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The Advantages and Disadvantages of the Municipal Waste Management System in Poland with an Example of Selected Communes

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Abstract : When joining the European Union, Poland adopted the objectives of Council Directive 1999/31/EC of 26 April 1999 on the storage of waste, at the same time declaring a reduction in the amount of waste deposited at landfills, among others, for recycling. However, despite numerous initiatives taken at the regional and national level, the environmental awareness of Poles is still low, and in addition, the growing costs of waste removal do not contribute to proper waste management. In the article, the authors present a comparative analysis of the advantages and disadvantages of the municipal waste management system in selected communes in Poland. Based on statistical data for 2020 for the communes of Częstochowa and Gorzkowice, the existing solutions aimed at minimising and proper waste management were analysed. The advantages and disadvantages of the system of incentives and fines introduced have been demonstrated, in particular with regard to the rates charged by communes for waste removal. The result of the analysis was to propose solutions aimed at improving the municipal waste management system in the analysed communes, and in particular at increasing the ecological awareness of residents, which will contribute to an increase in the level of recycling and recovery of waste collected selectively in the analysed communes.

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1 Introduction

Municipal solid waste management is currently one of the biggest challenges, especially when it comes to the environment, for both developing and developed countries. The amount of solid municipal waste is growing gradually around the world [16]. Population growth, a high standard of living as well as economic growth and urbanisation are all contributing factors [5].

Improper handling of waste, has an adverse impact on the environment, and in particular contributes to the deterioration of water quality and soil properties as well as the release of methane, which is responsible for global warming, while also affecting human health [4]. According to data obtained from publications [4], since 2004 the largest producer of municipal solid waste (MSW) in the world has been China, which in one year collected six billion tonnes of unprocessed MSW and about 200 of the country's 660 metropolises. In Poland, according to the data provided by the Central Statistical Office, there is an increase in the amount of municipal waste, i.e. waste collected from property owners and collected selectively. In 2020, 13,117 thousand tonnes were produced (Central Statistical Office report), which represents an increase by 2.9% compared to 2019. Per capita, the average Pole generated 342 kg of waste in 2020, which is 10 kg more waste than in 2019. The largest amount of waste per capita, i.e. 400 kg was recorded in 2020 in the Lower Silesian Voivodeship, while the lowest in the Podkarpackie Voivodeship, i.e. 236 kg. The volume of municipal waste generated depends strictly on the population and consumption patterns. The largest variation in the amount of waste generated is observed in communes. In 2020, in 29% of communes, less than 200 kg of municipal waste per capita was collected, while in 58% of communes, the amount of waste generated ranged from 200-400 kg per capita, while the largest amount of municipal waste was collected in tourist communes (in six communes, over 1000 kg of municipal waste was collected). According to the data from the report prepared by the Central Statistical Office, in 2020 there were 2239 selective municipal waste collection points (PSZOK), i.e. places where property owners can provide selected fractions of municipal waste free of charge as part of the general fee for waste management. Municipal waste collection services were provided by 1,306 enterprises. Unfortunately, the number of PSZOKs is not sufficient. The draft resolution prepared by the Ministry of Climate and Environment shows that the Polish rainwater management has significant investment gaps in this respect [21]. As indicated in the project, for the support of the waste management system in Poland, 814 new separate municipal waste collection points should be built, and about 30% of the existing ones require modernisation. In addition, in order to ensure the possibility of sorting separately collected waste, about 200 sorting plants are planned to be built by 2028, and further 30 by 2034. As regards the biological treatment of municipal solid waste, installations with a minimum capacity of 1,700,000 Mg/year, 34 fermentation installations with capacity of 30,000 Mg/year or 51 installations with a capacity of 20,000 Mg/year, and about 47-70 composting plants with a capacity of 15,000 to 10,000 Mg/year are planned to be built by 2028. In the field of recycling paper, glass, metal, plastics, bio-waste and multi-material waste, four glass cullet processing plants, paper processing plants, about 25 plastic recycling plants are planned to be built by 2028, as well as retrofitting existing metal recycling plants with separators along with the necessary tooling.

2 Municipal waste management in communes

Among other factors affecting the solid waste management system, the literature on the subject mentions, among others: the attitude to waste of the local population, legal conditions, the level of environmental awareness, transport infrastructure and many others [1]. One of the efficiency measures determining the degree of good municipal waste management in a given area is the general state of the urban environment in social, economic and public health terms [2,3]. Waste management contributes to a number of Sustainable Development Goals, such as good health and well-being, sustainable cities and communities, as well as responsible consumption and production. It is estimated that by 2025 the amount of municipal solid waste will increase to "1.42 kg/person/day (2.2 billion tonnes/year) generated by 4.3 billion inhabitants of cities worldwide". Solid and urban waste management has become a huge challenge for local authorities in developing countries, mainly due to the growing number of MSW, difficulties in managing higher costs of MSW within the commune budget, lack of scientific understanding of technical aspects related to various stages of MSW management and the level of public support. According to data obtained from literature, the most preferred ways to minimise municipal waste is the “10R” concept, which includes the following actions: Respect, Responsibility, Refuse, Reduce, Rethink, Repurpose, Reuse, Repair, Recycle, Restore. Integrated Municipal Solid Waste Management (MSWM) system consists of key processes from the moment of waste generation to the moment of final waste disposal.

The efficiency of the waste management system is most affected by poor route planning, lack of vehicles, improper way of collection, weak and tight road network and irregular waste collection planning [11]. Municipal waste management in Poland is a huge challenge, both from the environmental and economic point of view. The recycling levels of municipal waste in Poland significantly deviate from the highest European levels. The need for better municipal waste management is also related to the requirements of European law [14].

Waste management covers a wide range of activities related to waste management, from their generation to management, through the recovery of secondary raw materials to environmentally and humanly safe disposal. The issue of waste management due to its quantity, diverse composition and properties is very complex [2]. This results mainly from two aspects closely associated with one another. The first relates the increase in the mass of waste as the population grows, economic development, as well as the increase in the prosperity of society. The second is associated with nuisance and danger from waste, especially hazardous to the environment, and thus to humans. Therefore, it should be sought to establish detailed and precise legal and organisational rules for the management of various types of waste, which should also contribute to the application of these provisions in practice [20].

3 Factors determining proper waste management in communes

Among the many factors determining the efficient waste management system in communes, the main determinants are: waste rates and environmental education.

Proper choice of the method of setting the fee and the rate is of key importance for the municipal waste management system in communes. Municipal councils determine the method of setting the fee for the management of municipal waste collected from the owners of the property on which residents live. It is allowed to use more than one method of setting fees in the commune. For single-family properties, a different method of calculating the fee may apply than for multi-family properties. For the determination of the rate of the municipal waste management fee, the following shall be taken into account:

- the number of inhabitants of the property,
- the amount of water used in the property,
- the area of the housing unit and the rates of the fee,
- the rate of the household fee.

The amount of the rate may depend on such factors as:

- area of residential premises,
- the number of inhabitants of the property,
- collection of waste from rural or urban areas,
- type of building.

The municipal council may apply different criteria to differentiate the rates of the fee. The share of communes (based on 302 communes) on which the method of the fee rate is based on the number of inhabitants of a given property during the period of 2014-2018 is 86%, while based on the amount of water used, the share of communes is only 4%. Although the method of payment per person is not the most honest, it is still most often used in communes, which results from market research in 2014-2019. Due to the choice of such a method by the commune, every year, due to the increase in municipal waste fees, there is a drastic decrease in the number of declared persons. This is unlawful and unfair to people who systematically pay waste fees [9].

The second important factor affecting the proper management of waste in communes and the success of the transformation towards circular economy is the ecological education of residents. Research on sustainable consumption shows that the level of consumer knowledge of Poles is very low. Poles are also unaware of the impact of their behaviour as consumers on the environment, and consequently on the quality of life of present and future generations. Research on ecological awareness proves that Poles, on the one hand, are aware of the risks resulting from the excessive use of natural resources, and on the other hand, they do not know practical ways of preventing this phenomenon. As consumers, they focus on the price, not environmental considerations. Therefore, it is extremely important to carry out educational activities among all social groups and age groups aimed primarily at changing consumer behaviour. Knowledge about purchased products and their manufacturers in terms of environmental impact can be very important when it comes to building awareness and changing the way of thinking and consumer habits [14].

4 Municipal waste management in the analysed communes

The Gorzkowice commune is a rural commune located in the southern part of the Piotrków County, in the Łódzkie Voivodeship. Gorzkowice is the seat of the commune authorities. The commune covers an area of 102.29 km². According to data from 31 December 2021, the commune was inhabited by 8359 residents. Until 2009, in the area of the Gorzkowice Commune, in the village of Krzemieniewice, there was a landfill, which was rehabilitated. The landfill area was 0.75 ha, while the capacity was 13 thousand m3. Statistical data shows that in 1991-1998, the landfill was filled with 400 to 750 m3of waste per year. On the basis of a tender agreement, the collection of municipal waste from the residents of the Gorzkowice Commune and its management is carried out by REMONDIS Sp. z o.o., which has a branch in Częstochowa and a plant in Radomsko. In the Gorzkowice Commune, the rate of the fee for municipal waste depends on the amount and type of waste collected and the number of residents of the property. The number of people declared as of 4 June 2020 is 7358. The rate of the fee for residents conducting separate collection from 1 October 2020 is PLN 24.00 per person, while the cost of unsorted waste is PLN 72.00 per person. However, the current rate for the collection of municipal waste in the Gorzkowice Commune does not cover all costs (the amount of payments received from residents does not allow for the payment of remuneration to a company selected through a public tender). Due to the above, the Gorzkowice Commune Council decided to pay the missing amount from the communal budget so that the municipal waste fees are not increased. In 2020, the Gorzkowice Commune contributed the amount of nearly PLN 600,000. Owners of single-family properties who compost bio-waste constituting municipal waste in a household composting plant may additionally be partially exempted from the fee. The rate for segregated waste in the case of a composting plant may be reduced by PLN 2.00 per inhabitant per month [6-8].

The waste removal schedule is handed over to the commune by the waste collection company. Waste is collected divided into individual fractions from the single-family development area once a month, while from the multi-family development area twice a month. In addition, in the spring and autumn seasons, there is a collection of large-scale waste, used electrical and electronic equipment that is placed in front of a property.

In single-family housing, bio-waste can be composted in a special home composter. In the case of a discount for composting, bio-waste is not collected from the property by the company collecting municipal waste. The administrative authorities in the commune decided to selectively collect ash, due to the search for solutions to reduce the costs of waste. One of the ideas is to store it in mine excavations, then the municipality would not bear the costs of its storage. The fact that for residents with waste-free heating systems, no discount is granted for this reason, may be somewhat harmful. One of the forms of incentives for the selective collection of waste used in the Gorzkowice Commune are free bags [10].

For each bag issued to the waste collection company, a replacement bag is obtained. Each of the residents may apply for an additional number of bags at the Municipal Office. Used (small) batteries are collected from four points. As part of the payment of a monthly fee for waste, waste such as: hazardous waste, used electrical and electronic equipment, large-scale waste, construction and demolition waste, worn tires, packaging after plant protection products and fertilizers can be handed over to the Municipal Point of Selective Municipal Waste Collection (PSZOK) located in Gorzkowice every first Wednesday of the month at specified hours.

The Częstochowa Commune is located in the district of Częstochowa in the southern part of the Silesian Voivodeship. Częstochowa is the seat of the commune authorities. The commune covers an area of 159.71 km^2. It consists of three urban-rural communes and thirteen rural communes. According to data from 31 December 2021, the commune was inhabited by 207467 people. The Czestochowa waste landfill is located in the Poczesna commune, in the town of Sobuczyna. The landfill area is 128 ha. On the basis of a tender agreement, the collection of municipal waste from the residents of the Częstochowa Commune and its management is carried out by REMONDIS Sp. z o.o. In the Częstochowa Commune, the rate of fees for municipal waste depends on the amount of water used and the type of waste collected as well as the number of residents of a given property. The rate of the fee for residents for selective collection is PLN 9.60 per 1 m3 of water used (multi-family housing) and PLN 29.00 per each resident of a given property. The rate for unsorted waste was also set at PLN 19.20 per 1 m3 (multi-family buildings) of used water and PLN 58.00 per each resident of a given property. The schedule of municipal waste removal is handed over to Częstochowa by the waste removal company. The collected waste is divided into individual fractions from the single-family development area on average twice a month, while from the multi-family development area thirteen times a month. In addition, the waste removal company organises the collection of large-scale waste and collection of electrical waste.

In Częstochowa, there are eight Selective Municipal Waste Collection Points (TOPSZOK), located throughout the city. These are dedicated points and they include three containers in which the following waste fractions are collected. The Selective Municipal Waste Collection Point was built at Częstochowskie Przedsiębiorstwo Komunalne Sp. z o.o in Sobuczyna. SPSZOK is a comprehensively equipped facility adapted to the collection and temporary storage of municipal waste, namely hazardous, post-renovation and large-scale waste, provided by residents of the City of Częstochowa. The point operates in self-service mode, and municipal waste separately collected can be disposed of in special containers and bins.

Table 1 summarises the most important information regarding the analysed communes, in the context of municipal waste management, while Figure 1 presents a general scheme of municipal waste management in the analysed communes [12,13].

Table 1 Comparison of the analysed rural and urban communes

	Gorzkowice Commune	Czestochowa Commune
Location	Poland	Poland
District (Powiat)	Piotrkowski	Częstochowa
Vovivodeship	Łódzkie	Śląskie
Commune	Rural	City
The seat of the commune	Gorzkowice	Częstochowa
Area	102.29 km^2	159.71 km^2
Population	8.359	207,467
Waste removal company	REMONDIS Sp. z o.o.	REMONDIS Sp. z o.o.
Rate method	Single-family housing	
	Per person	Per person
	Multi-family housing	
	Per person	For 1 m^3 of used water
Amount of the rate for segregated waste, PLN	Single-family housing	
	24.00	29.00
	Multi-family housing	
	24.00	9.60
Amount of the rate for unsorted waste, PLN	Single-family housing	
	72.00	58.00
	Multi-family housing	
	72.00	19.20
Landfill	Jadwinów	Sobuczyna
Frequency of waste collection	single-family housing	
	once in a month	twice a month
	Multi-family housing	
	twice a month	eight times a month

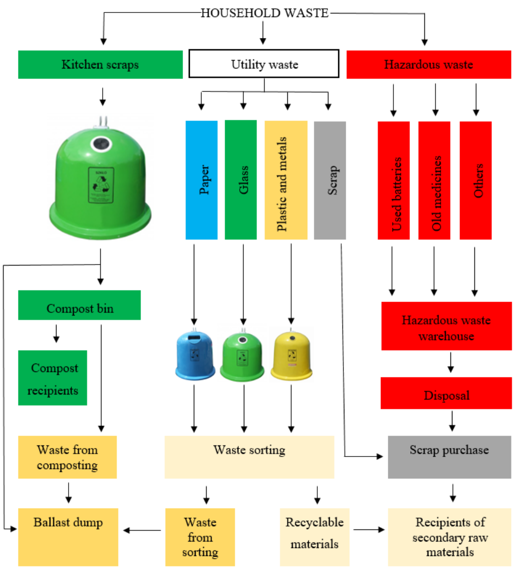

Figure 1 Types of municipal waste and ways of their management in the communes of Częstochowa and Gorzkowice [15]

According to the documents: Waste management plan for the Łódzkie Voivodeship for 2019-2025, taking into account the period of 2026-2031 [18] and Waste management plan for the Silesian Voivodeship for 2016-2022 [17,19], one of the key problems causing threats to the environment is an incorrect waste management system, in particular:

- insufficient number of Municipal Points of Selective Municipal Waste Collection to which all residents would have easy and unlimited access in terms of transferring specific fractions of municipal waste,
- insufficient control activities of the waste treatment plant, especially in terms of meeting the conditions set out in the law,
- lack of on-going tests in terms of morphological composition as well as physical and chemical properties of waste,
- too much mixed waste in the entire stream of municipal waste generated,
- storage of biodegradable waste separately collected,
- storage of mixed waste containing hazardous household waste, including expired medicines,
- the public's awareness of modern municipal waste management is still too low. Lack of knowledge of legal requirements, the need to limit the amount of waste generated, the principles of separate waste collection and recycling,
- insufficiently effective measures to eliminate illegal accumulation of waste.

Both the Waste Management Plan for the Silesian Voivodeship for 2016-2022 and the Waste Management Plan for the Łódzkie Voivodeship for 2019-2025, taking into account the period of 2026-2031, set the goal of developing a circular economy. The development strategy also includes the rehabilitation of closed landfills of municipal waste, the elimination of illegal landfills and the elimination of harmful asbestos. One of the priorities of the local government of the Silesian Voivodeship is to ensure efficient waste management by raising the ecological awareness of the inhabitants, etc. Educational activities include mainly leaflet printing, cyclical meetings "Cleaning the World", announcements on social media, press announcements, as well as meetings and scientific conferences. Numerous initiatives are also taken in the area of food waste. Throughout the voivodeship, there are “Food Banks” as well as and collection points for used electrical and electronic equipment. Similar activities are undertaken by local governments in the Łodzkie Voivodeship, which, in addition to the above-mentioned initiatives, promote the idea of composting bio-waste in home composting plants. Furthermore, due to the fact that minimising waste generation is the most effective strategy in waste management, it is planned to create repair and reuse points in the Łódzkie Voivodeship. The proposed solution may reduce the amount of waste generated by residents, and thus reduce the costs of their management. The creation of such sites would contribute in part to the objective of developing circular economy. Creating an efficient network of repair points and preparing for recycling is a major challenge for communes. The assumptions show that initially such points will be created at the already functioning points of selective municipal waste collection.

5 Summary

Waste management is currently one of the most serious environmental and economic challenges not only in Poland, but also globally [22]. Although the situation in the waste management sector has been subject to dynamic changes in the recent years, there are still numerous barriers and serious threats. Therefore in Poland, among other countries, it should be considered a priority to take action to build an economically and ecologically efficient waste management system. This system should be consistent with the waste hierarchy and the principles of sustainable development as well as the EU policy. In particular, it must take into account the ambitious objectives of circular economy in the coming years. Waste management is an eternal problem faced by Poland. Despite the fact that Polish society is often accused of lack of education related to ecology and environmental protection, in this case it cannot be blamed. Those who want to take a step towards a cleaner environment and support waste segregation face numerous obstacles on their way. The main problem is a complete lack or insufficient number of containers for sorted waste. Waste segregators are forced to dump them later in mixed waste containers. Where containers have been delivered, there are often too few of them or they are emptied too rarely and the waste simply does not fit in them. The analysis of the waste management system in selected communes in Poland carried out in the article indicates, at the regional level, not only the disadvantages of this system, but also the advantages. Particular attention should be paid to the methods of payment of fees and rates for waste removal. Both in the Gorzkowice Commune and in the Częstochowa Commune, the methods of the calculating the fee are based on the number of inhabitants living in a single-family property. The fee depends on the specificity of the given commune, including the wealth of residents and the type of buildings. A good solution used in the Gorzkowice Commune is to set a high rate for unsorted waste. This is to force residents to selectively collect waste. One form of incentive is also free bags for property owners. The system of charging fees in multi-family housing according to the amount of water used in the Częstochowa commune raises continuous controversy, as evidenced by numerous complaints from residents. A resident of an apartment building who consumes a large amount of water must bear in mind the very high costs of waste collection. Concerns of residents of multi-family housing are also caused by the fact of measurement inaccuracies affecting the amount of the fee. The dependence of the waste collection fee on water consumption when there is a breakdown, water leakage in an apartment or in a common area is also very harmful, as it does not refer in any way to the amount of waste generated. Taking into account the logistics system, and thus the same frequency of collection of municipal waste in the areas of the analysed communes, the Częstochowa Commune should become an example for the rural commune. In the Gorzkowice Commune, however, the obstacles are the technical and organisational capabilities in the area of management of municipal services, which the commune is facing. Regardless of the length of the publication period, only one company has been continuously participating in the tender for several years. The fact that other companies are not interested in providing the service in question in the rural commune does not allow certain decisions to be made, as the vision of no waste collection is frightening. However, the support provided by the commune regarding the additional payment to the waste management system is a dominant advantage and compensates for disadvantages in the system.

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Innovative Methods in Monitoring and Analysis of Emission Production in Solid Fuel Heat Sources

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Abstract: In this paper, different and innovative ideas of monitoring and analysis of emissions produces by small heat sources are presented and described. This paper follows up research made in master's thesis from 2022 where two wireless prototypes meant for analyzing emission production were designed, constructed and successfully tested. First prototype made from Polymethymethacrylate (PMMA) successfully analyzed parameters such as concentration of CO, CO_2, VOC or dust particles PM in air of indoor temperature during various types of tests. Second prototype made from stainless steel was used to analyze flue gases directly connected to the chimney from a household using small stove and different kinds of fuel. Evaluation of these experiments in IoT platform named ThingSpeak showed significant increase of concentration of emissions produced during burning unsuitable fuel (such as wet grass) compared to more suitable fuel such as dry wood.

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1 Introduction

Emissions are one of the key aspects of climate and environmental health that can have detrimental effects on the landscapes and biosphere. As the ozone layer further increases caused by the increasing emission of greenhouse gasses, the average temperature of Earth rises. The European Union set a target for 2030 to decrease the European production of emissions by 55% lower as 1990 levels and aims to achieve emissive neutrality by the year of 2050 [1]. Without accurate and up-to-date data, it will not be possible to discern if any mitigations or placed regulations are effective.

One of the most popular solutions to such problem is implementing a so-called continuous emission monitoring system, or CEM for short. The systems is composed of a gas analyzer, a sampling interface and a data acquisition program. "*Remote sensing systems have no interface between the stack gases and the sensing instrument, other than the ambient atmosphere. They thus avoid problems associated with a stack or duct interface.*" [2]

On that note, that aim of the article is to present the continuation of an innovative design of a wireless emission monitoring system. The low-cost device allows autonomous measurements, wireless data transmission, and display air-quality parameters on a smart phone application directly from household boilers via chimney.

2 Design of monitoring prototypes

The Master's thesis of 2022 at Department of Power Engineering on University of Žilina consisted of the design of two separate wireless data transmitting prototypes of monitoring system, their models, construction and evaluation of outcoming results from experiments.

The first prototype was made of Polymethylmethacrylate (PMMA) material and was intended specifically for indoor use (should not exceed temperature of 70°C because of the risk of material dissolution). In other words, this prototype had the idea of monitor and analyze air conditions and properties in a normal environment, as well as monitor changes made by various experiments.

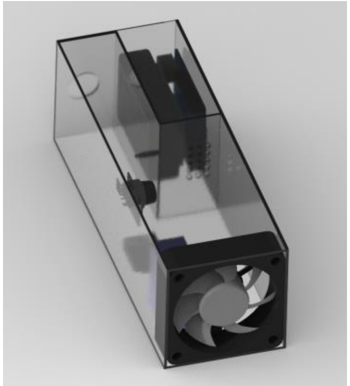

Figure 1 CAD model of prototype from PMMA

Second prototype, manufactured from stainless steel, was constructed with the aim of analyzing production of flue gases emitted directly from the chimney during the combustion process of solid-based fuel.

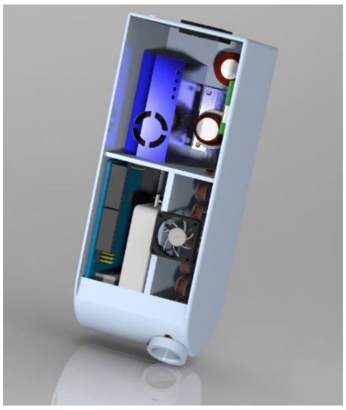

Figure 2 CAD model of prototype from stainless steel

Both prototypes transmitted data from measurements and monitoring via IoT platform called “ThingSpeak”, which displayed the data on a custom friendly environment in the shape of graphs, meters or simple outcome numbers representing the result [3].

Figure 3 IoT Platform “ThingSpeak”

2.1 Construction and parts of prototypes

Both prototypes were designed with the aim of being as small as possible, since the system should have the ability of being fully mobile and portable, not being too heavy or difficult to move from place to another. The internal electronics, the driving heart of the system, are however even more important. Both devices share the same internal composition, as shown on Figure 4.

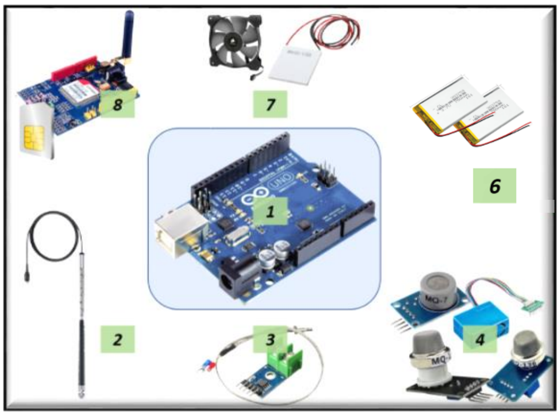

Figure 4 Components of prototypes

The main parts are described below:

1. Microcomputer Arduino Uno
2. Sampling probe
3. Thermocouple
4. Emission monitoring sensors [4]
5. (Excluded point) Additional power source
6. Main power source – 2 x Li-ion batttery (type 18650, 2600 mAh, 3,7V)
7. Ventilator
8. Telecommunication unit – SIM 900 GPRS/GSM shield [5]

2.2 Construction of prototype from PMMA

The first prototype made in the master’s thesis was chosen to be made from a clear, see-through material, that could allow users to see the inside of the box. This device was the first to made because of the approximate dimensions of parts included, included Arduino microcomputer, power source (Li-On batteries), various types of emission monitoring sensors such as CO, CO_2, VOC, and dust particles $PM_{2,5}$.

The construction consisted of four long plates of PMMA, mounted together with the help of four L-shape aluminum parts. A 12V ventilator was placed on the bottom part with aim of sucking the air through all the parts from the system and vent out afterwards. The electronic part (Arduino microPC and batteries included) was divided separately from the sensor chamber. The sensors consisted of emission monitoring devices that were readily available on market as following:

1. Thermocouple **MAX6675** (flue gas temperature sensor)
2. **PMS5003** dust sensor (particulate concentration sensor for PM_{10}, PM_5 and $PM_{2.5}$
3. Emission sensor **MQ-7** (carbon monoxide CO concentration sensor)
4. Emission sensor **MH-Z19** (carbon dioxide CO 2 concentration sensor) [6]
5. Emission sensor **MQ-135** (concentration sensor for organic gaseous compounds VOC)

2.3 Construction of prototype from stainless steel

This prototype was made with the aim of direct analyzing the flue gases produced by small heat source (in this specific case it was home stove) during the process of burning different kinds of fuel.

It was made from four flat plates of stainless steel that were mounted together with many small steel spots allowing it to be reassembled. In the last part of the construction, parts were welded together excluded one plate (allowing it to open and replace other non-mounted parts, i.e., microcomputer, batteries etc.).

3 Experimental testing and results

Both prototypes were repeatedly tested to prove their ability to function. In this chapter a few examples of experiments will be described also as their results.

3.1 Experimental testing of protoype from PMMA

First experiment with the prototype from PMMA was conducted to make an initial test to acknowledge the ability of all internal components (including all the emission sensors, batteries etc.) to function altogether connected to one microcomputer and monitor the quality of outside air. The graph on Figure 5 shows concentration of dust particles $PM_{2,5}$, PM_5 and PM_{10} (as concentrations of other emission substances were normal).

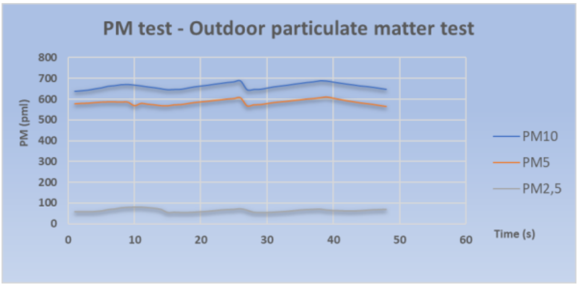

Figure 5 Measurement of dust particle concentration using the PMS5003 sensor and Arduino Uno

Second experiment with this prototype was conducted to prove the ability to withstand the temperature difference and to function despite the increased temperature and change of the air while cardboard paper underneath the device was being burned. Results of this test proved the resistance of sensors to smoke and higher temperature caused by the flame. Figure 6 shows results from this test, specifically concentrations of VOC (Volatile organic compounds) and CO.

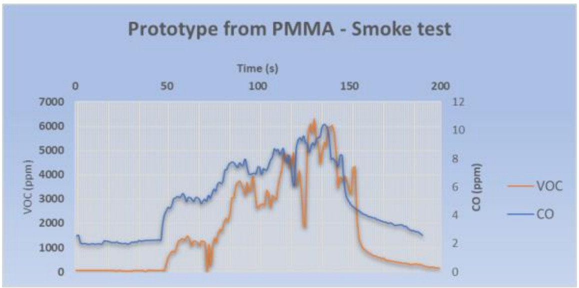

Figure 6 Smoke test of prototype from PMMA

As showed, the values of each substance significantly rose while the sensors were exposed to smoke from burning cardboard paper.

3.2 Experimental testing of prototype from stainless steel

Since results from using the prototype from PMMA have proven that all inner parts can withstand adverse air conditions, there was just one experiment left to be conducted with the prototype from stainless steel. As mentioned, this device is meant to be used to monitor production of flue gases directly near the chimney (sampling probe put in the middle of the up end of chimney).

This experiment consisted of two parts made simultaneously - using two thermocouples to measure the temperature of inside of the chimney while the second thermocouple measured temperature inside of the device (near the emission sensors). This was made to avoid overheating and possible burning of the internal parts of the device due to high temperature.

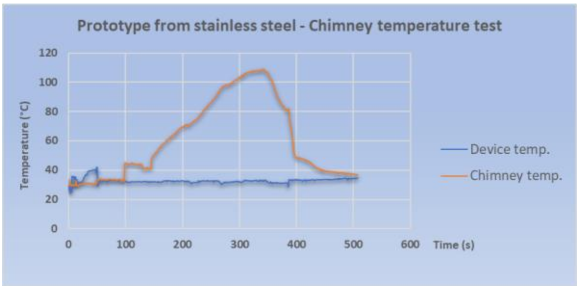

Figure 7 Chimney temperature test with stainless steel prototype

Second test started with a few minutes analyzing outside air with no pollution (not near a heat source) and afterwards the sampling probe from analyzing device was placed to the middle of a 4-meter-high chimney where wood was burning. As Figure 8 shows, concentrations of all measured substances increased during wood burning. Last step from this experiment was to add any kind of inappropriate fuel to burn in the stove – in this case wet grass was used. Blue curve on the graph is representing measurements from the VOC emission sensor (MQ135) in PPM (parts per million).

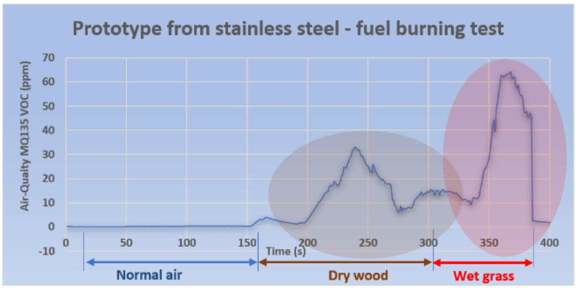

Figure 8 Fuel burning test with stainless steel prototype

Results show significant increase of VOC emissions when inappropriate fuel is added to the stove, an increase to 65 ppm concentration levels. Therefore, as this data as acquired completely wirelessly (powered by batteries), the experiment can be considered successful.

4 Conclusion and future design steps

In this chapter the conclusion from all the experiments will be stated and future steps will be presented.

4.1 Conclusion of experimental results

The results of all the experimental measurements performed in the thesis also proved that the prototypes are able to successfully locate the smoke in the flue gas ducts. They are also able to determine the state of air quality in the vicinity of the TS and in the future, through the application, reliably share the measured data in the form of graphs and displays, which will be easily presented and interpreted in a natural way by the end-users.

The inner stainless steel device temperature remained the same thorough the whole experiment (which is one of the most important outcome of the whole testing part). Therefore it can be concluded, that stainless steel device is ready for using directly during the process of burning fuel to monitor and analyse the outcomes. These tests also allow a further research to be carried out, as none of the prototype devices was destroyed nor it did not get broken in any way.

4.2 Future design steps

The future design steps consist of step-by-step improvements, verification tests and experiments of new prototypes in aims of validating the system more. Several intermediate prototypes shall be built and tested to ensure that proof-of-concept is attained.

Build 1 ESP8266 + LoRa telecommunication module

The goal of the first build is to show functionality of a LoRa SX1278 module along with the ESP8266 microcomputer. The goal is to combine one up to three emission sensors and transmit the measured signal to another LoRa Module that shall act as a receiver. The distance that is possible to transmit shall be assessed.

Build 2 New PM sensor + ESP8266 + Adafruit IoT Platform

The second build comprises of a very simple model that shall be connected via WiFi connection directly to a new Adafruit IoT platform. This platform shows great flexibility and simple buildup of apps and signals. The goal is to measure the accuracy of the SDS011 sensor alongside two other MQ-series sensors. It is very important to show that there is not data or signal interference.

Build 3 Digital Nextion display prototype

The last prototype shall test the user interactivity using a nextion 2.6’ display. It shall be programmed using the Nextion HMI software, that allows simple drag-and-drop functions and data to be displayed (CO_2, PM, temperature values). The goal of this prototype is to have a fully portable and functional „all-in-one“ box to use for emission measurement in any room or area.

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Potential of Using Hydrogen in Combined Heat and Power

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Abstract : Nowadays, when we can observe unstable energy prices, the use of cogeneration technologies seems very convenient. Using these kind of technologies could help in many different ways, such as reducing the amount of emission released while producing heat and power or even cutting costs for operation. One of the solutions appears to be hydrogen, which can be mixed with natural gas and burned together in one engine. There were more types of hydrogen that had to be assessed and compared in terms of emissions as well as from economic point of view, since they can differ in terms of the type of origin or how they were produced. Thus, it was found that at the current prices of used fuels, it would be economically worthwhile to use gray and blue hydrogen, and green hydrogen has also potential for the future, but its dependend on the costs of electricity. Thus, in general hydrogen has the potential to slowly replace natural gas, but first it is necessary to figure out its more energy-efficient production, as well as its distribution.

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1 Introduction

Combined heat and power production is currently widely used, when we are watching the rise in energy prices or efforts to reduce carbon emissions. Various technologies for the combined heat and power production are demonstrably more efficient compared to separate production, they also contribute to reducing the consumption of primary energy sources, and last but not least, they are more environmentally friendly. One of the technologies is combustion stationary engine used as a cogeneration unit, in which blends of natural gas and hydrogen are used as fuel. At the moment, we have to deal with alternatives that could replace natural gas as one of the traditional fuels in the future, for various reasons. There are more reasons for this, for example, geopolitical conflicts, and there is also an effort to reduce the use of fossil fuels, or the directly related production of carbon emissions. One of the alternatives appears to be hydrogen, which in this case is mixed into natural gas in various concentrations.

2 Analysis of fuels used in combined heat and power

Table 1 compares the properties of natural gas, hydrogen, hydrogen-enriched compressed natural gas (NG+H_2, 10% of hydrogen in volume), and gasoline is reported in Table 1.

Table 1 Properties of fuels [1]

	NG	**H_2**	**NG+ H_2**	**Gasoline**
Air to flow ratio [m^3/m^3]	9,43	29,53	22,8	1,76
Autoignition temperature [K]	813	858	825	501–744
Flame temperature in air [K]	2 148	2 318	2 210	2 470
Burning velocity [$m \cdot s^{-1}$]	0,45	3,25	1,10	0,37–0,43
Lower heating value [$MJ \cdot kg^{-1}$]	48	120	66	43,4

Mixing natural gas and hydrogen is not directly and always advantageous because it is necessary to optimize the amount of hydrogen according to the working conditions of the engine. As the level of hydrogen increases at a fixed engine operative point, the in-cylinder temperature increases too, while the combustion duration reduces. [1]

2.1 Emission factors of most common fuels

This subchapter summarizes the most commonly used fuels, which are used in cogeneration units, specifically in combustion engines. Among these fuels we can include liquid (gasoline, diesel, LPG, heating oils) or gaseous (natural gas). Thanks to their combustion, we obtain either electrical or thermal energy, but at the same time, other combustion products such as CO_2 emissions are also produced. Since there is an effort to reduce these emissions, it is necessary to choose fuels that produce less of them. At the same time, individual sources of pollution must comply with certain emission limits determined by legislation. The indicator that tells us how much CO_2 individual fuels produce when they are burned is the emission factor, which indicates how many kg of CO_2 are produced when burning, for example, 1 kg of fuel, or when producing 1 kWh of energy.

Table 2 Comparison of basic fuels

Fuel type	Heating value	Emission factors CO_2	
		1kWh of energy	1kg of fuel
	[kWh/kg]	[kg_{CO2}/ kWh]	[kg_{CO2}/ kg]
Natural gas	13,47	0,2	2,7
Gasoline	12,2	0,25	3,1
Diesel	11,7	0,27	3,2
Propan butan (LPG)	12,78	0,23	2,9
Heating oil	11,22	0,28	3,1
Other oil fuels	11,67	0,26	3,0

Table 2 summarizes the properties of the selected fuels, where the calorific value of the fuels and their CO_2 emission factors are mentioned. It is obvious that of the traditional fuels mentioned, natural gas has the best position in terms of calorific value, but at the same time it also has the lowest emission factors. It follows from the fact that among fossil fuels it is the most efficient and also the most environmentally friendly.

2.2 Mix of hydrogen and natural gas

Natural gas combustion engines are characterized by a low combustion speed and this can be solved by increasing the flow intensity in the cylinder, while this measure always increases the heat loss on the cylinder wall and increases the combustion temperature as well as NOx emissions. One effective method to solve the problem of low burning rate of natural gas is to mix natural gas with a fuel that has a high burning rate. Hydrogen is considered the best alternative to natural gas due to its very fast burning rate, and this combination is expected to improve combustion characteristics and reduce engine emissions. The hydrogen content in natural gas can range from 5 to 30% by volume. [2]

Table 3 Comparison of parameters of natural gas, hydrogen and their mixtures [3]

	NG	NG+ H_2	NG+ H_2	NG+ H_2
Amount of H_2 [% obj.]	0	10	20	30
Air to flow ratio[kg·kg^{-1}]	17.00	17.23	17.51	17.86
Density (20 °C, 101 325 Pa) [kg·m^{-3}]	0.705	0 643	0.582	0.520
Lower heating valure [kJ·kg^{-1}]	48 825	49 770	50 916	52 336
Lower heating valure [kJ·m^{-3}]	34 412	32 018	29 624	27 232

As can be seen from the Table 3, as the proportion of hydrogen in natural gas increases, the lower calorific value per 1 kg of fuel increases, but as the density decreases, the calorific value of the mixture per volume unit also decreases.

3 Economic evaluation of fuels

To calculate the cost of operating a cogeneration unit, it is necessary to know the price of fuel. In our case, it is natural gas and hydrogen. As for natural gas, it is known that it is currently difficult to estimate the direction in which it will go. Alternatives to this fuel are currently being sought for various reasons, one of which is hydrogen. Natural gas prices are also rising, and it is expected that this trend will continue for the next few years. The development of the price of natural gas is shown on the graph (Figure 1), which was obtained from the website tradingeconomics.com [4]. The price of gas on the TTF market (virtual trade hub Title Transfer Facility in the Netherlands) has been changing rapidly over the last period, when compared to last year it increased by tens of € per MWh. It reached its peak of the first half of the year in March 2022, when the price for 1 MWh was up to €230. At the time of writing this article (October 2022), the price stabilizes slightly around 170€/MWh, after the highest peak that we could follow in the end of August.

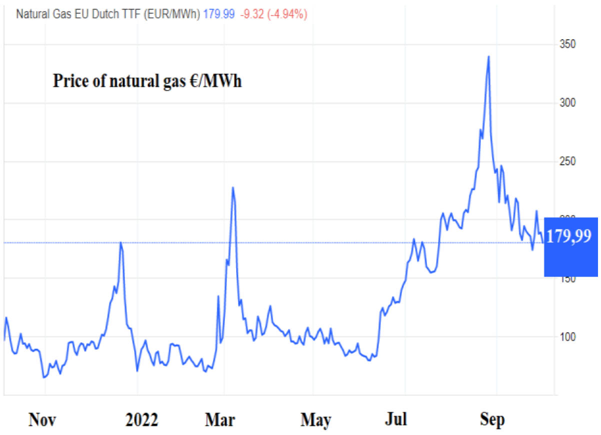

Figure 1 Price development of natural gas [4]

In the case of hydrogen, the price is also complicated, since various methods of hydrogen production are known from a technological, economic, but also environmental point of view. Since production technologies for some types of hydrogen are directly dependent on natural gas, the price of these types of hydrogen will change automatically when natural gas prices change. Depending on the production process, source and resulting greenhouse gas emissions, hydrogen is commonly classified as follows (Figure 2), although this classification is somewhat simplified and not complete:

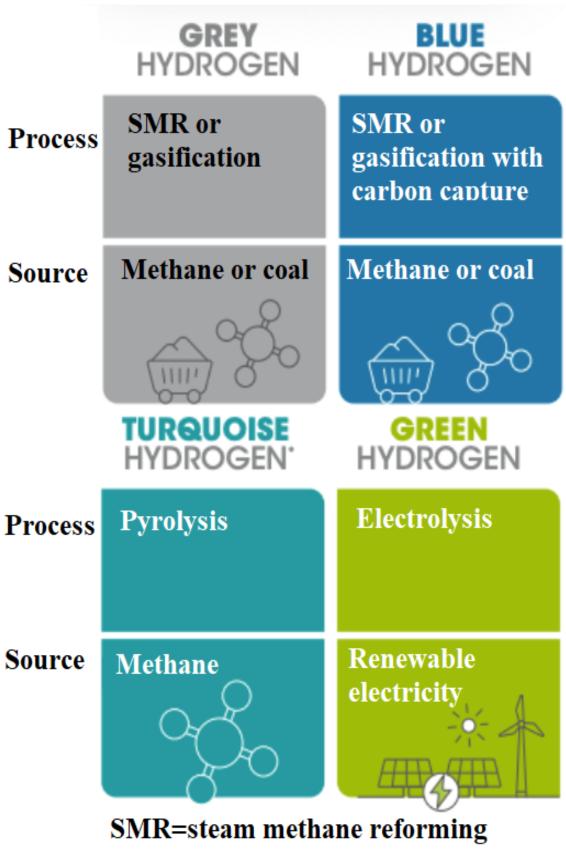

Figure 2 Types of hydrogen [5]

- Gray hydrogen is produced from natural gas by steam methane reforming. Its price varies depending on the price of gas and carbon emissions. This production process results in emissions of approximately 9,3 kg of CO_2 per kg of hydrogen.
- Blue hydrogen uses the same production processes as gray hydrogen, but the CO_2 is captured and stored permanently. In terms of price, it is more expensive than gray hydrogen, but cheaper than green hydrogen.
- Turquoise hydrogen is produced by pyrolysis of natural gas, with pure carbon as a by-product that can be sold on the market. It is still in the early stages of development, but has the potential to become a cost-effective process.
- Pure hydrogen ("renewable hydrogen" or "green hydrogen") is produced by electrolysis of water using electricity from renewable energy sources. In terms of price, this type of hydrogen is still the most expensive. No greenhouse gases are released during the process.

The individual prices of the mentioned types of hydrogen can vary and in different countries their differences can be large. For example, in places where renewable energy sources have been used for the production of electricity for a long time and in the majority, the price of green hydrogen has even dropped below the value of the price of gray hydrogen. Table 4 summarizes the average prices in euros of hydrogen per 1 kg. These data were used from the website europarl.europa.eu. [6] As mentioned, prices can be different, and therefore averaged prices were inserted into the table, which could be used for an approximate calculation of the costs of operating a cogeneration unit. Subsequently, the table also shows the price in euros per MWh of energy produced, since we know that we can produce 33.33 kWh of energy from 1 kg of hydrogen.

Table 4 Average hydrogen prices

Type of hydrogen	Price [€]	
	per kg	per MWh
Grey hydrogen	1,5	45
Blue hydrogen	2	60
Green hydrogen	5	150

4 Operating costs of the cogeneration unit

Once the fuel prices, the consumption of the cogeneration unit and the fuel input, which were calculated before, are already known, it is possible to calculate the hourly costs of operation. First of all, it is necessary to determine the fuel consumption expressed in kW, necessary for operation during one hour, when the cogeneration unit can produce electricity and heat. It was calculated that the input power in the fuel of this engine is 101,35 kW. The comparison of different amount of hydrogen mixed with natural gas were made. The results of the calculations are shown in the Figure 3.

After analyzing the results of the calculations, it was found that gray hydrogen is definitely the most advantageous from an economic point of view, blue hydrogen is a little worse, and due to the still high price of green hydrogen, this type of fuel is not yet worth using, respectively, it is interesting to observe the trend of increasing the price of natural gas, which helps green hydrogen to become more convenient. Currently, we can expect that the price of natural gas should continue to rise in the coming months. Therefore, new solutions and technologies are currently being sought to replace this fossil fuel.

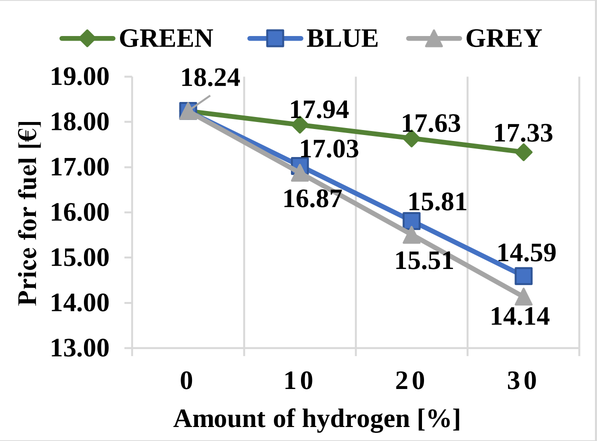

Figure 3 Costs of one hour operation

Although natural gas is the most advantageous of all fossil fuels from the point of view of air pollution and the overall production of emissions when it is burned, it is still moving in the direction of reducing its use. And that's for various reasons, whether it's geopolitical conflicts or others, it is needed to start thinking about other alternatives. Another of the reasons that basically force us to reduce the use of natural gas are new legislative rules, regulations or obligations towards the European Union, since the Slovak Republic is a member of it. One of the alternative solutions is the use of cogeneration technologies, which can be proven to save both money and energy and, last but not least, produce a smaller amount of emissions. Natural gas has been used in various types of combined production of electricity and heat in previous years, whether it is in combustion engines, combustion turbines, fuel cells, or, for example, in steam-gas technologies.

5 Conclusions

In the case that we have to consider other types of fuel, hydrogen appears to be one of the advantageous alternatives for the future. Recently, this topic has been appearing more and more, and we can expect a significant increase in its production and use for energy purposes in the coming months or years. Whether the use of hydrogen is effective, there is already something to think about, since its price, production, storage and transportation costs, as well as its availability, are not ideal. Three main types of this fuel were mentioned: gray, blue and green hydrogen. Of course, the most ideal solution for the future is to use green hydrogen, since almost no pollutants are produced during its production. But, as already mentioned, the main problem for now is its price, since its production using water electrolysis requires electricity, which has also become more expensive recently. Another problem may be that renewable sources are needed to produce this electricity used for green hydrogen. This can be a problem for some countries, as well as for Slovakia, where the use of these resources are limiting. As for blue hydrogen, it appears to be one of the better solutions at the moment, as it is much more affordable and at the same time the carbon emissions produced during the production of this type of hydrogen are captured and stored. The last remains gray hydrogen, which is by far the cheapest and, like blue hydrogen, is most often produced by steam methane reforming, but with the difference that no carbon emissions are captured. So we can consider this type of hydrogen to be disadvantageous in the long term. The common disadvantage of all types of hydrogen is the fact that it has high storage costs. But also in this direction, research is already dealing with new hydrogen storage technologies.

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