy and heat energy transfer for domestic use. During the non-cooling season, this system can be used in the reverse mode. In this mode, the ambient air serves as a heat source.

Production of cold and other cooling operations mean the removal of heat from the environment. Thus, the concept of "air conditioning" mainly refers to heat removal, while in some cases it may also include heat supply. Cooling loads for comfort in private and office buildings are expected to increase in the future, so it is important to look for alternative energy sources to reduce greenhouse gas emissions on a global scale. Lower costs of the system components and innovative solutions for solar technologies open wider opportunities for their use in different sectors of the economy. The Solar Heating and Cooling Association "SHC IEA" published reports on the increase in the number of solar air conditioning systems in the last decade [7]. Literature offers several ways of converting solar energy into another form of energy. Solar energy cannot be efficiently converted into heat removal. Therefore, solar cooling technologies operate by using either thermal energy or electricity.

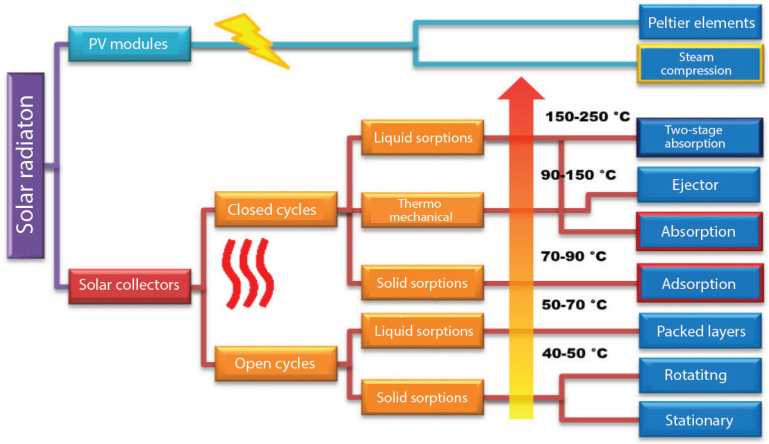


*Fig. 1.* Solar energy cooling technology scheme.

The solar cooling technology scheme shown in Figure 1 was created by summarising the latest information from various sources.

Solar cooling can be passive or active. Passive solar cooling means that there is no external energy supply; passive systems are not divided by type, such division being irrelevant. Active solar cooling, in turn, uses electricity or thermal energy as the energy transfer agent. Thermal energy for heat driven coolers is mainly produced by solar collectors. Electricity for electrically operated coolers is obtained from photovoltaic (PV) modules or from large solar power stations with the use of steam turbines. The solar cooling technology is selected depending on the energy source, use, and climatic conditions.

Today, the most popular technologies are thermally operated absorption and adsorption chillers in combination with solar collectors [7]. However, given the high costs of sorption machines and solar collectors, the market for these technologies is growing very slowly [8]. At the same time, the PV market is developing rapidly, as the prices of PV modules are constantly decreasing. The attractiveness of solar electric air conditioning systems is higher due to cost-related reasons, so the combination of PV modules with an electrically operated cooling system is at the basis of the PV generated energy air conditioning concept. Notably, all the PV based electricity operated air conditioning system components are freely available on the market.

Electrically operated heating and cooling equipment, such as steam compression heat pumps (HP) [9], [10], coolers, or reverse heat pumps connected to energy storage equipment, is an attractive energy supply solution for buildings. However, except for some European regions, only a few complete system solutions using photovoltaics for the energy supply of building are available on the market, and none of them combine PV and cold generation installations into a single system. For this reason, there is lack of information on the performance and overall costs of such systems.

The Solar Heat and Cooling Association (SHC IEA) expects rapid development of solar technologies in line with the increase in renewable energy sources (RES). The increase in RES is facilitated by the support mechanisms in the energy sector established by the EU directives and regulations on energy use. The subtask of the Buildings Directive 2009/28/EC is to reduce the increase in energy capacity. The Energy Performance of Buildings Directive (2018/844/EU), which requires reduction in the consumption of fossil fuels and electricity, has been of no less impact. Energy consumption can be reduced without compromising comfort levels by using energy-saving technologies, including solar thermal and cooling technologies. This implies that we are on the verge of facing substantial changes in the heating, cooling, and electricity supply systems of buildings, which will necessitate a great deal of work in the near future.

## 2. METHODOLOGY

By projecting combinations of different technologies for ensuring energy supply to the household, analysing and evaluating them with the help of selected criteria, we have identified the advantages and disadvantages of different technologies.

In the standard case, electricity for household needs is provided from external sources: the grid or a local electricity generator. By equipping households with solar modules, it is possible to supply part of the electricity consumed. Unfortunately, the solar technology energy generation schedule does not coincide with the electricity consumption schedule. This implies: 1) either use of local accumulators or 2) connecting to a bi-directional power exchange system.

As regards the first option, it should be borne in mind that power accumulation is expensive because of the high initial costs of the installations, and the number of operating cycles is limited. Choice of the second option implies possible restrictions in bi-directional electricity exchanges due to technical constraints, such as limited capacity, as well as legal restrictions that may vary from country to country and even across the regions of a single country. In the regions where electricity tariffs are higher than the cost of power storage, a combined solution is worth considering.

Household heat supply is required for both heating and hot water supply. Solar systems cannot deliver the required amount of thermal energy under central and northern European conditions because the seasonal schedule of heat demand does not coincide with the available solar schedule. However, in the warm months of the year, the full amount of thermal energy for hot water preparation can be provided by solar systems alone. Thermal energy can be efficiently obtained using solar collectors or solar power station systems. With solar collectors, solar radiation is converted directly into heat energy, which can be stored in water reservoirs and, accordingly, used through a heat exchanger. Solar modules, on the other hand, convert solar radiation into direct current electricity, which can be further used either directly by running an electric heater or by using more efficient electrically operated technologies, attracting the building external heat for satisfying the indoor heat demand.

Household cooling is required for indoor air during the hot months of the year. Solar cooling technologies are divided along two lines: technologies that yield electrical power through a solar panel system and use electricity for operating a compression machine; and those that yield heat through solar collectors and use it in thermally operated cooling machines. Thermally operated cooling installations are massive, they take up a large volume of space, they are heavy and expensive, consume water for efficient heat output, and also emit additional heat energy indoors in the form of heat loss. On the other hand, electrically operated compression machines are relatively compact, contain fewer metals and components, which makes them lighter and cheaper. However, the operation of a compression machine is noisy, and their efficiency largely depends on the temperature difference between the source of thermal energy and the consumption.

A 200 $m^2$ two-story building with four residents was adopted as the reference household. According to modern standards, the building is well insulated, U=0.35 W/K/$m^2$. Glazing makes 25 % of the external wall area, with active lamellae for shading at outdoor temperatures above 25 °C. Warm floors are used for heating, while cooling is provided by air conditioning installations. Indoor heating temperature is 20 °C. Cooling indoor temperature is 24 °C. Hot water is provided at 50 l/per day per person, with hot water temperature at 50 °C. The hot water consumption schedule is appropriate for a family home of four.

## 3. RESULT AND DISCUSSION

By analysing the information available in public databases and other literature sources on the diverse use of solar technologies in household energy supply, a list of energy supply systems with different combinations of technologies was compiled. In the conceptual phase, the different technologies were analytically assessed, and inappropriate technologies were excluded from further research.

In the technological phase, the technological scheme of solar trigeneration was developed. The identification of the basic component types relied on the assessment of the technical data producers as well as on the recommendations of manufacturers and installers. In the modelling phase, the simulation program Polysun was used to determine the size of the required equipment.

As the diversity of the technologies was assessed, the advantages and disadvantages of the technologies were summarised and analysed in detail. As a result, an electrically operated compression machine in combination with solar modules was selected as the basic system. The main advantages of the technology are as follows: the capacity of the compressor can be modified and linked to the amount of available solar electricity; either of the modes – the direct mode or the reverse mode – can be operated to generate cold or heat as required; it is technologically possible to remove indoor heat by transferring it to hot water preparation in the cooling cycle; indoor equipment occupies little space, its dimensions and placement can be optimised. Electric accumulators were considered for additional equipment since their economic feasibility should be verified during the study.

The hot water related heat demand generates high peaks in consumption. This requires an increase in the size of the basic equipment and a mode of operation that permits rapid variations. By equipping the system with a heat accumulator, it is possible to use the compressor in a gentler mode by reducing the rapid variations in consumption. The use of an accumulation tank for heating purposes is not necessary, as the results of the study showed that a temporary interruption of the heat supply in the heating circuits would not contribute to a sharp decrease in indoor temperature. At high solar intensity, the cold accumulator for cooling purposes can cool the heat transfer fluid for later use. The results of the study showed that the peak demand for cooling capacity came 1–1.5 h after the solar intensity peak. The thermal inertia of the building can stabilize the indoor temperature at temporary fluctuations in the power supply. As a result, a cold storage accumulator becomes optional.

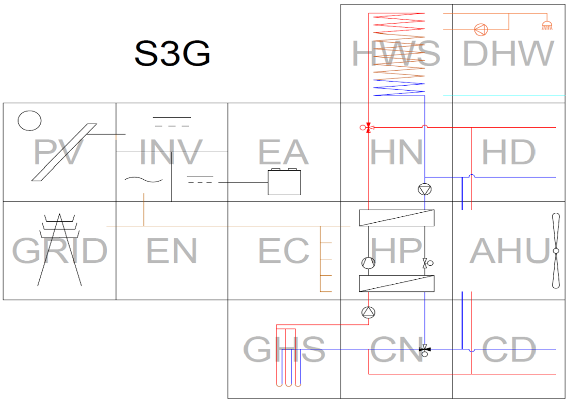


*Fig. 2.* The technological scheme of solar trigeneration.

The following principal scheme was developed in the Polysun simulation program. The results of the study showed that algorithmic management and process priorities had a significant impact on the balanced operation of the system. The process priorities are structured as follows:

1. The hot water storage tank is heated to 50 °C with a heat pump by heating the upper part of the storage tank.
   1.1. During the cooling season, it is required to use the indoor air heat.
   1.2. If the outdoor air temperature is higher than the ground temperature, it is required to use the outdoor air heat.
   1.3. If not, it is required to use the ground heat.
2. During the heating season, it is required to use the heat pump to heat the indoor spaces.
   2.1. If the ground temperature is higher than the outdoor air temperature, it is required to use the ground heat.
   2.2. If the outdoor air temperature is higher than the ground temperature, it is required to use the outdoor air heat.
3. During the cooling season, it is required to use free heating or heating without the heat pump to cool the supply air temperature. It is required to transfer the heat into the ground.

4. During the cooling season, it is required to use the heat pump to cool the supply air temperature.
    4.1. The hot water storage tank is heated to 55 °C, then the indoor heat is transferred for the preparation of hot water.
    4.2. If the ground temperature is lower than the outdoor air temperature, it is required to transfer the heat to the ground circuit.
    4.3. If the outdoor air temperature is lower than the ground temperature, it is required to transfer the heat to the air.
5. Excess solar energy is transferred for heating the hot water storage tank with the help of a tubular heating element.
6. The rest of the electricity is fed into the grid.

The correct sizing of components was performed through multiple iterations of the simulation model. The size of the components included in the simulations are consistent with the size of the components widely available on the market. The simulation model iterations were first performed on the basic components of the system. After determining the optimal selection of all components, another round of optimisation iterations was performed. This helped rule out any inaccuracies due to secondary components of the system.

## 4. CONCLUSION

The available information about the solar trigeneration system and its subsystems was gathered and analysed. The advantages and disadvantages of the technologies were summarised and analysed in detail.

The technological scheme of solar trigeneration was developed with the purpose of covering self-consumption of required electricity, heat and cooling. The Polysun simulation program was used to determine the size of the required equipment. The correct sizing of components was performed through multiple iterations of the simulation model.

The results of the study showed that algorithmic management and process priorities had a significant impact on the balanced operation of the system.

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