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Comparison of Convection Models for Hot Blast Stove Regenerative Chamber

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Abstract : Low error numerical solutions of convective heat transfer in high-temperature air regenerative heat exchangers in the convective regime rely on the correct determination of the wall heat transfer coefficient. Presented are results of simulations computed using a similarity theory-based numerical model. They imply that the current empirical formulas based on the theory of similarity, derived for analogous model cases of convective heat transfer do not allow to achieve satisfactory accuracy. Actual dependencies of parameters and criteria yielding more representative heat transfer coefficient values might be obtained through the means of experimental research in thermodynamics of an experimental device.

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1 Introduction

The utilisation of numerical modelling proves extremely useful in an effort to control or optimise any thermodynamic system operation. The models based on the first principles of heat and mass transfer often yield highly reliable results utilising CFD algorithms. However, necessary computational power requirements do not allow operative and real-time data processing. Therefore, applications demanding immediate outputs have to take advantage of models mostly based on enthalpy balancing and the similarity theory.

Predictive modelling of hot blast stove (HBS) allows evaluating the upcoming operating conditions and qualitative technological indicators. NM of this nature can be used in testing the design of innovative elements and solutions aimed at increasing energy efficiency and reducing the environmental impact of equipment (examples include the use of alternative fuels, combustion air enrichment, use of alternative materials for regeneration, or elimination of heat losses). However, the primary benefit lies in the fact that their implementation into the automated system control of HBS technology has the potential to stabilise the qualitative indicators of the process and at the same time reduce the specific energy consumption.

The focus of this paper is an analysis of a simplified numerical model (NM) based on the similarity theory. Assuming that the CFD simulation provides a more detailed view of the thermodynamics, the accuracy of the NM outputs were compared to the referential CFD simulation. Identified were areas of concern in which further research is necessary. Application of newly obtained data in the following optimisation of the NM will yield lower theoretical errors.

Heat transfer in regenerative heat exchanger units occurs in the accumulation regime by radiation and convection of the fluid to the accumulation brick surfaces and by conduction in the volume of the bricks (in case of HBS ceramic checker bricks). However, when creating simplified models, the biggest problem arises in determining the convection heat transfer coefficient. Therefore, in the previous work, the attention was focused on the analysis of convective heat transfer. Consequently, in order to eliminate radiation, all presented simulations were conducted using dry air as a fluid domain. It applies for both accumulation and blasting regime of HBS models.

2 Methodology

Convective heat flux can be expressed by Newton's law of cooling, where the convective heat transfer coefficient is obtained by empirical correlations of the Nusselt criterion, depending on the nature of the turbulence. Alternatively, Zhong (2004) reports the calculation of the convection heat transfer coefficient based on empirical temperature dependence [1]. Its application, however, yields significantly nonrepresentative values even at relatively low temperatures—the reason being the fact that the correlation bases only on the temperature of the fluid and was derived for blasting regime only. However, convection is mainly affected by the temperature difference between the fluid and the wall surfaces. More accurate model of convective heat exchange in the channels with a turbulent fluid flow is described by the empirical formulas based on the Nusselt criterion, according to M. A. Michejev [2, 3]. It describes heat exchange in smooth pipes and ducts with relatively low error. However, with the higher temperatures of the fluid and the higher surface roughness of the channel walls, the inaccuracy of the calculation increases. Heat exchange in regenerative heat exchangers was addressed by Zatterholm (2015), who in the NM of HBS sets the Nusselt number depending on the nature of the turbulence using correlations of Gnielinsky and Hausen [4, 5].

2.1 *Geometry*

Standardly, perforated ceramic bricks form the accumulation filling of HBS (see Figure 2a)). The blocks fill the volume of the regenerative chamber and create streams that pass through the entire height of the chamber. In standard HBS, approximately 13,000 streams are created in this way. However, for NM purposes, it is necessary to ensure the simplicity of computational nodes. Geometric symmetry of the bricks (see Figure 2b)) facilitates the computation. The symmetry element is sufficient enough to determine the mean temperature of the checker bricks over the entire cross-section of HBS. To ensure relatively high accuracy of outputs and at the same time ensure carrying out the simulation in a sufficient timeframe, the optimal height of the calculation element has to be defined in order to discretise the model in height.

2.2 *Numerical model*

In a simplified manner the flowchart of Figure 1 describes the concept of the iterative algorithm for determining temperatures in a calculation element. Several simplifying assumptions have been adopted, which are described in detail by Zhong (2004). In particular:

- the possibility of reverse flow is neglected,
- thermal processes within a time step are considered to be quasi-stationary events,
- heat transfer by conduction along the height of the model is neglected,
- considered is an even distribution of the flow throughout the cross-section of the regenerative chamber [1].

2.2.1 Calculation procedure:

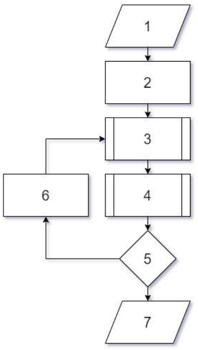

Figure 1 Iterative procedure for temperature calculation

1. reading temperatures from the previous time step and the previous zone (or boundary and initial conditions),
2. initial estimate of the fluid temperature at the end of the zone:

$$t_{f,2,i,e} = \frac{t_{f,1,i} + t_{s,i-1}}{2} \qquad (1)$$

3. calculation of the mean brick temperature at the end of a time step:

$$t_{s,i+1} = \frac{c_i \cdot t_{s,i} - \dfrac{\Delta Q}{m_s}}{c_{i+1}} \qquad (2)$$

$$\Delta Q = \Delta\tau \cdot \dot{m}_f \cdot \left(c_{p,2} \cdot t_{f,2,i,e} - c_{p,1} \cdot t_{f,1,i}\right) \qquad (3)$$

4. calculation of the fluid temperature at the end of the zone:

$$t_{f,2,i} = \frac{c_{p,1} \cdot t_{f,1,i} + \dfrac{Q_K}{\dot{m}_f}}{c_{p,2}} \qquad (4)$$

$$Q_K = \Delta\tau \cdot \alpha_K \cdot S \cdot \Delta t_{ln} \qquad (5)$$

$$\alpha_K = f[Nu = f(Re, Pr)] \qquad (6)$$

5. accuracy check of the estimate:

$$\left|t_{f,2,i,e} - t_{f,2,i}\right| < \varepsilon\ (\varepsilon = 0.001\ °C): \qquad (7)$$

6. estimate correction:

$$t_{f,2,i,e} = \frac{t_{f,2,i,e} + t_{f,2,i}}{2} \qquad (8)$$

7. output: temperature field.

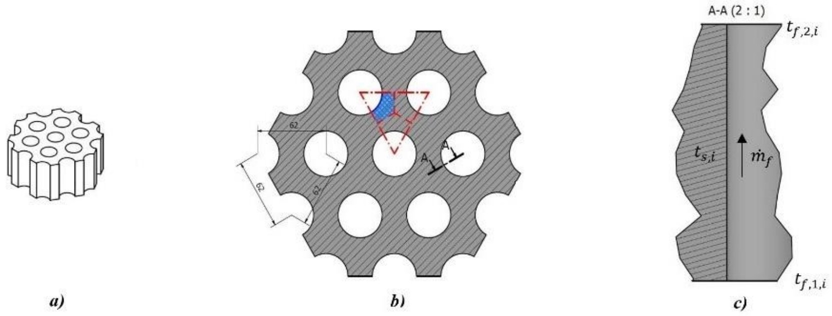

Figure 2 a) ceramic checker brick, b) cross-section of a brick with channels of a 40 mm diameter, symmetry elements are shown in red c) cross-section of brick filling in height, description of temperature field - indexes: s - solid (brick), f - fluid

2.3 *Referential CFD simulation*

CFD modelling is a powerful analytical tool that provides robust numerical methods for solving heat and mass transfer, the complexity of which allows to achieve relatively high accuracy of outputs. Since it is currently not possible to verify the NM results experimentally, the NM outputs are compared to a CFD simulation developed in ANSYS Fluent. However, the advantage is the possibility of eliminating inaccuracies caused by leaks, heat losses, or inhomogeneities of regenerative material that may occur on physical experimental device. However, it is still necessary to interpret the results only on a theoretical level. A simulation of a one-hour long accumulation of a 0.7 m high silica brick (Dinas) was performed. The 3D geometry is based on the sketches in Figure 2 under the conditions specified in Table 1.

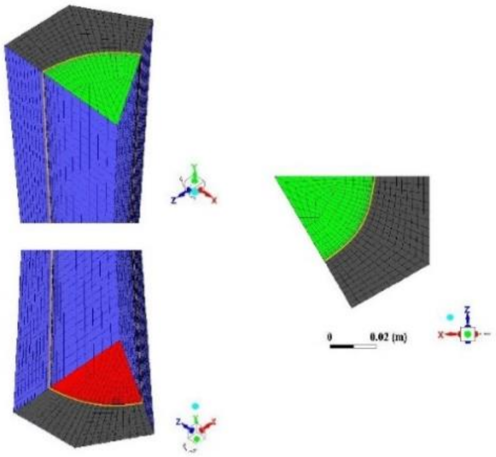

Figure 3 Symmetry element 3D geometry. Inlet, outlet, top view

Table 1 Simulation setup

Main setup	
solver	pressure-based
time	transient
turbulence model	k-ω, incompressible
energy equation	yes
Boundary conditions (see Figure 3 for colouring)	
walls	symmetry
walls	coupled wall, surface roughness 0.00025 m
walls	wall, null heat flux
inlet	$5.298.10^{-3}$ kg.s^{-1}, 921 K, 102 325 Pa
outlet	outflow
Initial conditions	
brick temperature	18 °C

2.4 *Physical properties of modeled materials*

The materials used for calculations are silica brick (Dinas, specific mass 2350 kg.m^{-3}) and dry air. Regression analyses of tabulated properties were carried out for the mean specific heat capacity of Dinas, the mean specific heat capacity of air at constant pressure and thermal conductivity [6]. The outputs are polynomial functions of temperature with coefficients of determination $r^2 > 0.99$. The functions are for individual properties in the following form:

$$A + B \cdot T + C \cdot T^2 + D \cdot T^3 \tag{9}$$

Table 2 Temperature dependence of specific heat capacity

Material	A	B	C	D
	(Jkg^{-1}K^{-1})	(Jkg^{-1}K^{-2})	(Jkg^{-1}K^{-3})	(Jkg^{-1}K^{-4})
Dinas	805.71	0.25	0	0
Air	905.56	0.31	$-8.62 \cdot 10^{-5}$	$8.62 \cdot 10^{-9}$

Table 3 Temperature dependence of thermal conductivity

Material	A	B	C	D
	(Wm^{-1}K^{-1})	(Wm^{-1}K^{-2})	(Wm^{-1}K^{-3})	(Wm^{-1}K^{-4})
Dinas	0.99	$6.4 \cdot 10^{-4}$	0	0
Air	0.01	$7.55 \cdot 10^{-5}$	$-2.06 \cdot 10^{-8}$	$4.04 \cdot 10^{-12}$

3 Results

In addition to the referential CFD simulation of the accumulation regime, calculations of the accumulation regime and air blasting regime were performed using the presented NM. For comparison, the method of Zhong and two Nusselt criterion-based methods (Michejev and Hausen) were used to determine the heat transfer coefficient.

The individual outputs differ significantly. The heat transfer coefficient is in the accumulation regime (Figure 4) at the levels around 34-35 W.m^{-2}.K^{-1} during the whole period (based on the reference model). Zhong's model appears to be unsuitable in the accumulation regime, mainly because it is based only on air temperature. In this regime, the blown air is at a temperature of 700°C. Consequently, the heat transfer coefficient becomes too high. Models based on the Nusselt criterion, on the other hand, achieve significantly lower values than the reference model. Nevertheless, they appear to be the more appropriate method.

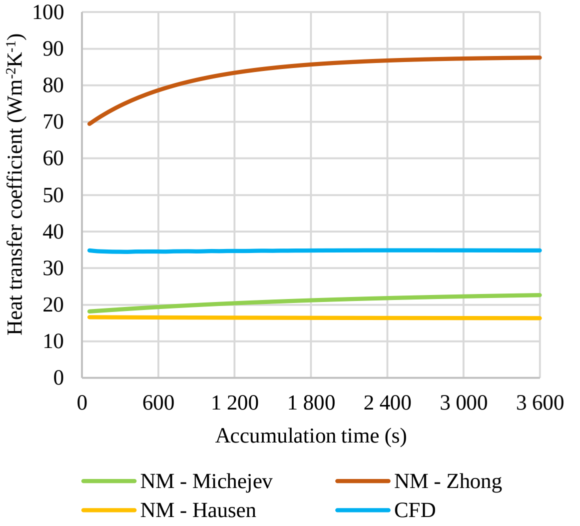

Figure 4 The course of the convective heat transfer coefficient value in the accumulation regime

The CFD simulation of the blasting regime (Figure 5) has not been carried out yet. Nonetheless, once again the outputs of the individual NM variants differ significantly. NMs based on formulas according to Michejev and Zhong have a decreasing course dependent on a gradual decrease in air temperature and a temperature difference. On the contrary, Hausen's model predicts an increasing course. However, by reducing the temperature difference, the value of the heat transfer coefficient should stabilize.

Based on the increasing and decreasing nature of the curves, it can be seen their differential decreases, so stabilization of the values can be expected with further heating. However, it is not clear which model has the potential to describe convective heat transfer with the lowest theoretical error, from the presented outputs.

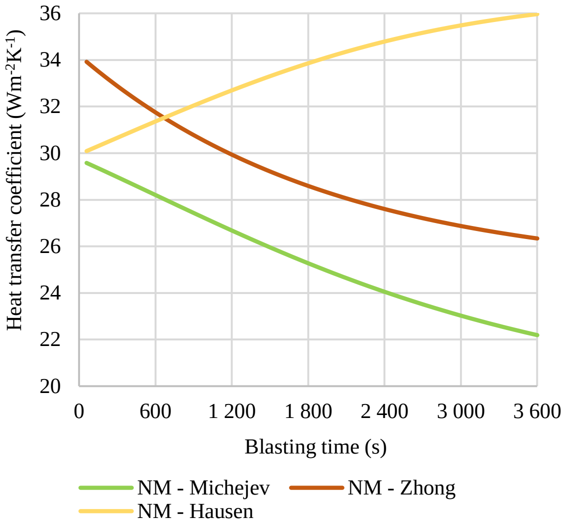

Figure 5 The course of the convective heat transfer coefficient value in the blasting regime

Heat transfer coefficient value primarily characterizes the intensity of heat transfer and thus affects the rate of temperature changes in any NM (Figure 6). Therefore, determining the correct value is crucial. A higher value of the factor according to the referential simulation causes a faster rise of temperatures in the accumulation process than in the case of NM, according to Michejev, which yields lower values.

The presented NMs bases on the concept of thin-wall body heating. However, the output of the reference CFD simulation proves that the heat accumulation in such regenerator does not behave as one of a thin-wall body. Value of Biot number also predicted such behaviour. The mean temperature inside the brick heats up (or cools down) with a delay which is influenced mainly by the thermal conductivity of the material (see Figure 7). Therefore, it will be necessary to incorporate a conduction heat transfer model into the future versions of NM. Its solution can be obtained by a numerical method. Experimental research of thermodynamics on a specific device, however, will allow solving the conduction analytically. The benefit would be a significant jump in the calculation speed.

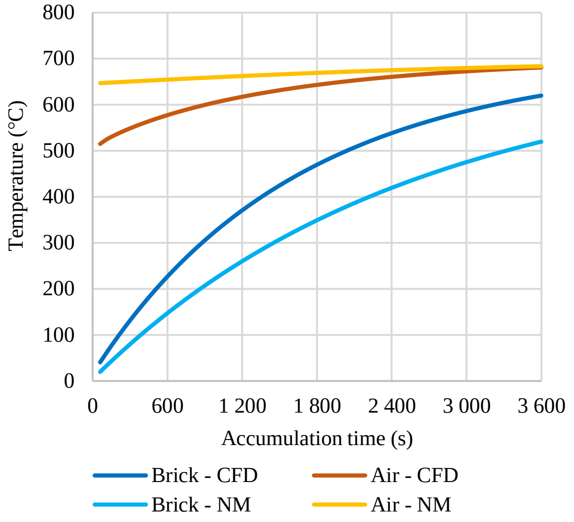

Figure 6 CFD simulation and NM outputs comparison

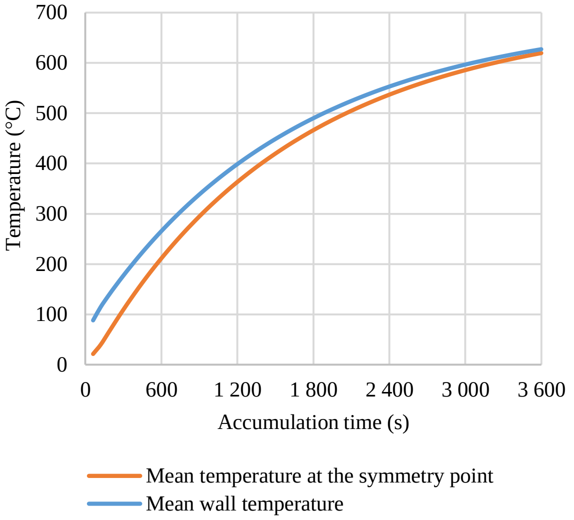

Figure 7 Brick temperature profile during the accumulation

4 Conclusions

The numerical solution of convective heat transfer is usually dependent on the accuracy of determining the convection heat transfer coefficient. The subject of this paper was to analyse the possible methods applicable to the convection solution and to compare those methods to the outputs of a referential CFD model. The ambiguity of the results of the known empirical correlations of the Nusselt criterion further encourages us to further research on this issue. It should include experimental research on heat transfer by convection in HBS. The research will aim to define an empirical dependence of the Nusselt criterion on the nature of the flow, geometrical similarity and thermo-physical properties of the processes in accumulation and blasting regime individually.

Nomenclature

α_K: convective heat transfer coefficient $(W.m^{2}.K^{-1})$
c: mean specific heat capacity $(J.kg.K^{-1})$
cp: isobaric mean specific heat capacity $(J.kg.K^{-1})$
ε: desired accuracy $(°C)$
m_s: mass of the solid in a calculation element (kg)
$\dot{m}_f$: mass flow rate of the fluid $(kg.s^{-1})$
Nu: Nusselt number $(-)$
Pr: Prandtl number $(-)$
ΔQ: change in enthalpy (J)
Q_K: heat exchanged by convection (J)
Re: Reynolds number $(-)$
S: heat exchange surface (m^{2})
t_f: temperature in fluid domain $(°C)$
t_s: temperature in solid domain $(°C)$
Δt_{ln}: mean logarithmic temperature difference between wall temperature of solid and mean temperature of fluid in calculation element $(°C)$
$\Delta\tau$: time step size (s)

Indexes:

i: timestep
$1,2$: position in a calculation zone
s: solid (brick)
f: fluid (air)
e: estimate

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Phase change materials for energy storage: A review

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Abstract : Phase change materials are one of the most suitable materials to effectively utilize the thermal energy from renewable energy. This review is based on the thermophysical properties of various phase change materials. In particular, the melting point, thermal energy storage density and thermal conductivity of organic, inorganic and eutectic phase change materials are the main selection criteria for various thermal energy storage applications over a wide operating temperature range..

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1 Introduction

Energy is the key condition to bring technology Progress and economic development Society around the world [1]. Endless consumption Non-renewable resources and the escalation of the global situation Warming has forced the trend to shift to use Sustainable energy [2]. Therefore, it is imperative Explore renewable and sustainable resources to meet thermal energy conversion and storage requirements. Can decarbonize the energy sector by combining renewable energy with various Thermal energy storage system with round-trip efficiency of > 96% [3]. Currently, more than 18% of global energy consumption from renewable energy. Renewable energy it is undeniable that resources are more favored than the use of non-renewable energy, because it is long-term availability and accessibility of resources and environmental benign [4, 5]. Integration/Hybrid Energy systems containing different technologies. To reduce peak power demand (load balancing) it is being systems deployed in a complementary manner. Most of the hybrid power system uses auxiliary heater as secondary energy carbon-based fuel to overcome intermittent of renewable energy [6]. However, yes secondary energy/carbon-based fuel can be minimized improve efficiency by applying thermal energy storage (TES) and a cleaner energy system, which improves reliability thermal energy from renewable resources and eventually contained global warming [7]. Besides, if energy production exceeding energy requirements, TES system can be used for storage bridging the demand-supply gap by providing surplus energy during peak power demand [8]. Latent heat storage material is called phase change material (PCM). PCM is a group of materials with inherent absorption capacity release heat during the phase change cycle, thereby during charging and discharging. PCM can be organic inorganic or eutectic mixture [9]. There are several problems, such as low thermal conductivity, poor thermal stability, high flammability, undercooling, corrosiveness, and volume and pressure changes during phase transitions, and leakage of molten PCM around the TES system, which limits the commercialization of PCM feasibility [10, 11].

2 Thermal energy storage

Multiple choices of thermal energy storage can be integrated into the energy system including renewable energy, such as solar energy, wind energy, geothermal, hydraulic or waste heat recovery. Thermal energy can be stored both chemically and physically method.

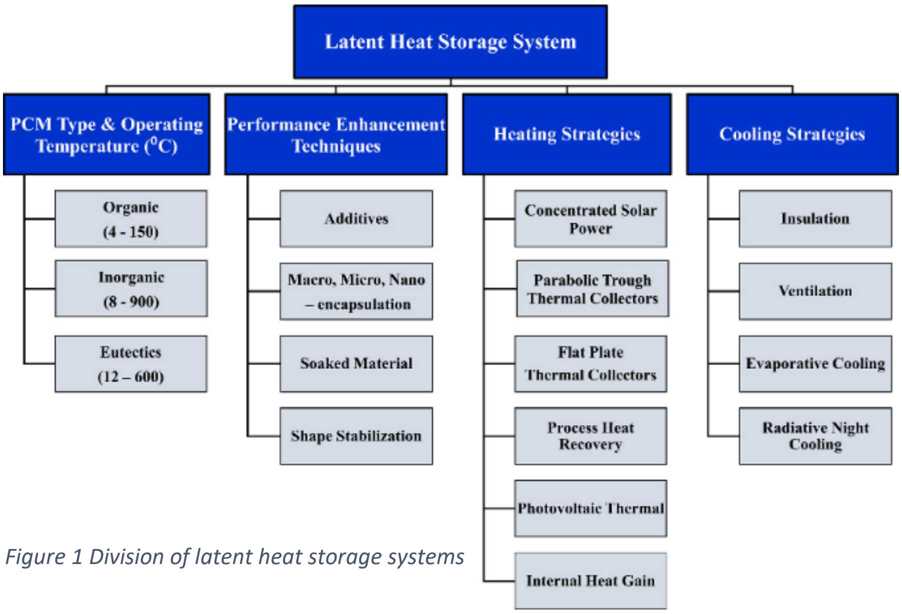


Figure 1 Division of latent heat storage systems

2.1 *Physical methods*

Heat transfer mechanism leads to storage heat energy and ability to maintain heat depends on specific thermophysical properties material. Latent heat storage (LHS) and sensible heat storage (SHS) is classified as physical storage. For SHS, thermal reasons is energy storage the temperature of a particular material through heat transfer through conduction, convection or radiation, while LHS involves accumulation of heat at the molecular level in matter make a phase change [12] [13]. The heat stored in the SHS depends on the quality, heat Gradient between storage material capacity and temperature Initial state and final state. The SHS can either be done in a solid or liquid storage media. In the case of solid-state storage dielectrics, metals and non-metals are widely used. Non-metallic concrete, rock, gravel, brick, marble, granite, sandstone, etc. are candidate materials, but their specific heat capacity is low, thermal conductivity is the main obstacle to reliability this type of storage [14,15]. Copper, aluminum, cast iron and other metals iron and pure iron and other alloys are suitable for high temperatures SHS, but the cost of the TES system with the following content is high. These metals are the main obstacles to commercialization. Metal and graphite have high thermal diffusivity, so suitable for applications involving fast charging and discharging, and rocks, gravel and stones have low thermal diffusivity, more suitable for slow charging and discharging applications cycle. The liquid storage medium of SHS includes molten salt, water, thermal oil (e.g. Calorie HT43) and other commercially available products existing products, but low energy storage density and heat conductivity limits this type of broad-spectrum application TES [16]. The high specific heat capacity of water makes it one of the promising candidates for SHS for temperatures below 100°C whereas molten salts have comparatively desirable thermophysical properties and are being adopted for various high temperature TES applications. Special measures are to be taken for storage assembly to prevent the corrosion, which increases the overall cost of the storage system as well [17]. The amount of heat stored in LHS depends upon the mass and latent heat of fusion of the PCMs. The energy storage equation for the PCMs comprises both the sensible and latent heat equations as the temperature rise of the material leads to the phase transformation. The working mechanism of PCMs involves absorption of the considerable amount of heat at reaching the phase change temperature, which is necessary for phase transition and the heat absorbed during this process is either called latent heat of vaporization or latent heat of fusion depending upon the phase of the material under consideration [18].

2.2 *Chemical methods*

In chemical TES, energy is stored and released due to the reversible reaction. Chemical methods of TES are classified as sorption storage and thermochemical energy storage [19]. The thermochemical energy storage comprises solid-gas or liquid-gas or gas phase systems. Energy is stored in thermochemical heat storage as a result of dissociation reaction which is then recovered in a chemically reversible reaction and its thermal cycle consists of charging, storing and discharging]. The amount of heat stored in thermochemical energy storage involving solid-gas phase depends upon the pressure of the gas, whereas the heat transfer is far greater in liquid solid systems compared to gas-solid systems [20]. They have also reported the short-term cyclic stability in the case of the solid liquid reaction of strontium chloride and ammonia for thermochemical heat storage. Potential candidates for thermochemical energy storage based on solid-gas reversible reactions various metal carbonates, oxides, and hydroxides as promising thermochemical energy storage materials depending upon their operating temperature and reaction enthalpy [19].

Currently, various thermochemical energy storage materials are in use. At the development stage, no such system is commercially available. The commercial feasibility of LHS is limited by the material characteristics, so it is in the development stage compared to SHS. This has been largely commercialized.

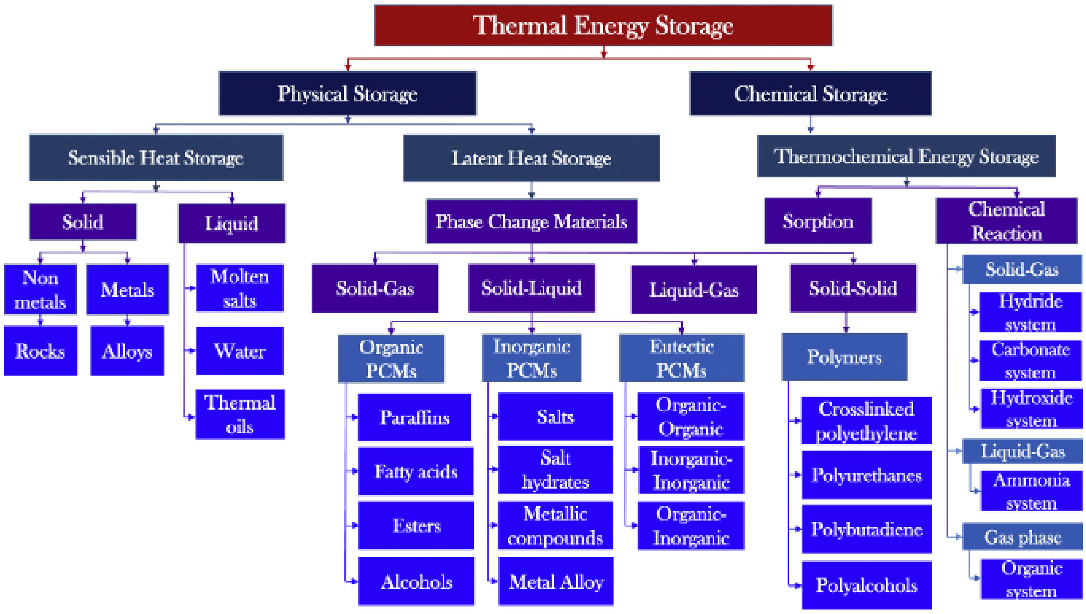


Figure 2 Materials for thermal energy storage

2.3 Comparison of thermal energy

Operating temperature range, storage density, TES commercial status/feasibility and durability gives wise, potential or chemical energy storage methods in Fig. 3. Generally, the storage density of LHS media is higher larger enthalpy change than SHS media Phase change, but thermochemical energy storage has compared with the other two modes, the storage density is the highest.

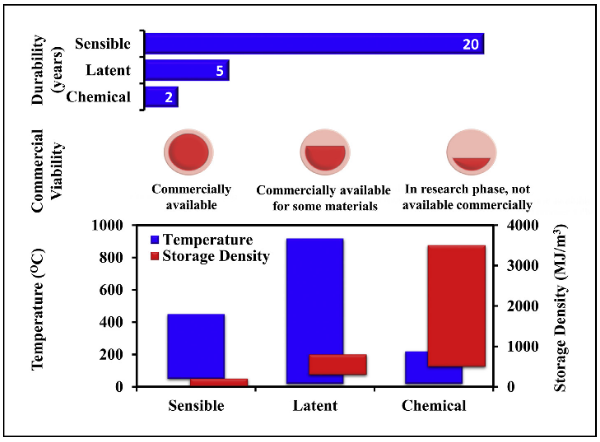


Figure 3 Storage capabilities of PCMs for thermal energy storage

It can be clearly seen from Fig. 3 in contrast, the durability of SHS materials is about 20 years. The service life of LHS material is a quarter of its service life and thermochemical energy storage, about one tenth the service life of SHS materials [21]. Among these different types of TES, LHS has the most flexible operating temperature range, after which a significantly lower operating temperature range is used for explicit and thermochemical energy storage [33]. Compared with latent heat storage technology, the advantage of using latent heat is that its TES density is 10 times higher and the capacity is 50-150 kWh/t. The round-trip efficiency is 75–96% [3].

3 Classification of phase change materials

PCMs can be classified depending upon the phase change mechanism and phase transition temperature, as show Figure 3.

3.1 Phase change mechanism

Due to large volume requirements and volume changes, TES systems consisting of liquid-gas or solid-gas phase changes are impractical it is related to the phase change and high voltage of the system, For example, noncommercial water vapor systems Suitable for large TES. For solid-solid PCM, the heat associated with the transition from one crystal form of the material to another (and vice versa) is the reason for TES. Compared with solid-liquid PCM, the phase-change heat of solid-solid PCM is relatively small [22]. Most PCM considered for TES are solid and liquid. Transition materials classified according to the nature of the material (e.g. organic, inorganic and eutectic) as shown below in Figure 3. Initially, solid-liquid phase change materials behaved like SHS materials. After they absorb heat, the temperature starts to rise. Different from conventional when PCM reaches its phase transition temperature, SHS material they continue to absorb heat without increasing significantly until all materials are turned into liquid phase. When the temperature around the melted PCM drops, it solidifies and the stored latent heat tends to be released. Organic PCMs used in TES are paraffins, alkanes, esters, fatty acids, alcohols and various compounds, including ketones, amides, sugars, dienes, oily carbonates, etc., while inorganic PCMs can be subdivided into salts, hydrates, and metal. Among various metal salts (such as carbonate, chloride, sulphate, fluoride and nitrate), magnesium chloride hexahydrate and sodium sulphate decahydrate are the most suitable PCMs. Aluminium alloy used because PCM has high thermal reliability for TES applications [23]. Special engineering materials with required thermophysical properties which characteristics are determined by each component mole eutectic point derived from its phase diagram is called eutectic PCM (EPCM) [23]. EPCM may be composed of a eutectic mixture of multiple components, these components are organic components, inorganic components or a mixture of the two, so they are classified as organic eutectic, inorganic eutectic and organic-inorganic eutectic [24].

3.2 Phase transition temperature

PCMs is divided into low temperature, medium temperature and high temperature PCM according to its phase transition temperature. PCM with a melting point below 220°C is a low temperature material, PCM with a melting point between 220 and 420°C is a medium temperature material, and PCM with a melting point above 420°C is a high temperature material [25]. The melting points of selected organic compounds are on Figure 4 [26].

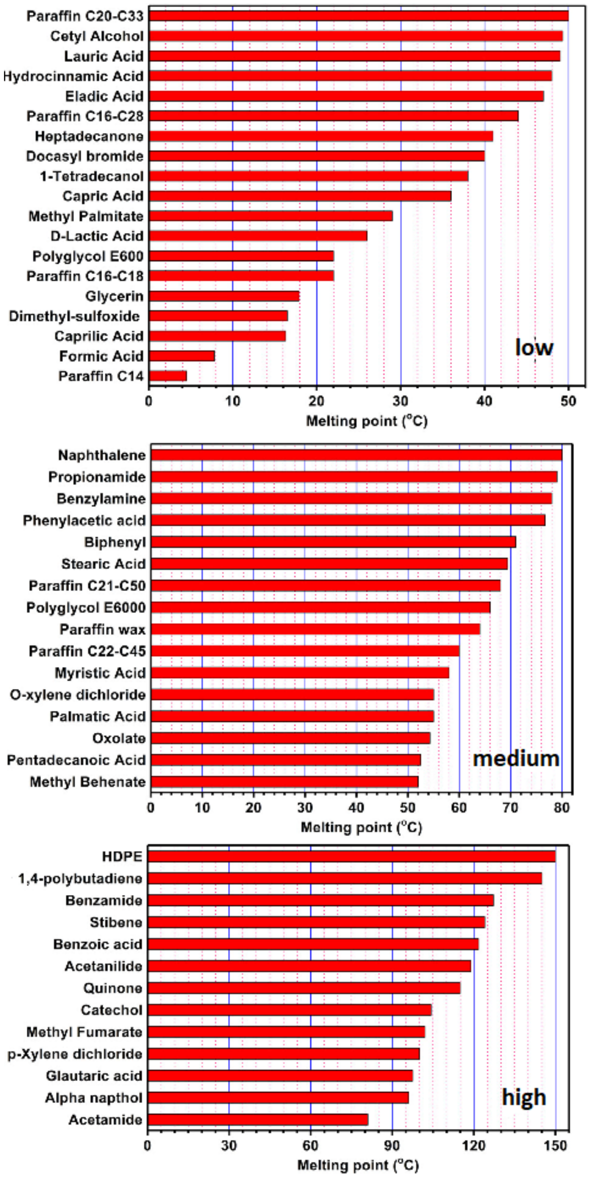


Figure 4 Melting points of selected organic PCMs

Most salt hydrates have melting points below 220°C. However, the melting point of inorganic salts is 1000°C higher than that of hydrates. These inorganic salts, such as metal carbonates, chlorides, sulphates, fluorides and nitrates, have been widely used as PCMs for high-temperature TES applications requiring operating temperatures in excess of 500°C [27]. Metal alloys and inorganic eutectics have extremely high melting points and are ideal for concentrated solar applications (CSP). Eutectic aluminum alloys are of great significance for high-temperature TES systems [28].

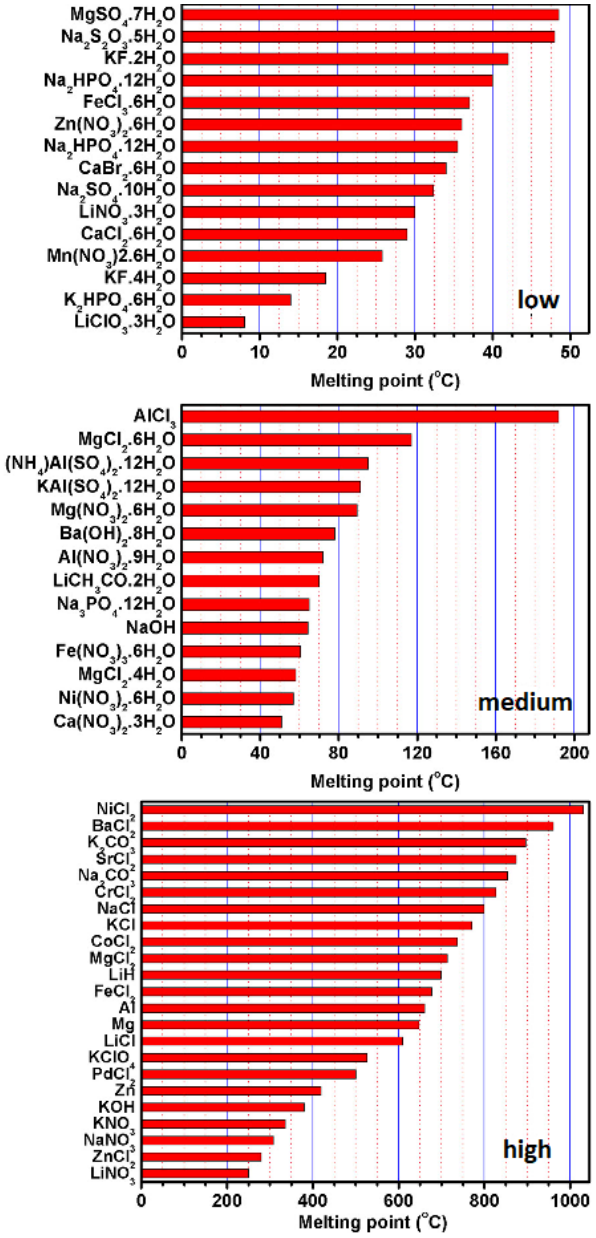


Figure 5 Melting points of selected inorganic PCMs

4 Selection criteria for materials

Various characteristics of materials (such as physical, thermal, chemical, and kinetic characteristics of materials as well as cost, ease of use, product safety, adaptability, and reliability) are considered as key selection parameters for PCM for any specific TES application. The general selection criteria for PCM is shown in Figure 6.

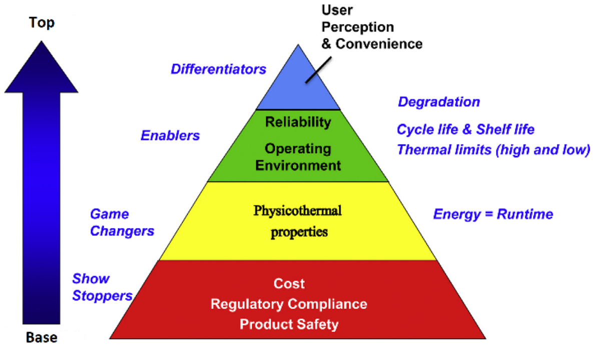


Figure 6 Selection characteristics of PCMs for thermal energy storage

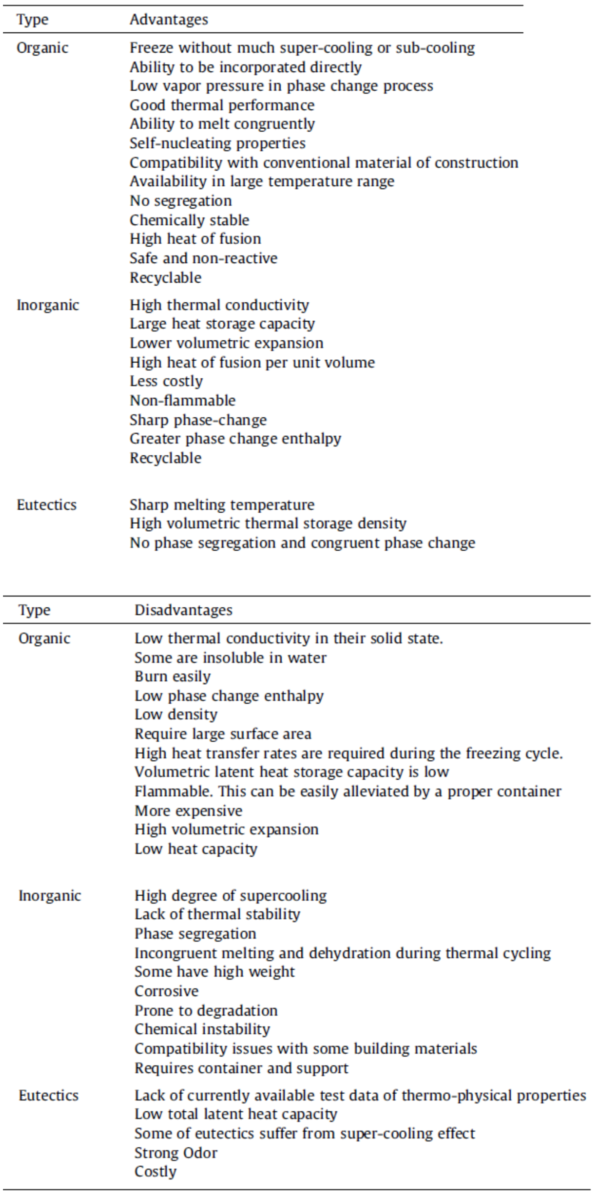
In addition to the technical aspects of PCM-based TES, its environmental and social impacts are also considered as part of the evaluation criteria. The main characteristics of PCM are its thermal, physical, kinetic and chemical properties, in addition to availability and cost [29]. In order to evaluate the suitability of a particular PCM in a specific application and temperature range, it is important to determine its thermophysical properties. There are several characterization devices and techniques for determining chemical and thermal stability to select PCM for specific applications. Measurement of properties such as melting/freezing temperature, latent heat of fusion and specific heat capacity by using differential scanning calorimetry (DSC) technology [30]. Use thermogravimetric analysis to determine the thermal stability, thermal reliability, and thermal capacity of a specific PCM. Cyclic stability is critical to the adaptability of a particular PCM in order to analyze the degree of deviation in thermophysical properties. In thermal performance, the phase change temperature of PCM falls within the operating temperature range is one of the key requirements when selecting a specific TES application. Other ideal thermal performance to ensure optimal performance PCM includes ideal latent heat, higher thermal conductivity, energy density and heat capacity [26]. Latent heat value and heat capacity are related to quantity the specified PCM can store or release energy [31]. Higher latent heat and heat capacity indicate the energy storage/release capacity of PCM, and higher thermal conductivity can ensure faster TES and release rate in TES [32]. Organic, inorganic and eutectic materials are commonly used in LHTES applications and have been extensively studied. PCMs with high thermal energy storage density are commercially available, with a wide range of paraffin and fatty acid PCMs operating temperature range from 40 to 151°C. Most of the selected organic materials have latent heat higher than 100 kJ.kg^{-1} and energy density higher than 100 MJ.m^{-3}. The energy density of paraffin is very small, between 0.14 and 0.19 MJ.m^{-3}. Formic acid, acetamide and erythritol have high latent heat (> 250 kJ.kg^{-1}) and energy density (> 300 MJ.m^{-3}). Their melting points are 7.8, 81 and 118°C, respectively.

Generally, inorganic materials have a higher energy density than organic materials. The energy density of all inorganic PCMs is higher than 200 MJ.m^{-3}. The latent heat and energy density of the selected eutectic mixtures Al-Si, LiF-CaF$_2$ and NaF-MgF$_2$ have the highest latent heat and energy density values. The latent heat values are 560, 816 and 860 kJ.kg^{-1} respectively. The energy density values are 1490, 1950 and 2425 MJ.m^{-3}, and the corresponding melting points are 577, 767 and 650°C, respectively. Thermal conductivity scattering: [26]. The thermal conductivity of organic materials ranges from 0.13 to 0.33 W.m^{-1}.K^{-1}. Inorganic materials generally have higher thermal conductivity than organic materials. The thermal conductivity of most inorganic PCMs is between 0.5 and 0.9 W.m^{-1}.K^{-1}. The thermal conductivity of the inorganic salt eutectic is in the range of 0.4- 2.1 W.m^{-1}.K^{-1}, while the thermal conductivity of the metal eutectic is much higher (>70 W.m^{-1}.K^{-1}). For example, Al-Si (180 W.m^{-1}.K^{-1}). Paraffin and alkanes also have the advantages of low cost, high thermal stability and chemical stability, no toxicity and a small amount of supercooling. However, the problem with organic PCMs is their lower thermal conductivity for different organic PCMs, which results in a lower heat transfer rate for energy storage, thereby deviating from the desired charge and discharge cycle time. However, recent developments have been trying to solve these problems by using a stable metal matrix or by incorporating micro or nano metal or metal oxide particles in an attempt to enhance the thermal conductivity of organic PCMs. Table 1 compares the advantages and disadvantages of organic, inorganic and eutectics PCMs [33].

5 Conclusion

The focus of this review is to develop TES technology using PCM, which utilizes latent heat. In addition to a series of flexible operating temperatures, PCM with higher thermal storage density can also reduce the size/volume of the storage tank. However, the large-scale commercial application of latent heat PCM is still limited, and its durability is lower than sensible heat materials. The choice of organic, inorganic and EPCM is based on Kinetics, thermodynamic properties and availability as well their melting point, latent heat, energy density, thermal conductivity and their cost. Since inorganic materials exhibit high energy density, high thermal conductivity, and relatively high melting temperatures, they are too bad more corrosive and exhibit a supercooled state. Of particular importance is that nanomaterials are used to increase the specific heat and thermal conductivity of PCM

Table 1 Advantages and disadvantages of PCMs



Type	Advantages
Organic	Freeze without much super-cooling or sub-cooling Ability to be incorporated directly Low vapor pressure in phase change process Good thermal performance Ability to melt congruently Self-nucleating properties Compatibility with conventional material of construction Availability in large temperature range No segregation Chemically stable High heat of fusion Safe and non-reactive Recyclable
Inorganic	High thermal conductivity Large heat storage capacity Lower volumetric expansion High heat of fusion per unit volume Less costly Non-flammable Sharp phase-change Greater phase change enthalpy Recyclable
Eutectics	Sharp melting temperature High volumetric thermal storage density No phase segregation and congruent phase change

Type	Disadvantages
Organic	Low thermal conductivity in their solid state. Some are insoluble in water Burn easily Low phase change enthalpy Low density Require large surface area High heat transfer rates are required during the freezing cycle. Volumetric latent heat storage capacity is low Flammable. This can be easily alleviated by a proper container More expensive High volumetric expansion Low heat capacity
Inorganic	High degree of supercooling Lack of thermal stability Phase segregation Incongruent melting and dehydration during thermal cycling Some have high weight Corrosive Prone to degradation Chemical instability Compatibility issues with some building materials Requires container and support
Eutectics	Lack of currently available test data of thermo-physical properties Low total latent heat capacity Some of eutectics suffer from super-cooling effect Strong Odor Costly

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Development of electricity prices in the V4 countries and econometric model of forecasting spot electricity prices in Slovakia

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Abstract: In this article, the authors focused on the development of electricity prices on wholesale and retail markets in the Visegrad Four countries (V4). The main goal of the paper is to design an econometric model of predicting spot electricity prices in Slovakia. Therefore, the model of multiple linear regression is used, based on knowledge from the literature and existing studies. The model can be used to predict the possible development of electricity prices depending on several relevant variables - coal prices, gas prices and the share of renewable energy sources. The data were obtained from Eurostat and OECD databases, investment sites, which showed the development of commodity prices on wholesale market, or from power exchanges or a short-term electricity market operator. RStudio software was then used to evaluate created models. The result was price forecasts for further periods, which were also compared with the actual spot prices.

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1 Introduction

Energy in any form is an essential resource for ensuring that normal and especially economic activities of a country are achieved. Thus, the use of electricity has become a key aspect. However, electricity is a secondary source that can be generated by transformation from various primary sources, such as fossil fuels (coal, natural gas, oil, etc.) or is obtained from renewable sources (hydro, solar, wind power) or nuclear energy. The type of energy used by a country on its territory then reflects its economic, social and political situation.

Four countries of Central Europe - the Czech Republic, Hungary, Poland and Slovakia - which are called the Visegrad Group (abb. V4) co-operate also in energy matters with one another. Most V4 countries are dependent on the import of primary resources, as either they do not have required energy source or their internal conditions cannot generate enough energy. In the long run, the most important supplier for these countries is Russia, which provides the largest share of oil, natural gas and solid fuel imports to the EU among other export countries. By the 1990s, most internal electricity and gas markets were monopolistic, but over time and with greater demands from the EU and the Member States, liberalization directives began to emerge to be implemented in the national policies of all EU countries. Thus, the markets of the V4 countries began to open up slowly to competition since 2006, which mainly led to the right of free selection of energy suppliers for businesses and households, as well as to the separation of energy transmission, distribution and supply and the creation of an independent energy regulator.

The liberalization process has also brought regulation of certain components of energy prices for households and smaller businesses through established regulatory bodies whose methods may differ across the V4 countries. Energy prices in individual countries therefore reflect not only political decisions (e.g. VAT and other taxes, levies), but also market decisions (e.g. final wholesale prices, supplier margins) or regulator decisions.

Electricity is a specific commodity. As it is not efficient to store in terms of high costs, it must constantly flow in order to ensure the stability of the entire transmission network (balance between production and consumption). The demand for electricity depends on the weather, the intensity of economic activity or daily activities. Thus, if there is an increase in demand compared to supply, the price may rise several times due to non-storage, creating mostly short-term fluctuations and peaks. Compared to other markets, the electricity market is defined by its characteristic price dynamics, which show daily, weekly and annual seasonality, but also the above-mentioned sudden short-term fluctuations, which are usually unexpected (e.g. as in the case of unplanned shutdown of nuclear reactors in France). The liberalization of the electricity market, that began worldwide in the early 1990s and became a key energy objective of the European Union, has also contributed to greater price dynamics due to increased market competition.

The aim of this work is to create a suitable econometric model of predicting spot electricity prices in the Slovak market according to appropriately selected variables.

2 Energy consumption in the EU and in the V4 countries

Approximately 2/3 of the total energy available in the EU is consumed by end users (citizens, industry, transport and other sectors) each year and up to 1/3 is lost during generation (consumption of the energy sector itself), transformation, distribution or in non-energy uses (asphalt, bitumen). [1]

Table 1 Final energy consumption of the V4 countries and the EU 28 - comparison of 2000 and 2018 (in %)

2000	**EU 28**	SK	CZ	HU	PL
Petroleum products	**42.2**	16.9	21.5	25.5	28.4
Natural gas	**24.1**	42.0	24.7	40.7	12.1
Electricity	**20.4**	19.1	17.0	16.2	15.7
Other	**13.3**	22.0	36.8	17.6	43.8
2018	**EU 28**	SK	CZ	HU	PL
Petroleum products	**37.0**	28.1	27.7	31.8	35.5
Natural gas	**23.1**	26.7	21.7	30.7	13.6
Electricity	**22.8**	22.5	19.9	19.0	18.2
Other	**17.1**	22.7	30.7	18.5	32.7

Source: Own scheme according to Eurostat data

Most energy is consumed in the industry and manufacturing industries, followed by the transport sector, households and services. Solid fuels, a major source of energy in the past, have seen the largest decline in consumption in recent years, as more and more economies are giving up on their use in order to reduce their carbon footprint as much as possible. Hence, renewable energies are a better solution, but they are still in a smaller percentage among other energy sources.

Table 1 shows the final energy consumption in 2000 and in 2018 with regards to the most represented energy sources - petroleum products, natural gas and electricity. There were several significant changes in 2018 compared to 2000. In the EU, petroleum products remained dominant, but now with a smaller percentage (decline by 5.2%). The share of natural gas also slightly decreased, as well as solid fuels (decline by more than 1%), but on the other hand, the consumption of renewable energy (rise by more than 5%) and electricity (rise by 2.4%) increased.

3 Electricity in the V4 countries

Electricity is mainly produced from fossil fuels (e.g. coal, oil, natural gas and peat) and nuclear fuels (nuclear energy). In a lesser amount, it comes from a variety of renewables that offer a cleaner alternative to energy, such as wind power, hydropower, solar power, geothermal power and biofuels. To illustrate, for generation of 1 kWh of electricity is required, for example:

- 0,43 kg of black or 1,30 kg brown coal
- 0,32 m^3 of natural gas
- 0,28 l of heating oil
- 0,022 g of natural uranium
- 43,2 m^3 of water falling from 10 m high [2]

In terms of the amount of greenhouse gas emissions produced, is for the environment the cleanest and the safest form of electricity (compared to energy from fossil fuels) nuclear energy, as well as energy obtained from renewable sources. Nuclear fuels provide a much higher energy content than fossil fuels, where the consumption of 1 kg of uranium equals to the use of approximately 20,000 kg of coal, which is their main advantage. The price per unit of such energy is quite lower in comparison with other sources. There is also almost no CO^2 production, if we consider not only the generation of electricity itself, but also the construction of nuclear power plants and the transport of energy. However, the idea of a possible accident of a nuclear facility and its consequences is particularly frightening for the public. Besides, the situation with the safe storage of radioactive waste, which is currently a non-usable material and therefore must be stored in surface, below surface or in deep underground repositories, remains a global problem. However, the hope in the future may be the process of transformation (transmutation) of radioactive substances in particle accelerators, where this waste would not only be incinerated, but could also produce additional energy. [3] [4] [5]

Likewise, renewables such as hydro, wind and solar power produce almost no emissions, if we again consider not only their production, but also the construction of such power plants and energy transport. Another advantage is the low operating costs, but the biggest disadvantages include their dependence on climate conditions (rainfall capacity, wind strength, the amount of sunshine days), high construction costs (hydro and wind power plant), low energy content, which is associated with the need of a large number of facilities to achieve required output (wind and solar power), as well as the necessity to build standby capacities due to non-reliability of the production (due to climate conditions), resulting in a negative impact to the end price of the produced electricity. One of the renewables are also biofuels, that produce CO^2, but in a smaller amount than fossil fuels. However, they are related to higher costs during construction and operation of such power plants. [5]

3.1 Electricity flows

Electricity within the V4 countries is largely produced by domestic power plants and only a small percentage is imported. These two components (import and production/transformation) then form the basis for final consumption. Excess production is usually exported to bordering countries.

For a more detailed analysis is used table below (Table 2), which shows data on selected electricity flows of the V4 (in GWh), as well as of the individual V4 countries (as a percentage of share).

Table 2 Countries share in the total electricity flow in 2018 (in GWh and in %)

	V4 (GWh)	SK (%)	CZ (%)	HU (%)	PL (%)
Import	**56 430**	22.0	20.5	33.0	24.5
Production	**317 047**	8.5	27.8	10.1	53.6
Electricity after transformation	**370 995**	40.5	26.5	13.6	49.4
Export	**46 612**	18.8	54.7	9.1	17.4
Final consumption	**263 831**	9.8	22.0	14.9	53.2

Source: Own scheme according to Eurostat data

In 2018, the total import of electricity of the V4 countries represented 56,430 GWh. For comparison, in 2000 it was only 27,489 GWh, which means an increase of more than 100%. The largest amount of electricity flowed to Hungary (33%) and Poland (24.5%). The production/transformation of electricity in the V4 area is many times higher than imports and unlike natural gas, that must be imported, countries have their own power plants. In 2018, the electricity production/transformation was at 317,047 GWh, while in 2000 it was slightly lower, 284,997 GWh, which is an increase of 11%. From all countries of the V4, the largest production of electricity was in Poland (53.6%). The Czech Republic accounted for the largest share of electricity exports (54.7%). A total of 46,612 GWh was exported, which represents an increase of 8% compared to 2000 (43,135 GWh). In 2018, the final consumption had the highest share in Poland (53.2%), almost half as much as in the Czech Republic (22%). Final consumption for all countries combined made up to 263,831 GWh, while in 2000 it was around 198,906 GWh, which is an increase of 33%.

Most of the electricity produced in Slovakia in 2018 was generated by the nuclear power plants in Mochovce and Jaslovské Bohunice (55%) (Table 3). In second place were power plants burning flammable fuels (28%) with the largest share of natural gas, brown and black coal. Even though there are many hydropower plants in Slovakia, their share in electricity production was relatively low (15%), which is mainly due to production of low energy content.

Table 3 Gross electricity production by the type of source, 2018

Energy	SK	CZ	HU	PL
Nuclear	55 %	34%	49%	0%
Flammable fuels	28%	59%	46%	90%
Hydro	15%	4%	1%	2%
Solar	2%	3%	2%	0%
Wind	0%	1%	2%	8%

Source: Own scheme according to Eurostat data

The Czech Republic produced in 2018 the most electricity from flammable fuels (59%), as there are still many thermal power plants in the area, using mainly brown coal (approximately 43%). Followed by nuclear energy (34%), which was generated mainly by nuclear power plants in Temelín and Dukovany. Most of the electricity in Hungary in 2018 was generated by the Paks nuclear power plant (49%). Then by power plants burning flammable fuels (46%), especially natural gas, of which there are still enough in the country (more than 20). Poland is a country dominated by the production of electricity from flammable fuels (91%), mostly coal and lignite (78%), which was noticeable also in 2018. Unlike other V4 countries, Poland currently has no source of nuclear energy. In renewables, the production is mainly represented by wind power (8%) and to a lesser amount by hydropower (2%).

3.2 Electricity prices

In addition to the general macroeconomic situation (e.g. inflation or economic growth), electricity prices are for the most part affected by the prices of coal, but also by other commodities used in the production of electricity, as well as the price of emission allowances for CO_2. Climate conditions affect consumption of electricity more in the summer months, leading to the generation of energy from expensive sources, as a result of increased demand. Weather also affects the actual extraction of commodities or the production of electricity itself, especially from renewable sources, which are more prone to it. There can also be less frequent situations, such as unplanned shutdown of nuclear reactors due to failures [6].

3.2.1 Electricity prices on wholesale markets

Within the framework of international markets, energy trading is performed mainly on regulated markets (power exchanges) through multilateral trading facilities (MTF) or over-the-counter (OTC) transactions and bilateral agreements, either directly or indirectly.

In terms of time, there can be long-term or short-term markets to which are linked related contracts. In the long-term electricity markets are traded mainly futures and forward contracts, options or contracts for difference. However, there is no physical supply of electricity, only it's securing at a certain time in the future.

In the short-term electricity markets, an order matching system creates the so-called **spot price** and participants trade with the delivery of electricity for a few days or hours in advance.

Within the short-term market we distinguish:

- **Day-ahead market.** Orders (purchase/sale bids) are placed at least one day in advance for each hour of the following day (i.e. 24 periods), resulting in a marginal price for these periods.
- **Intra-day market.** Trading on a given day in case of an unplanned shortage or excess of electricity, at least one hour before the delivery.
- **Balancing market.** Providing balance between electricity consumption and production in a country. The traders are transmission system operators with the delivery of so-called regulating electricity. In the Czech Republic terminated as of 31.1.2020 [7] [8].

Block orders, such as “base load” (full day delivery, i.e. 00:00-24:00), “peak load” (peak delivery, i.e. 8:00-20:00) or “off-peak load” (off-peak delivery, i.e. 00:00-8:00 and 20:00-24:00) are traded in these markets. Futures contract represents the average of expected spot prices, being less volatile. It is generally used as a basis for determining the prices paid by final consumers.

Figure 1 shows the evolution of a electricity market price traded on the PXE power exchange, as well as the price of emission allowances traded within the EU (via Energy Trading System) and coal ARA (next year's coal price with supply to Europe ARA - Amsterdam, Rotterdam, Antwerp). The development of futures contract (electricity PXE, coal ARA) and spot price (emission allowances) since 2014 is presented. The price of electricity is expressed in euros per unit of megawatt-hours (EUR/MWh), for emission allowances it is the price in euros per tonne of CO_2 (EUR/t CO_2), for coal the price in dollars per tonne (USD/t).

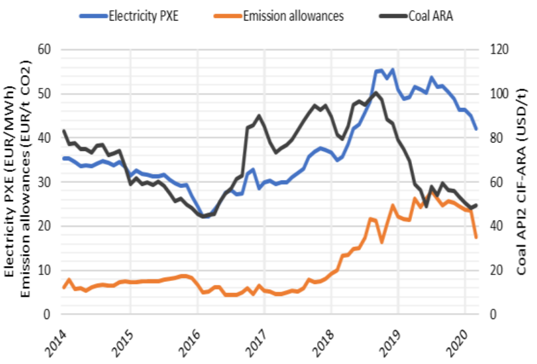

Figure 1 Development of electricity prices on PXE power exchange, emission allowances and coal prices between years 2014-2020

As mentioned, the wholesale electricity price is affected by various factors. Therefore, to reflect these dependencies, the emission allowances prices were selected, which producers also include in the price of electricity itself, and the price of coal, as they are the most significant. At first glance, the dependence between emission allowances and electricity can be seen, as their development was only mildly fluctuating from 2014 to the end of 2015, in comparison to coal. At the beginning of 2014, the price of electricity was at €35 per MWh, the price of emission allowances was at €5 per tonne of CO_2 and the price of coal was at $81 (€59) per tonne. The price of electricity had a rather declining trend during the following periods, however, from 2016 started to rise gradually. On the one hand, it was the warmest year in recent period, but there was also a temporary shutdown of 20 nuclear reactors in France during autumn, which caused an increase in electricity prices, as well as price of coal, as an alternative to nuclear power. The growth did not stop even in 2017, when the electricity price was climbing up due to cold weather at the beginning of the year and also because of other problems in French nuclear reactors, which again caused an increase in demand for coal and gas due to substitution of electricity production from these sources, that drove prices of coal very high. Also, the drought in Scandinavia and Southern Europe during the year reduced electricity production from renewable sources and increased overall electricity consumption because of the use of air conditioning. In 2018, the growing trend continued and at the end of the year it reached its long-term maximum, the price for electricity was at almost €56 per MWh, which was the highest price in the last 9 years. This growth was first driven by the growth of coal, but also by the prices of emission allowances, which goal is to gradually reduce CO_2. The year 2019 was led by the greatest volatility in electricity prices, coal had a declining trend mainly due to its large reserves. In the second half of the year, it was the hot summer that caused prices to rise. The fall in the prices of emission allowances, electricity and coal in August resulted from fears of the signalled arrival of the recession, but the prices began to rise again in September. Due to the high temperatures, there were also problems with nuclear reactors in France, where the river water used to cool the reactors could no longer be used due to its higher temperature, resulting in reduced reactor power and replacement of electricity production with coal, which also contributed to the rising prices in international markets and increased demand for coal and emission allowances, whose prices have almost tripled since the end of 2017. The expected Brexit has also led to a negative mood in the markets. In 2020, however, markets were affected by the threat in a form of coronavirus, which pushed prices down. As of 31.3.2020, the electricity price was at €40 per MWh, the price of emission allowances was at €18 per tonne of CO_2 and the price of coal was at $50 (€46) per tonne [6] [9] [10] [11].

3.2.2 Electricity prices on retail markets

Electricity prices on retail markets are partially influenced by wholesale prices, but due to market liberalization and regulation, which aims to protect consumers and ensure competitiveness among suppliers on the domestic market, lower rates are offered or a maximum price cap (or other form of regulation) is set for households, as well as for smaller businesses - the so-called vulnerable customers. Electricity retail prices thus differ between suppliers, so in general, there is no universal price. For large consumers, such as industries, prices may be the result of negotiated contracts, on the other hand, for smaller consumers are usually set according to the quantity consumed together with a number of other aspects. Therefore, in addition to the price of the energy itself, the final price of electricity also includes charges for transmission, distribution, storage or other services, as well as taxes or levies. However, it also depends on a number of other factors, such as seasonality and the influence of weather, when consumption is also affected, or economic growth or inflation. [12]

The electricity price for the final consumer consists of several components:

- price of energy and supply;
- network costs;
- value added tax (VAT);
- renewable taxes;
- other taxes, fees and levies.

The development of final electricity prices in the internal markets of the V4 countries in recent time is shown in Figure 2 for households, for businesses in Figure 3. To express the movement of these prices, there were used data from Eurostat according to the size of annual consumption. We worked only with the category of customers with medium consumption:

a) households DC (2500 kWh – 5000 kWh),
b) businesses IC (500 MWh – 2 000 MWh).

As non-household consumers are usually entitled to a refund of VAT and certain other taxes, their final prices are presented without them. For households, all taxes and fees are included in the displayed prices (Figure 2). The unit of electricity price is the unit expressed in euros per kilowatthour (EUR/kWh).

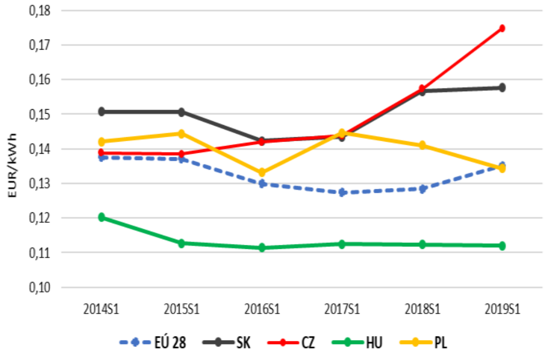

Figure 2 Development of electricity prices for households
Source: Own scheme according to Eurostat data

From the V4 countries (but also compared to the EU 28 average), Hungary has the lowest long-term prices for medium-sized households, with the highest share of the "energy and supply" component, as well as the "network costs" in the total electricity price, what rather affects the final price and thus we can say, that Hungary has the lowest electricity prices for medium-sized households, despite the highest VAT among the other V4 countries. The second lowest prices are currently in Poland, which in the first half of 2019 reached a price almost identical to the EU 28 average, on the other hand the Czech Republic and Slovakia are among the countries with the highest electricity prices in this category and significantly outrun the EU 28 average. In the first half of 2019, the Czech Republic was even more ahead of Slovakia, although they had a very similar price development since 2016. These countries differ mainly in the amount of VAT and the method of price regulation - Slovakia, the Czech Republic and Hungary apply different stimulating methods or their combinations, while Poland applies non-stimulating methods. In Slovakia and Poland, taxes, fees and levies have the largest share in the final electricity price. In the Czech Republic and Hungary, it is the price of energy and supply, but network costs are also very important in all countries. In terms of prices in the first half of 2019 compared to the first half of 2014, the largest change was in the Czech Republic, when prices increased by almost 26%, in Slovakia prices increased by less than 5%. On the contrary, a decrease in prices of more than

5-6% occurred in Hungary and Poland. We can also notice the increase in prices in the all V4 countries after the first half of 2016 (in the Czech Republic after the first half of 2015), which in some countries continued in the following periods. Year 2016 was the warmest year since 1880, which led to a higher electricity consumption due to the increased use of air conditioning, but also to the rise in hydropower prices due to the severe drought. Emission allowance prices have also risen and there have been several problems with nuclear reactors in France, causing greater demand for coal and natural gas, which led to higher wholesale prices, forcing regulators to increase next year's regulated energy prices. In 2017, the electricity price was again pushed up by cold weather at the beginning of the year, that also caused a boost in demand for non-renewable energy sources and thus a further increase in the prices of emission allowances. The growing trend on international markets did not stop even in 2018, when prices reached long-term highs, which was seen especially in the Czech Republic and Slovakia [13].

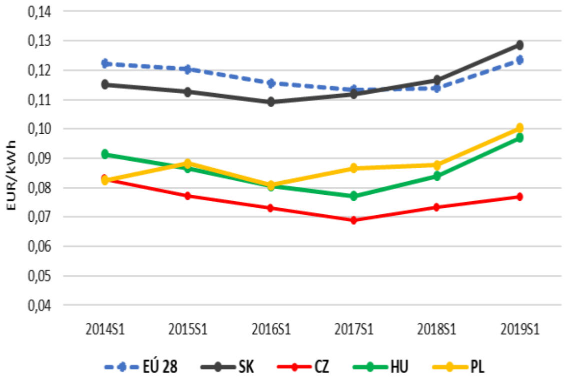

Figure 3 Development of electricity prices for businesses
Source: Own scheme according to Eurostat data

In the long-term, Slovakia has the highest electricity prices for businesses, which are currently above the EU 28 average (Figure 3). Poland together with Hungary are in second place followed by the Czech Republic, which, on the other hand, has the lowest long-term prices for this category of customers. In comparison with prices in the first half of 2019 and the first half of 2014, the largest change occurred in Poland where prices rose by almost 22%. The price increase also affected Slovakia (12%) and, to a lesser extent, Hungary (6%). However, in the Czech Republic there was an overall decrease in prices by nearly 7%. As mentioned, these prices do not include taxes, charges or VAT, so the price of the energy and supply, as well as the network costs, which vary considerably between countries, have the greatest impact on the change in prices. Although, they are also affected by the situation in international markets, since 2014 the price of a commodity has been declining, but from 2016 has been gradually rising, which was then reflected in retail prices. The year 2016 was the warmest year, but during the following periods there were several factors, that affected the electricity price in the markets, such as the shutdown of nuclear power plants in France, cold weather in early 2017, or substitution of nuclear power by coal and natural gas.

4 Electricity price forecasting

In recent years, a variety of different methods and models have been developed for electricity price forecasting, each of which has its strengths and weaknesses and thus a different degree of success. In general, many of the approaches use the so-called hybrid solutions, combining various modeling and price forecasting techniques [14].

4.1 Selection and definition of relevant variables - studies overview

According to Bunn and Karakatsani (2003), the development of electricity price forecasting models took a new turn after the 1990s, as until then prices had been subject to monopolies, often state-owned, or subject to strict regulation. Therefore, the price of electricity mainly reflected the government's social and industrial policy, so the price forecasts focused more on costs, i.e. the prices of input fuels, technological innovations and production efficiency. In their work they focused on different approaches to modeling and predicting spot prices where they also mentioned several possible influencing factors, which they classify as:

- market mechanism (fuel prices, demand),
- market structure (e.g. margin),
- non-strategic uncertainties (demand forecast error),
- efficiency variables (volume, availability indices),
- behavioral variables (price volatility, demand volatility, time, lagged price)
- time effects (daily, weekly, yearly seasonality).

They also indicated, that despite the ongoing liberalization, the effects of government policies on electricity prices should not be underestimated [15].

A more extensive study on modeling energy prices development (electricity and gas) using econometric analysis is from Breitschopf et al. (2016). This study examines the impact of certain variables on electricity spot prices in Europe using linear regression. The independent variables in the model are (among others):

- the share of various energy sources in electricity generation,
- commodity prices (coal, oil, natural gas),
- emission allowance prices,
- market behavior (competition, regulation, liberalization),
- consumption,
- deflator (GDP), inflation rate,

- exchange rate,
- heating/cooling degree days [16].

In a similar study by Gonçalves, Ferreira, Odete (2019), future electricity spot prices in the integrated market of Spain and Portugal are predicted using linear regression. The used independent variables are:

- energy sources,
- electricity import-export balance,
- electricity consumption,
- heating/cooling degree days,
- the share of renewables in electricity generation,
- industrial production index,
- Brent crude oil price [17].

Another study from Italy (Gianfreda, Grossi, 2012), examines how the following variables affect electricity spot prices:

- technology,
- market concentration,
- network congestion,
- volume (consumption) [18].

Singh and Mohanty (2015) consider the following variables to be important:

- demand,
- weather conditions,
- fuel costs,
- emission allowance prices,
- available transmission capacity and
- generation reserve in case of higher demand (e.g. during peak hours) [19].

4.2 Econometric model of electricity spot price development in Slovakia – input variables

The used data are in a form of time series, i.e. the individual variables are observed over a period of time - in our case monthly data for a period of four years - to ensure a sufficient number of observations, which will increase the accuracy of the model. As time series often show a certain trend or seasonality, a second-order exponential smoothing (for variables with a trend) and third-order exponential smoothing (for variables with a trend and seasonality) were used to adjust them. The electricity spot price on the Slovak short-term market was then selected as the dependent (explained) variable and the goal is its forecast for the upcoming periods. The decision for spot price is explained by the fact, that most statistical models focus on spot prices rather than derivative prices due to the fact, that derivative prices are not easy to predict, as they also reflect the investor's relative risk aversion and risk costs, but it can also be only a speculative trade. Spot prices reflect supply and demand in real time, i.e. the physical supply of electricity in a very short period (e.g. several hours, a day). Therefore, electricity spot price modeling with econometric techniques needs to capture as many factors, that influence current supply and demand, as possible. However, the question arises, as to which variables should be included in the model. It is therefore necessary to identify and include all relevant variables and, on the other hand, to not include unnecessary, irrelevant variables. We select only those variables, that are closely related to the explained variable.

The explained variable in our econometric model is the **electricity spot price on the Slovak short-term cross-border market**, organized by OKTE, JSC. This market interconnects individual participants, enabling them to cover their supply or demand for electricity on a daily basis, thus reducing the deviation between the planned and actual value of electricity supply/demand, ensuring a stable and balanced transmission of electricity in the grid.

Based on the studies mentioned in Chapter 4.1, the following variables were selected as input (independent) variables (Table 4):

- amount of electricity produced,
- share of renewables in electricity generation,
- electricity consumption,
- market prices of input commodities (natural gas, coal, oil),
- emission allowance prices,
- inflation (HICP).

The aim of the model is to predict the development of electricity spot price for the upcoming months.

Table 4 Selected variables of the econometric model for electricity spot price forecasting in Slovakia

Dependent variable	Label	Unit of measure	Source
Spot price of electricity	CENA	EUR/MWh	OKTE

Independent variables	Label	Unit of measure	Source
Production of electricity	PROD	MWh	OECD
Share of renewables	OBN	%	OECD
Electricity consumption	SPOTR	MWh	OECD
Brent crude oil price	ROPA	EUR/barrel	Kurzy.cz
Coal price	UHLIE	EUR/t	Investing.com
Price of natural gas	PLYN	EUR/MWh	Kurzy.cz
Price of emission allowances	EMISIE	EUR/t CO2	Investing.com
HICP inflation	INFL	%	Eurostat

Source: own scheme

Production of electricity. The price of electricity depends mainly on the available quantity produced by power plants in the country. In case of increased demand (during peak hours) or failure of one of the sources, the production is immediately replenished by another source to ensure the balance in the power grid, but at the same time, the price is affected as a result of this change (e.g. replacement by coal leading to increased demand for coal, its price and therefore the price of electricity). As mentioned, nuclear, solar and wind power are in the long run suitable for producing a stable amount of electricity, while other sources (e.g. hydropower, natural gas, coal) can adapt to changes in demand more quickly and satisfy it, if increased.

Share of renewables. In Slovakia, as in other countries, there is a gradual increase in the share of additional energy sources (renewables) in electricity production, which together with their technological development helps to reduce wholesale electricity prices. Within Slovakia, hydropower has the largest share. In 2018, hydropower accounted for 15% of the electricity produced, solar power for only 2% and wind power for only an insignificant amount.

Electricity consumption. Consumption is the difference between production and possible distribution losses together with the consumption of a pumped storage plant, so it is largely equal to production itself, as supply and demand for electricity must be balanced, as storing electricity is not economic and must flow constantly. The demand for electricity is also associated with seasonality, whether of the season, when consumption is higher in colder months or conversely in warmer months, it is also higher during weekends, holidays, or during peak hours - from 8:00 to 20:00.

Brent crude oil price. Coal price. Natural gas price. Even though a large amount of electricity in the world is produced by hydropower or nuclear power, some countries use fossil fuels still in significant amount: natural gas, coal or oil. Slovakia is no exception and the prices of input fuels alone create the largest share of energy production costs. Therefore, the price of ARA coal, Brent crude oil and natural gas on the PXE power exchange is important for Slovakia.

Price of emission allowances. Emission allowances for emitting CO_2 represent a way of regulating businesses, which, for example, in the production of energy (especially from fossil fuels) create greenhouse gases. A maximum value is set for pollutant discharges over a period of time, which must not be exceeded. If the company does not produce such a large amount of emissions, it can sell its "surplus" to another company, that has a shortage. The prices of emission allowances are an important factor, as they can be directly included in the wholesale electricity price by producers, therefore influencing the price.

HICP inflation. The Harmonized Index of Consumer Prices is an economic indicator, that provides the official rate of consumer price inflation in the euro area. It measures the change over time in the prices of consumer goods and services acquired by households. Therefore, it also includes electricity prices.

The dependence intensity between selected indicators and between dependent variable CENA is shown by the correlation matrix (Table 5). CENA has the strongest correlation with the variable PLYN (r = 0.72), a medium dependence with the variable OBN (r = -0.58) and UHLIE (r = 0.52) and a mild dependence with the variable ROPA (r = 0.45). The correlation between electricity spot price (CENA) and prices of gas (PLYN), oil (ROPA) and coal (UHLIE) is positive, which means, that if the price of fossil fuels rises, so does the price of electricity. On the contrary, the dependence on the share of renewable energy sources (OBN) is negative, which means, that the higher the share of renewable energy sources in electricity production, the lower the price. The correlation between other variables and electricity spot price is not statistically significant, so it is not relevant to use them in the econometric model.

Table 5 Correlation matrix of variables selected for econometric model

	CENA	PROD	SPOTR	OBN	UHLIE	PLYN	ROPA	EMISIE	INFL
CENA	1	-0,198	0,247	-0,584	0,523	0,724	0,345	0,224	-0,262
PROD	-0,198	1	0,617	-0,179	-0,230	-0,463	-0,570	-0,083	0,207
SPOTR	0,247	0,617	1	-0,437	0,366	-0,089	-0,443	-0,302	0,041
OBN	-0,584	-0,179	-0,437	1	-0,121	-0,304	-0,024	-0,339	0,517
UHLIE	0,523	-0,230	0,366	-0,121	1	0,346	0,078	-0,561	-0,093
PLYN	0,724	-0,463	-0,089	-0,304	0,346	1	0,756	0,505	-0,142
ROPA	0,345	-0,570	-0,443	-0,024	0,078	0,756	1	0,560	-0,070
EMISIE	0,224	-0,083	-0,302	-0,339	-0,561	0,505	0,560	1	-0,049
INFL	-0,262	0,207	0,041	0,517	-0,093	-0,142	-0,070	-0,049	1

Source: own calculation

4.2.1 Model selection

In this paper we propose a single-equation model of multiple linear regression, which is the most widely used econometric model examining the effect of several independent variables on one dependent variable, in the following form:

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_k x_{ki} + u_i \qquad (1)$$

where:
y_i – dependent variable
$x_{1\dots k,i}$ i – explanatory variable
β_0 – intercept (constant term)
$\beta_{1\dots k}$ – regression coefficient
u_i – random variable (error term) [20]

Based on the observations, we then constructed the model itself. Several combinations of independent variables were tested, considering the dependence on the electricity spot price, from which 10 models emerged. We subjected each model to the information criteria AIC (Akaike information criterion) and BIC (Schwarz information criterion) and selected only the most suitable models. Model_5 is the best model according to both information criteria, model_1 is the second best:

1. model_5: dependence of electricity spot price on gas and coal prices and on the share of renewables:

$$CENA_i = \beta_0 + \beta_1 PLYN_i + \beta_2 OBN_i + \beta_3 UHLIE_i + u_i \quad (2)$$

2. model_1: dependence of electricity spot price on the prices of gas, coal and oil and on the share of renewables:

$$CENA_i = \beta_0 + \beta_1 PLYN_i + \beta_2 OBN_i + \beta_3 UHLIE_i + \beta_4 ROPA_i + u_i \quad (3)$$

We subjected both models to statistical tests, using only the proper one for prediction.

4.2.2 Statistical testing of econometric model

When testing the statistical significance, as well as individual variables in both models, we concluded, that the variable ROPA in model_1 is not statistically significant, so it is necessary to remove it, which gives us model_5. The result of testing the statistical significance of model_5 is shown in Table 6. All three regression coefficients are statistically significant, also the model itself (p-value <0.05). In addition, 75% of the dependent variable CENA depends on listed independent variables (coefficient of determination = 0.75).

Table 6 Results of testing statistical significance of model_5

	Beta	t	p-value
(Intercept)	10.604	1.126	0.268
PLYN	1.908	5.082	0.000015
OBN	-73.521	-4.274	0.000161
UHLIE	0.215	3.206	0.003051
p-value for model_5	9.203e-10		
Coefficient of determination	0.750		

Source: Own calculation in R

The interpretation of the estimated Beta regression coefficients is as followed:

- PLYN estimate: positive dependence; if PLYN increases by 1 €/MWh and other factors remain unchanged, CENA will increase by 1.91 €/MWh.
- OBN estimate: negative dependence; if OBN increases by 1% and other factors remain unchanged, CENA will decrease by 73.52 €/MWh.
- UHLIE estimate: positive dependence; if COAL increases by 1 €/t and other factors remain unchanged, CENA will increase by 0.22 €/MWh.

To verify correctness and reliability of the proposed model, we tested the following hypothesis with appropriate statistical tests:

- Residual normality - zero mean and normal distribution of random variable
- Homoscedasticity – constant variance of random variable
- Absence of autocorrelation of random variable
- Absence of multicollinearity - explanatory variables in the model are linearly independent
- Correct specification

The assumptions were all met. Thus, the chosen model is suitable for modeling electricity spot price development in the short-term.

Using RStudio software, we created forecasts for individual input variables for the next three months of 2020. Then, based on these predictions, we proceeded to predict electricity spot price with this model.

Table 7 Forecasts of individual explanatory variables and forecast of dependent variable - first three months of 2020

	January 2020	February 2020	March 2020	Direction of change	Dependence on GDP
PLYN	20.76	20.84	20.93	↑	positive
OBN	0.2174	0.2156	0.2139	↓	negative
UHLIE	54.21	53.42	52.63	↓	negative
CENA	**45.88**	**46.00**	**46.13**	↑	

Source: Own calculation in R

We can notice in Table 7, that the model predicted a gradual month-on-month increase in gas prices and, on the other hand, a decrease in the share of renewables and coal prices, which then affected the development of electricity spot price.

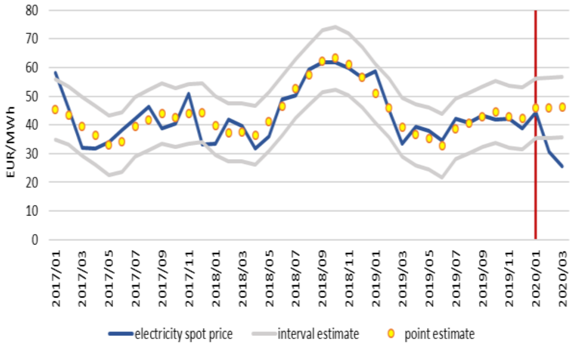

Figure 4 Monthly development of electricity spot price in Slovakia since 2017, considering results and predictions of model_5
Source: Own calculation in R, data from OKTE

The result is shown in Figure 4, which displays the development of the average monthly spot price in the Slovak short-term market since 2017, as well as the interval estimate (95% confidence interval) and point estimate of these prices and their next predictions, using model_5. However, we remind, that this model explains only 75% of the total variability of the dependent variable, so we cannot consider it accurate and therefore, it is not advisable to make long-term forecasts, as it does not reflect the influence of all factors or possible unexpected shocks.

As we can see, the model's point estimate largely imitated the development of real electricity spot prices, but its predictions were overestimated. We compared them with the actual values in the given months (January, February, March) of 2020. In January, the model predicted a price increase to approximately 45.88 €/MWh (95% confidence interval 35.42-56.33 €/MWh) and the actual value at that time did increase, but only to 44.37 €/MWh. In the following two months, the predicted prices were higher than actual prices - the model predicted a further increase, which did not take place due to coronavirus pandemic outbreak. In fact, prices in oil, emission allowances, gas and coal markets fell, which was also reflected in electricity spot price in the short-term market. Electricity consumption decreased too, which was caused by warmer weather in January (+ 0.4°C) and February (+ 1.5°C), compared to previous year. Even though March was slightly colder (-2.2°C) than the last year, with the arrival of restrictions on preventing coronavirus spread, many institutions, schools, offices began to close temporarily, leading to a significant reduction in electricity consumption, especially in the industrial sector, despite the fact that household electricity consumption has increased at the same time. Household consumption could not fully compensate for this decline. During one day in March (22.3.2020), the spot price even fell to -0.98 €/MWh, when producers (or other participants) had to pay for "getting rid" of their electricity.

5 Conclusions

The paper focused on evaluation of electricity prices development in the Visegrad Four (V4) countries between 2014 and 2019 and on the prediction of electricity spot prices in Slovakia. The results were obtained on the basis of an econometric model with three initial measured parameters - Brent crude oil price, coal price and share of renewables. The model used monthly data over the years 2017-2019, gathered from Eurostat databases.

The results show that the theoretical values of electricity prices calculated according to our proposed econometric model approximately copied the actual values. Within two variables, the model showed a positive dependence on the explained variable, i.e. an increase in gas prices (with other factors unchanged) and coal led to an increase in the electricity spot price, while an increase in the share of renewables led to a decrease in spot prices. This can be considered as expected behavior, as rise in market prices of commodities, that are also input sources in electricity generation, will lead to higher electricity production costs, which will increase the spot price itself. On the contrary, bigger share of renewables leads to lower spot prices, as such generators are usually less expensive from an operational point of view and due to technological progress, also there are also various forms of financing and support from the government. As for the forecast, the model predicted a gradual month-on-month increase in gas prices and a decline in the share of renewables and coal prices, which also affected the overall development of electricity spot prices.

The model estimated correctly only the development in the first forecasted period (January 2020), which differed from the actual price by only a few cents. In the next two periods (February and March) there was supposed to be a slight increase in prices, which did not take place due to the coronavirus pandemic outbreak in the world.

Yet, we think that this model can be used for a rough estimate of electricity spot price development in Slovakia.

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Thermal Treatment of Municipal Waste in Poland on Example of RDF Pyrolysis

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Abstract : In the face of the constant tightening of environmental regulations, alternative sources of fuels and energy are being increasingly sought. The European Union strives to introduce waste-free or low-waste closed-loop technologies using material and energy recovery to manage natural resources in a rational manner. Therefore, European regulations require member states to progressively restrict the amount of landfill waste. In Poland, these requirements have been included in the Act on waste and the Act on order and cleanliness in the commune. In addition, since 1 January 2016, it has been forbidden to store waste with a calorific value exceeding 6 MJ/kg, which is why in recent years there has been an increase in interest in the thermal transformation of municipal waste. Therefore, the article presents the current shape of waste management in Poland, and also introduces the dominant form of RDF management in the cement industry. Nevertheless, the capacity of cement plants is limited, and the energy use of fuels from waste encounters difficulties related to a significant reduction in pollutant emissions, which is why the use of modern installations for the thermal conversion of waste such as pyrolysis and gasification is increasingly considered. Taking into account the promising energy properties of secondary fuels obtained during the pyrolysis process, the chemical composition of gas from RDF pyrolysis was modeled for a pilot installation operating in Poland using CHEMKIN-PRO software. Determination of the combustible components allowed the calorific value of pyrolytic gas to be estimated, ranging from 28.2 - 28.7 MJ/m^3. The obtained calorific value is much higher than the average calorific value of RDF (11-18MJ/kg) [1], which encourages wider use of the waste pyrolysis process in order to obtain secondary fuels with promising energy parameters. It will contribute to a further reduction in the amount of deposited waste, and thus to creating environmentally-friendly closed-loop waste management.

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1 Introduction

The main legal act regulating the principles of municipal waste management in Poland is the Waste Act of December 14, 2012. The amendment to the said act, which entered into force on 6 February 2015, modified the definition of a regional municipal waste treatment installation (in polish: RIPOK), opening it to new technologies. In the current definition, the use of other technologies not used to date in regional installations is allowed, for example pyrolysis, gasification or the plasma process, regardless of the fact that the process is qualified as thermal transformation. In addition, the legislator foresaw the possibility of removing a regional installation that does not meet the requirements of environmental protection or other measures provided for it from the resolution on the implementation of the Voivodeship Waste Management Plan (VWMP) Furthermore, the entry into force of the law on order and cleanliness in municipalities (01/01/2012), giving Polish municipalities 18 months to prepare for implementation of the new system, seems important from the point of view of proper waste management. Since 1 July 2013, the said municipalities have been responsible for the collection of municipal waste, as well as the collection of fees from residents. The above legal act contributed to an increase in the importance of selective municipal waste collection and its recycling. Observing the changes in the share of individual forms of waste management in previous years (Figure 1), a gradual decrease in the amount of waste deposited in

Poland can be noticed (except for 2012, where a slight increase was recorded), in favor of other forms of their use, especially recycling and thermal transformation. The last-mentioned form has a great chance of developing because according to Annex 4 to the Regulation of the Minister of the Economy regarding the admission of waste for landfills of 16 July 2015, since 1 January 2016, a ban on depositing waste with a calorific value exceeding 6 MJ/kg of dry matter at landfill sites has been in force in Poland. The aim of the above-mentioned solution is to maximize the use of the highest calorific waste, which will allow the landfilling of only waste whose energetic use would be unprofitable. Therefore, it seems appropriate to consider the use of these wastes in developing innovative waste treatment installations. At the same time, the Waste Act of December 14, 2012 defined thermal transformation as: *combustion of waste by its oxidation*, other waste thermal treatment processes other than those indicated in the literature, including pyrolysis, gasification and the plasma process, as long as the substances resulting from the above-mentioned processes are subsequently incinerated.

These Polish legal acts on waste management have contributed to an increase in waste recovery, including its recycling, while opening up to new technologies of thermal transformation, giving the opportunity to recover energy from waste and increasing the level of environmental protection [3–5].

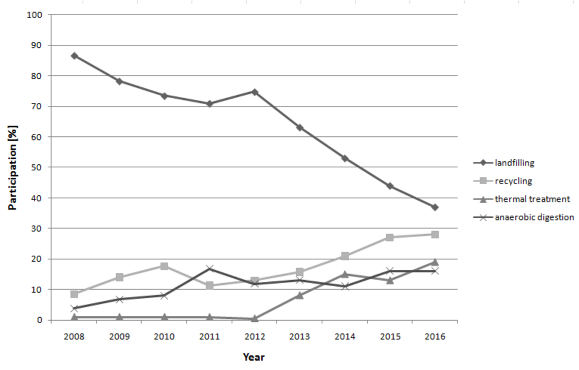


Figure 1 The share of forms of municipal waste management in Poland in 2008-2016 (Eurostat)

As an EU member state, Poland strives to achieve the community waste management requirements. These requirements relate to gradual implementation of the Zero Waste and Closed-loop Economy plans. A good indicator of changes for the better in Polish waste management is the amount of waste disposed of by landfilling per capita (Figure 2). Comparing the approach of Poland and other EU countries to landfilling, one can notice a disproportion between the amount of deposited wastes per capita. Although the amount of the above-mentioned municipal waste in Poland per person was higher in 2012-2015, there is a downward trend. In 2016, in this country, the amount of waste managed by landfilling per inhabitant was lower than in the EU. In addition, at the end of 2012, there were 527 active controlled landfills in Poland, accepting municipal waste, with a total area of nearly 2,198 ha. During the analyzed year, 61 landfills of this type were closed, with an area of almost 132 ha. At the end of 2016, there were 320 active controlled landfills receiving municipal waste, occupying a total area of over 1800 ha. In 2016, 36 such facilities were closed, with an area of nearly 80 ha. Over 200 waste landfills were closed within the analyzed period of five years, which confirms that Poland implements European regulations on waste management to national law on an ongoing basis, and then meticulously fulfills them, achieving the required environmental effects.

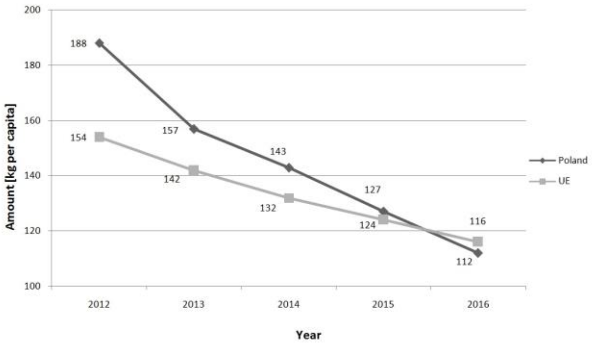


Figure 2 Municipal waste neutralized by landfilling in Poland and the EU per capita (Eurostat)

Poland has committed itself to achieving the required recycling targets, up to 30% in 2018 and 50% in 2020 respectively. In addition, from this year a commitment was made to prohibit municipal landfills containing more than 35% biodegradable mass compared to the volume produced in 1995. The above actions constitute elements of the National Waste Management Plan for 2015-2022, including mainly: limiting the amount of waste generated and increasing public awareness of proper waste handling, achieving the assumed recovery and recycling goals for individual types of waste, adopting a system of selective waste collection in all households in Poland, discontinuing the landfilling of biodegradable waste.

The aspect regarding the increase in public awareness of waste management seems to be particularly important. Recently, the Polish government, through new legal regulations, has been trying to change citizens' bad habits. One of them is the regulation of the Minister of Development and Finance regarding the requirements for solid fuel boilers, from 1 July 2018 prohibiting the sale of boilers that do not comply with emission class 5, in accordance with standard PN-EN 303–5:2012. The said legal act excludes the use of boilers having a so-called "Emergency grate" enabling waste incineration. In addition, this regulation is an element of limiting the phenomenon of low emission, contributing to the formation of smog. This phenomenon deprives many people of health and even life every year, which is why proper education of children and youth is equally important. Another significant legislative change was introducing the Act of 12 October 2017 amending the act on the management of packaging and packaging waste as well as some other acts (Journal of Laws, item 2056), imposing from 1.01.2018 a recycling fee for each plastic bag offered when shopping. The aforementioned fee is to discourage Poles from buying plastic bags in favor of reusable bags which serve for years and do not generate additional quantities of plastic waste. The above activities combined with high levels of raw material and energy recovery will contribute to creating effective closed-loop waste management that cares for the environment, as well as reasonably managing natural resources [4,7–12].

2 Characteristics of RDF

RDF is a specific type of alternative fuel (Figure 3), characterized by high calorific value (average 16-18 MJ.kg^{-1}) [13] as well as homogeneous particle size. The production process of this fuel involves separation of combustible parts from the overflow fraction of municipal waste (paper, plastics, textiles, wood, rubber) by sorting them, as well as subjecting them to a multi-stage process of grinding and then briquetting [14–18].

Figure 3 *View of the RDF fuel [own elaboration]*

Currently in Poland, RDF is most often used as an alternative fuel in the cement industry. This is due to the specific temperature conditions prevailing in the rotary kiln for burning clinker, as well as the possibility of dispensing fuel into its various zones, which allows the use of various forms of fuel - liquid, lumpy or silty. In addition, combustion in the said installation meets the requirements of the European Directive, ordering maintaining the appropriate temperature of exhaust gas (> 1370 K) for at least 2 seconds, minimizing the negative impact on the environment. As a result, alternative fuels have been applied in Polish cement plants for 15 years, using, in addition to RDF, also used tires and agricultural biomass. In 2008, the percentage of these fuels in Poland accounted for 26% and was higher than in the European Union (21%) and in the world (11%). Currently, the share of alternative fuels in the Polish cement industry accounts for 50% (and a maximum of 80% in the Chełm Cement Plant), which is largely due to the EU climate policy, introducing carbon dioxide emission limits. Polish producers, instead of participating in the emissions trading system, invest in emission reduction technologies, increasingly more often using alternative fuels for cement production.

The MBT/MBS reject fraction (RDF) processed in plants can be used in the co-combustion process with coal dust, both in the main burner of the rotary kiln and in the secondary burner, in the process of initial decarbonisation. In the second case, there are no problems related to ensuring proper combustion conditions, hence it is possible to use up to 100% of alternative fuel from waste, whereas in the main burner of the furnace it is necessary to ensure the appropriate temperature difference in the sintering zone (> 400 K), between the temperature of the clinker being burned and the exhaust gas temperature. Ensuring this temperature regime is possible with a calorific value of RDF greater than 22 MJ.kg^{-1}. A lower calorific value of the said fuel contributes to a decrease in efficiency and an increase in heat consumption. Taking into account the average calorific value of RDF at the level of approx. 16-18 MJ.kg^{-1} [1], determined by a high moisture content (biomass share), it can be concluded that obtaining high calorific fuel from waste will not be a simple task. The Polish experience shows that alternative fuel with a calorific value of 13 MJ.kg^{-1} allows about 10% of coal dust to be replaced, while RDF with a calorific value of 18 MJ.kg^{-1}, allows the replacement of already about 20% of traditional coal fuel [15,18–23].

3 Thermal conversion technologies

In recent years, the technology of thermal transformation of waste has become increasingly more important in Poland, which is why it seems that the development of innovative technologies for thermal conversion of waste will contribute to further reducing the amount of landfill waste, and thus creating environmentally friendly management of recyclable waste. The modern waste management system should include energy recovery, without which it is impossible to balance the management of many waste groups. Chemical energy contained in the majority of waste can be used for power engineering purposes like production of electricity [24] and heat in various technological variants of thermo-technical conversion, e.g. pyrolysis (Figure 4) [3, 4,6,25–27].

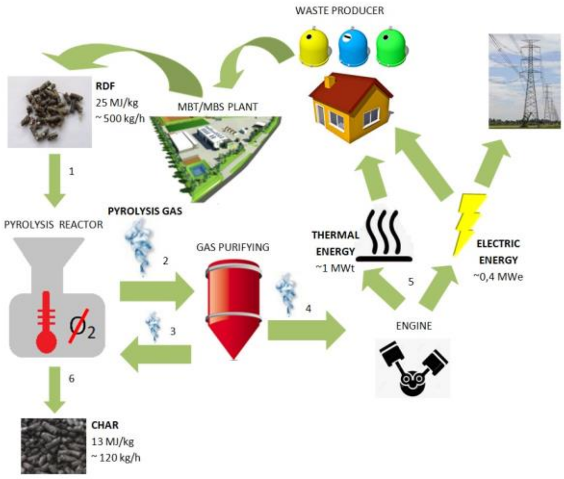


Figure 4 Modern Waste Management in Poland

Currently, there are 157 regional municipal waste treatment installations (RIPOK/MBT) in Poland, with a total capacity of 10 799 100 Mg/year, and a further increase in their capacity is planned, ultimately in 2020 to 12 414 133 Mg/year, which gives 179 MBT installations - the most in Europe. However, currently only 8 modern installations for the thermal transformation of municipal waste operate in the country: Bialystok (120 000 Mg/year), Bydgoszcz (180 000 Mg/year), Konin (96 000 Mg/year), Cracow (220 000 Mg/year), Poznan (210 000 Mg/year), Warsaw (60 000 Mg/year), Szczecin (150 000 Mg/year) and Rzeszów (100 000 Mg/year). Summing up the processing capacity of the above incineration plants, a promising efficiency of over a million Mg per year is obtained. Taking into account the National Waste Management Plan (NWMP) for the years 2016-2020, significant power surpluses of MBT installations in many voivodships are noticed, while at the same time noticeable amounts of RDF (currently almost 2 500 000 Mg/year). In addition to the use of this fuel in cement plants, it can also be used in power and heating. Unfortunately, in this case there are problems related to the adaptation of currently used installations for the co-incineration of waste, especially in the area of poor exhaust gas treatment systems. Due to the fact that cement plants can use only about 1 million Mg of alternative fuel from waste during a year, other effective methods of its management should be sought, therefore this article compares three methods for the thermal conversion of RDF: combustion, pyrolysis and gasification [3,28].

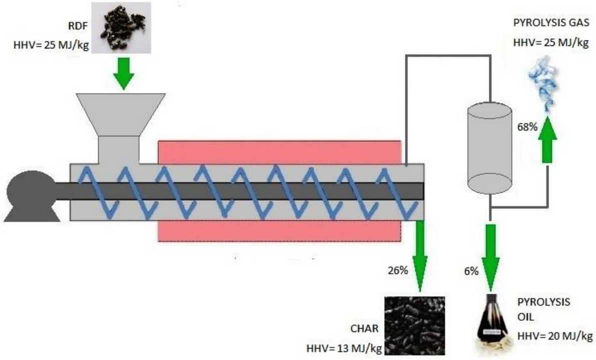


Figure 5 Scheme of RDF Pyrolysis (Polish pilot plant)

Pyrolysis and gasification allow the recovery of chemical energy in the form of secondary fuels or provide raw materials to carry out other processes (Figure 5), while combustion allows the recovery of electricity and heat. It seems that improvement in the total energy recovery from waste, by combining the efficiency of installations currently operating in Poland, using the rotary kilns of cement plants and new installations for pyrolysis and gasification, e.g. located in MBT (RIPOK) plants, will allow the role of landfilling in Polish waste management to be limited further. Firstly, it will ensure compliance with the increasingly demanding European regulations, and secondly, it will contribute to the rational use of natural resources, while at the same time increasing the level of environmental protection.

4 Results and discussion

Pyrolysis was selected for further analysis, as it shows the greatest flexibility of obtained products among the methods of thermal conversion of waste. Using the licensed CHEMKIN-PRO software, the chemical composition of gas from RDF pyrolysis was modeled for a pilot plant operating in Poland. Determination of the combustible components allowed the calorific value of the pyrolytic gas to be estimated for the changing conditions of the process, i.e. the temperature and residence time. A detailed chemical mechanism developed by the CRECK Modeling Group [38] was implemented for the calculations. The mechanism is dedicated to the chemical analysis of processes occurring during the thermal conversion of fuel [39–46] and includes 137 compounds and 4533 chemical reactions. Figure 6 shows a simplified scheme of the calculations.

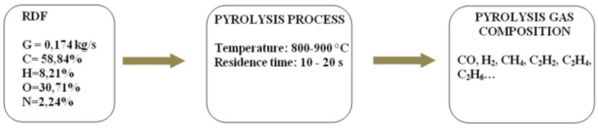
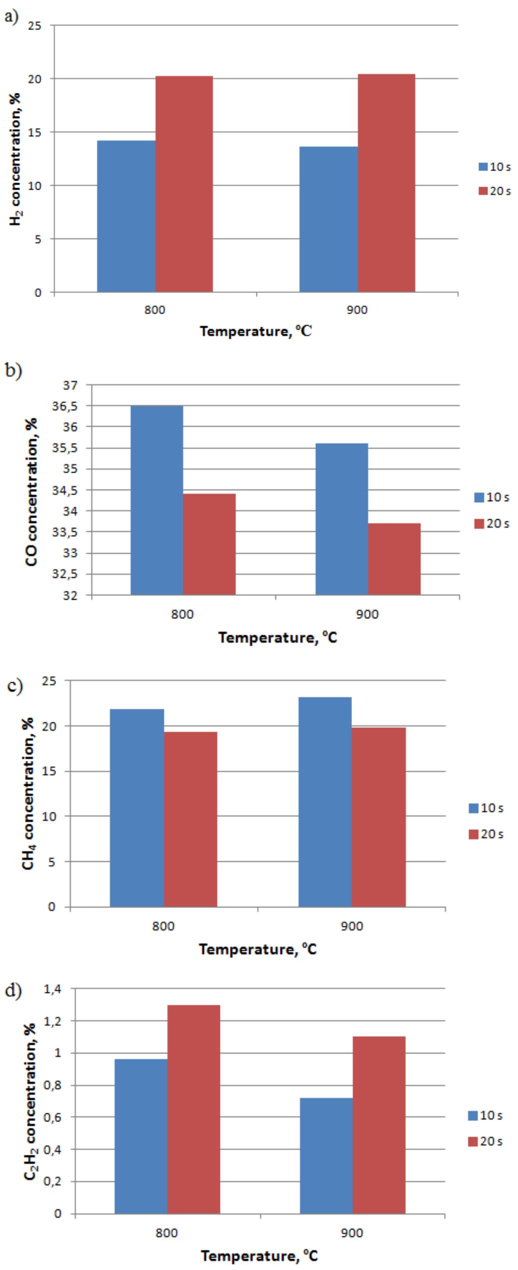


Figure 6 The scheme of calculations

The contributions of selected combustible gas components obtained as part of the calculations, namely: CO, H_2, CH_4, C_2H_2, C_2H_4 and C_6H_6 are summarized in Figures 7-8 as a function of the pyrolysis temperature and residence time.



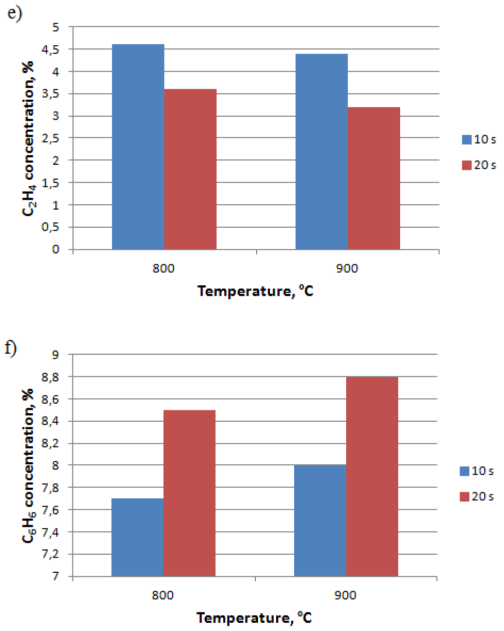
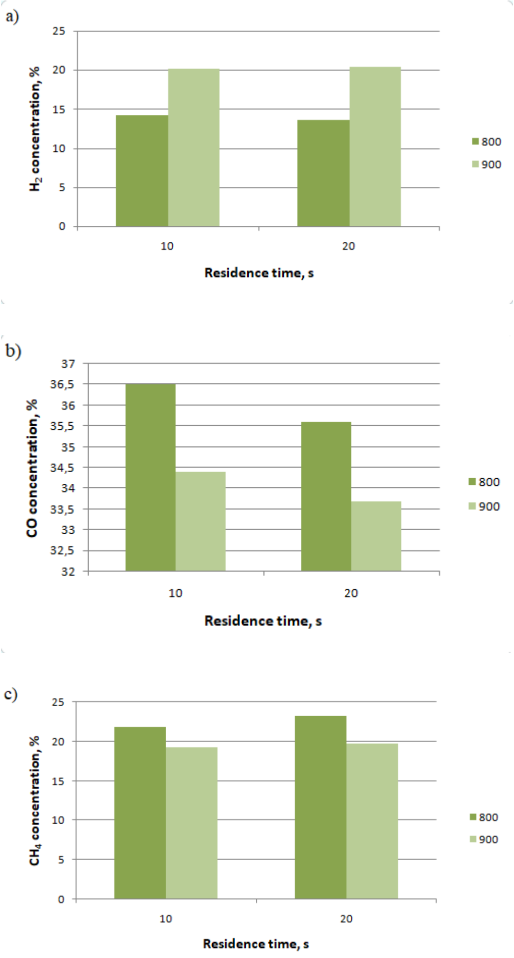


Figure 7 Influence of temperature on concentration in pyrolysis gas: a) H_2 b) CO c) CH_4 d) C_2H_2 e) C_2H_4 f) C_6H_6



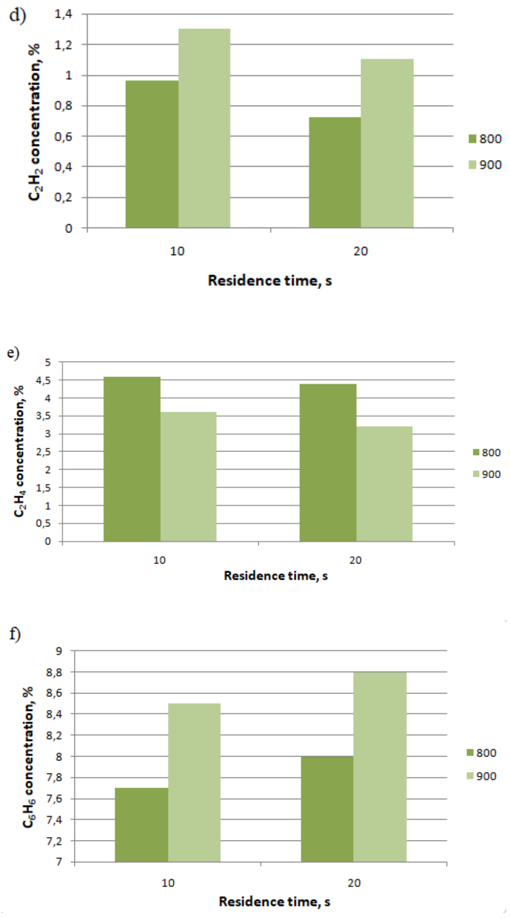


Figure 8 Influence of the residence time on concentration in gas from pyrolysis: a) H_2 b) CO c) CH_4 d) C_2H_2 e) C_2H_4 f) C_6H_6

Analyzing the obtained results, one can observe an increase in the content of combustible components of pyrolysis gas, i.e. hydrogen, acetylene and benzene, as well as a decrease in the content of carbon monoxide, methane and ethene, as the temperature rises between 800-900°C. On the other hand, a change in the residence time in the range of 10-20 sec contributed to a slight increase in the concentration of methane and benzene as well as a slight decrease in the concentration of carbon monoxide, acetylene and ethene.

Based on the calculated chemical composition of the pyrolysis gas, its calorific value was estimated. The calculated calorific value for the analyzed variants ranged from 28.2-28.7 $MJ.m^{-3}$. The obtained calorific value of pyrolytic gas is much higher than the average heating value of gas from RDF fuels (16-20$MJ.kg^{-1}$) from literature data. It seems that the reason for the above the discrepancy is the significant share of heavy hydrocarbons in the gas composition calculated for the Polish installation. The said fraction can constitute up to 30% of the volume of the pyrolytic gas, affecting changes in the elemental composition, and also significantly increasing its calorific value. In addition, the studies by (Efika et al. 2015) [47] show that an increase in temperature in the range 800-900°C caused a decrease in the gas combustion value from 24.8 $MJ.m^{-3}$ to 21.3 $MJ.m^{-3}$, also while reducing the concentration of higher hydrocarbons. Analyzing the aforementioned cases, it can be stated that with increasing concentrations of combustible components of pyrolysis gas, which are characterized by high heating values, the total calorific value of the gas also increases, which encourages wider use of the said secondary fuel for energy purposes.

5 Conclusions

In recent years, new trends in waste management have been observed in Poland, emphasizing the gradual reduction of the amount of waste stored, while developing installations for energy recovery, the so-called "Waste to Energy" (WtE). In the European Union, there is a gradual effort to eliminate landfilling in favor of a circular economy based on recycling and energy recovery from waste. As a result of thermal processes, it is possible to produce electricity and heat, but also to obtain new secondary fuels such as pyrolytic gas, suitable for energy use. CHEMKIN-PRO software helps choose the optimal parameters of these processes and select fuels with the expected properties. Therefore, the authors of this article undertook the task to estimate the calorific value of gas from RDF pyrolysis. The results obtained during numerical calculations allowed approximate calorific value of the pyrolysis gas (28.2-28.7 $MJ.m^{-3}$) to be determined. High-calorific pyrolysis gas may contribute to the reduction of natural gas consumption, and thus to the diversification of fuel and energy sources in Poland. Therefore, it is worth developing installations for the pyrolysis of RDF fuel, reducing the amount of landfilled waste, while gaining an attractive source of energy, so the development of pyrolysis technology seems to be the right direction.

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