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Analysis of the potential of electro-waste as a source of hydrogen to power low-emission vehicle powertrains

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The decarbonisation of transport is one of the key aspects in the context of environmental protection. These emissions are particularly noticeable in highly urbanised areas, where the possibility of dispersal of harmful substances is much lower. A way to improve emission factors is the introduction of hydrogen vehicles. Burning hydrogen in engines significantly reduces emissions of harmful substances into the atmosphere compared to the combustion of conventional fuels used today. Hydrogen can be obtained by gasifying waste in a steam atmosphere. Electronic waste is a special type of waste characterised by a high degree of commingling, which makes it difficult to treat. The volume of this type of waste is increasing year on year. As a result of this process, we are able to obtain syngas. This gas, after separation processes, can be a source of hydrogen, an energy carrier that could prove crucial in low-carbon energy or transport applications. This paper presents the results of the gasification of electronic waste, the composition of the syngas obtained in the process and an assessment of the potential of this waste treatment technology to power means of transport.

Key words: *gasification, hydrogen drives, hydrogen, low-carbon transport, e-waste*

1. Introduction

Transportation development progress is key to the growth of societies which branches and consolidate the different elements of their sectors. For all intents and purposes, it is the "bloodstream" that distributes the goods produced. Developing countries are characterized by a burgeoning service sector, a thriving industry and, consequently, a growing transportation sector. A growing transportation sector can cause increasing emissions of harmful substances, particularly nitrogen oxides. As indicated by the European Environment Agency, the share of transportation in total greenhouse gas emissions is 28.5%. Road transport accounts for the largest share of all emissions at 20.5% [4].

To prevent such problems, new technologies are being developed to decarbonize modes of transportation and, consequently, the entire transportation sector. Both familiar conventional drives are being upgraded, but new vehicle concepts are also being developed. Recent years have seen particular growth in the electric vehicle market, but there is also a growing emphasis on increasing the share of hydrogen vehicles. The development of these two competing technologies is having a positive impact on the concept of decarbonizing the transportation sector. The aforementioned technologies can be applied to road and rail transportation, where they are already successfully occurring in many parts of the world. The use of hydrogen in vehicles can have two facets. The use of hydrogen can give a second life to internal combustion engines used in transportation vehicles, but it can also be used in hydrogen cells. The potential of hydrogen technologies is particularly studied by the countries of northern and western Europe [8].

Electric and hydrogen vehicle technologies are competitors for each other in the market. However, hydrogen technologies in means of transportation have features that can be qualified as their strengths. First and foremost among these features, it is worth noting the short refueling time of the vehicles and the greater range of the vehicles. Thus, they seem to be an ideal alternative to electric vehicles for long distances [7]. In addition, the use of hydrogen in traditional internal combustion engines means that we will have a modern fuel in a proven propulsion design, making it easier to operate and reducing unwanted events.

Hydrogen vehicle technologies also have advantages in terms of propulsion system design. Hydrogen tanks monitored in the vehicles do not require rare elements for their construction, which distinguishes them from electric vehicle traction batteries. The world's supply of lithium, among other elements, is a serious constraint on the construction of electric vehicles and thus can be a major barrier to their development. Hydrogen vehicles have no such barrier, and the various ways of producing hydrogen through renewable and conventional processes provide ample access to the energy carrier.

According to the study by Ściążko et al. [19] hydrogen vehicles will already account for about 10% of total vehicles in 2030, and in 2050 their share of the automotive market will be about 60%. The study also indicates that electric vehicles will develop their market share but from 10% in 2030 to 25% in 2050 [19]. The disparity between the technologies being developed clearly shows that hydrogen vehicles are the future of low-carbon transportation. These technologies can keep classic internal combustion engines in use, and the development of green technologies for hydrogen generation, could prove crucial for the transportation sector and improving the quality of life.

2. Streams and characterization of e-waste as a potential source of hydrogen

The characterization of electronic waste as a potential source of hydrogen would have to be divided into two main axes. In order for this waste to be useful in terms of its use as a feedstock for the gasification process, it is important to know the characteristics of electronic waste and to know the streams of this type of waste. In particular, the second axis is very important in terms of potentially estimating the possibility of converting electronic waste in the gasification process.

2.1. Characteristics of electronic waste

Electronic waste is a very diverse group of goods, and consequently its composition can vary greatly depending on what type of equipment we are dealing with. According to the study by Forti, Baldé, Kuehr and Bel, we can distinguish 6 basic groups of electronic waste [6]. They include:

- temperature exchange equipment
- screens and monitors
- lamps
- large equipment
- small equipment
- small IT and Telecommunication equipment.

As can be seen, the waste groups can be characterized by different sizes and thus, by different shares of individual components in the product composition. There are particular problems in the department known as "large equipment". This waste is often generated, but there are numerous problems with its recovery. This type of electronic waste is deposited in places unsuitable for it, in wild dumps, and thus can negatively impact the local environment and threaten to contaminate the soil or water.

Electronic waste is characterized by a complex, integrated structure. Separating the various component fractions of devices is energy-intensive work. The development of the concept of gasification in a steam atmosphere makes it possible to solve the problem of both disassembling the individual components of the device and gaining access to reusable components. This allows easy access to rare or valuable elements such as copper [9].

Examples of electronic waste, the number of which is growing every year, are cell phones. They have the typical characteristics of electronic waste, that is, for example, an integrated structure. The stream of this type of waste is increasing due in part to technological advances and growing consumerism in rich countries.

The material composition of the sample phone is shown in Fig. 1.

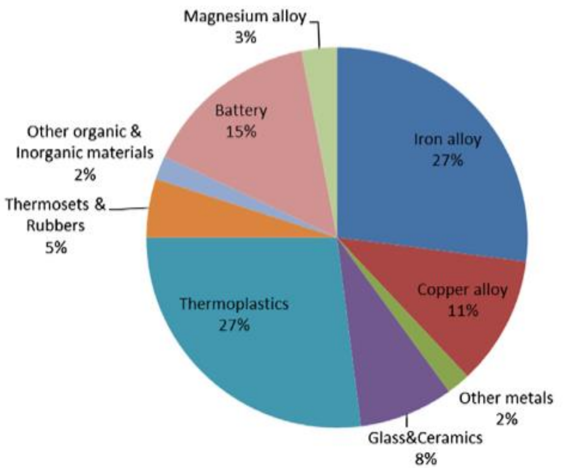

Fig. 1. Example of percentage material composition for a Nokia phone [20]

As Figure 1 shows, the composition of a standard cell phone is very complex. Most of the phone's composition is made up of various types of metals, with iron alloys making up the largest percentage. Thermoplastics account for the same percentage. The third component of the phone with the highest mass is the battery. Due to the large stream of this type of waste and the high proportion of polymeric materials in its composition, it can be a good substrate for the gasification process. In addition, the product after the gasification process is ready for material recycling of such components as copper alloys or magnesium alloys, among others. The process of gasification in a steam atmosphere has a positive effect on the process of disassembly of individual product components. Under the action of high temperature coming from steam, plastic components decompose and, with the gasification agent form syngas, which can be a hydrogen source after separation. This makes the plastic components, which are heavy to process, degrade, and can already be, in the form of a gas, an important element in terms of energy [20, 23].

Virtually every modern device is equipped with a printed circuit. This is one of the wastes that can be a substrate in the gasification process. In addition to it, devices are often equipped with various types of controllers, RAM or processors. This makes this type of waste stream advantageous in terms of its ability to be used as a potential source of hydrogen [23].

RAM may prove to be a particularly interesting waste. The popularity of RAM is increasing year by year. They are no longer used only in personal computers. The use of RAM can also be seen in modern vehicles, everyday devices such as smart coffee makers and televisions, and even smartwatches. The construction of RAM consists of two components, namely printed circuit boards and integrated circuits mounted on them. Materials in the form of RAM can be packaged in many ways, for example, using ceramic material [14].

Printed circuits can be characterized by different composition, which varies with the quality and proportion of materials used. According to the study "Valorization of Printed Circuit Boards from Electrical and Electronic Waste by Pyrolysis and Electronic Equipment by Pyrolysis", copper has the largest share in the construction of printed circuit boards and amounts to up to 27% by mass of the product. Metals account for about 40% of the product's mass and can be recovered in recycling after gasification. About 30% by mass is made up of plastics of various types, such as polyethylene and polyester. These plastics are very valuable in terms of treating electronic waste as a substrate in the gasification process. Their thermal decomposition in a steam atmosphere produces syngas [22].

2.2. Electronic waste streams

Electronic waste is growing every year, and the rate of increase in WEEE waste production is increasing. Parts of the world considered highly developed have a much higher per capita waste production. According to the study by Forti et al. [6], very high contrast in this regard is seen between Europe and Africa. Electro-waste generated per person in Europe is 16.2 kg, while for Africa, it is only 2.5 kg per person. At the same time, Europe is the leader of all continents in terms of the amount of electronic waste generated per person. Asia has the largest amount of electronic waste, with 24.9 Mt. The second largest amount of electronic waste is generated in North and South America, with 13.1 Mt. This shows a very large disproportion, and allows us to conclude that Asian countries such as Japan, South Korea and China place great emphasis on the development of electronic and electrical equipment, and are world leaders in this field, and therefore generate the most electronic waste [6].

We can conclude that the purchasing power of a selected part of the population clearly influences purchasing behavior, and, consequently the generation of electronic waste. This is related to a number of factors, one of which is certainly the standard of living that the selected groups prefer. A greater number of electronic equipment significantly increases the comfort of life, which in turn increases opportunities for development. We can observe a particular increase in the number of electronic equipment according to earnings in the case of laptops and cell phones. These relationships are shown in Fig. 2.

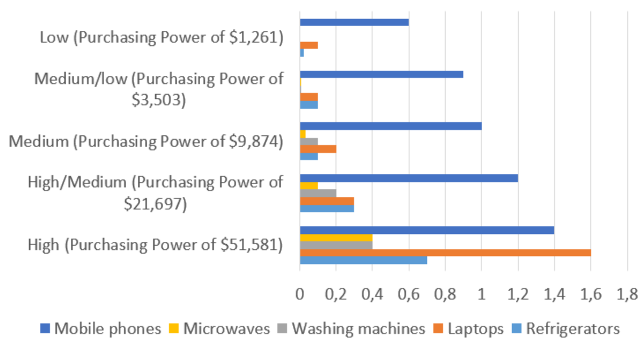

Fig. 2. Effect of purchasing power on the number of electronic devices owned [6]

As the graph in Fig. 2 shows, technological advances are making a significant contribution to increasing e-waste streams, thereby increasing the number of potential substrates that can be used in the gasification process [6].

The development of technology can be seen very well from the growth of the various sections of electronic waste. The increments were studied over the period from 2014–2019. During the period under review, electronic waste qualified as "Temperature exchange equipment" grew the most, with a 7% increase [6]. This indicates a pronounced trend in replacing equipment responsible for maintaining thermal comfort indoors. The new devices are characterized by higher efficiencies and lower energy consumption, which is beneficial from the point of view of consumers. In addition, the trend of using reversible heat pumps may increase the waste stream in this area, as may the increasingly popular use of photovoltaic panels. Photovoltaic panels are included in the division of large equipment, which growth in the period under review is 5%. In addition to them, the division includes washing machines and clothes dryers, for example. These are usually large appliances, problematic in terms of their transportation to waste disposal sites. The aforementioned photovoltaic panels are a very interesting and forward-looking type of waste. The popularity of the development of photovoltaic installations is very high especially for private entities. Taking into account the life cycle of photovoltaic panels and their decreasing efficiency with age will make them a large waste stream in 15–20 years. Increases in this area are already evident, as the first photovoltaic installations are just reaching the end of their life cycle. The amount of waste photovoltaic panels is shown in Fig. 3.

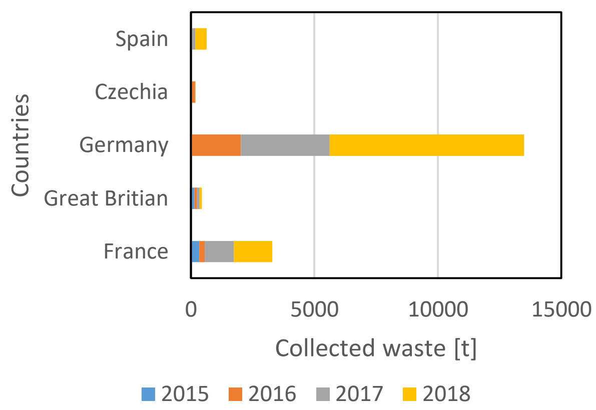

Fig. 3. Collected photovoltaic panels in selected countries in 2015–2018 [5]

3. Reverse logistics of e-waste

The issue of the amount of waste generated is only one component in the context of electronic waste management. An equally important issue is the aspect of waste collection and "recovery" after the device has completed its life cycle. This factor is very important, since it is not the number of wastes generated that really matters for the treatment process, but the number of wastes retrieved after the device has completed its useful life.

Europe compares very well with the world, where the amount of collected and reused electronic waste oscillates around 5.1 Mt, which is about 42.5% of the generated electro-waste. This result compares very well with other continents. In comparison, the percentage of electronic waste collection and reuse is 11.7% for Asia, and only 0.9% for Africa. This shows that the level of electronic waste collection stands at a low level in the world. Even in the case of Europe, it shows that 57.5% of electronic waste is not re-collected and reused [6].

According to the study by Nowakowski, the level of waste collection in Poland in 2015 was 38.38% [15]. Juxtaposing this with the previous figures, it appears that Poland compares quite positively with the world in terms of the amount of electronic waste re-collected, but further, the numbers are far from the high efficiency of electronic waste return logistics.

While the level of bulky waste collection is not at a low level, as it is about 41.84% in Poland as of 2015, the mass of waste that remains uncollected is by far the largest, at about 154 608 t [15]. This shows that bulky waste collection has a very large impact on the electrical and electronic waste stream and can be a very important source both in terms of recycling metals and also being a substrate in the gasification process.

Several issues are important in the development of e-waste reverse logistics systems. The subject of electronic waste should be approached holistically both by developing people's awareness in the context of environmental education and the scope of their responsibilities in the context of electronic waste, as well as an information campaign on waste collection points or treatment options. It would also be advisable to consider forms of gratification for people for fulfilling their obligations to segregate waste, especially electronic waste, as they can be a threat to the environment. The gratification concept could include, among other things, reducing the tax on the purchase of new electronic devices, assuming documented e-waste donation or reducing the waste disposal fee.

An important element in reverse logistics is the inspection stage of the received product. Not all previously used equipment or machinery has to be disposed of. Many components can be reused after appropriate processing or certain modifications. It is therefore important that the equipment is thoroughly inspected and properly categorized. This makes it possible for some machine and equipment components to have a longer life cycle and last longer as part of a new product [3, 15].

The use of mobile apps as an enhancement to the electronic waste collection process seems to be an interesting idea. The use of this method requires proper preparation of the application, or website. The idea is that any interested person can report the need to donate e-waste via the Internet. The database collects information on the type of waste and its mass or size, and the company's dispatch center makes a decision on the scheduled transport. An ideal improvement would be to incorporate artificial intelligence or neural networks into the operation of such a system. This would reduce the need for human labor, and the neural networks, after repeated processing, would be able to match optimal routes and means of transportation for the selected type of electronic waste [16].

E-waste reverse logistics, therefore, needs a highly interdisciplinary approach based on the cooperation of both transportation, IT and environmental specialists. The joint efforts of these aforementioned industries are able to guarantee an increased volume of waste received, and thus increase the stream of potential substrates for hydrogen production.

4. The gasification process.

Gasification is a process in which a given raw material is converted into a gas with the help of an oxidizing agent. It is the oldest technology for obtaining hydrogen. It is stated to be an intermediate process between combustion and pyrolysis. The temperature of the process is between 600 and 1000°C and the raw materials for the process can be either waste, biomass or fossil fuels. The composition of the gas resulting from the aforementioned process depends on a number of factors, which are its components. The composition of the gas depends on the substrate used in the experiment, the temperature of the process, the pressure used and the agent used for gasification. Among the reactants we can distinguish oxygen, steam, air or carbon dioxide, among others [9]. Processes based on the steam medium reach a hydrogen level of about 40% in the syngas mixture [12].

The gasification process is particularly useful in the processing of integrated products whose components may be valuable. The use of gasification for the processing of electronic waste makes it possible to obtain syngas from which, after appropriate transformation, we are able to obtain pure hydrogen and recover rare raw materials from the residue of the substrate after the gasification process. The composition of syngas is hydrogen, carbon monoxide, methane, carbon dioxide, nitrogen and steam [9].

Gasification may be carried out in the presence of a catalyst to improve the synthesis process and eliminate organic phases [9]. The use of a suitable catalyst is very important when it comes to creating syngas. Among the most important features of a suitable catalyst we must certainly include its price and availability on the market. Among the catalytic deposits, it is worth mentioning such active substances as dolomite, calcium oxide or iron oxide [18].

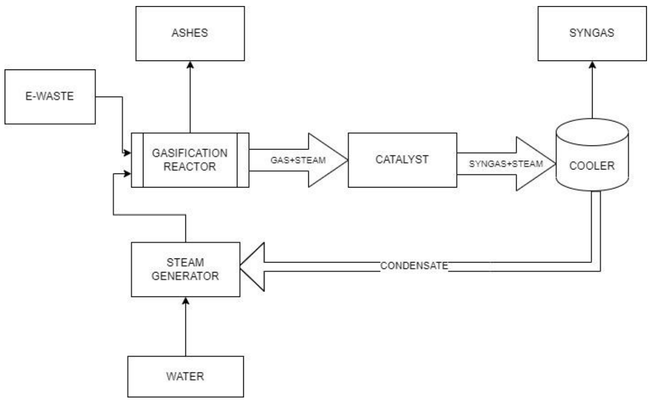

Fig. 4. Gasification process of electronic waste in a steam atmosphere

As shown in Fig. 4, the electronic substrate gasification scheme has its own closed circuit. The weakest point in the process appears to be the steam generator. It needs a power source, and thus a good solution would be to couple the gasification plant with a source of renewable energy. This would lower the economic cost of producing hydrogen, and the use of electricity from renewable energy sources would also lower the carbon footprint.

The gasification process supported by renewable energy sources is a very interesting concept. The cost of producing a kilogram of hydrogen by gasification is between $1.21–$3.5 and could be reduced by using renewable sources in the process [12]. Research on this topic includes both solar, wind and geothermal energy concepts. Concepts are also being developed for hybrid or cogeneration systems using waste heat of the process. Geothermal systems are a particularly interesting alternative for Polish conditions knowing our conditions regarding geothermal deposits. In addition, biomass, both waste and energy crops, can be used in the substrate gasification process. This makes the process capable of coming from renewable sources, and the resulting hydrogen can be an important factor in balancing energy systems [12, 13].

Current global trends promote low-carbon energy and low-carbon transportation. The gasification process seems to be an ideal solution to such problems. It makes it possible to manage various types of waste, such as electronic waste, plastics or sewage sludge, which can become substrates for the process. The process makes it possible to produce hydrogen, the use of which can be very wide, both in low-emission transportation, including internal combustion engines, as well as in the power industry for fueling gas turbines.

5. Separation of hydrogen from syngas.

The final product of the gasification process is syngas, which is a mixture of various elements, including hydrogen, carbon dioxide, methane, carbon monoxide or nitrogen. Among the side effects of the process, we can distinguish tars or ashes [17].

To obtain a carrier of clean energy in the form of hydrogen from syngas, several separation steps are needed. For industrial-scale systems, the first step is to use water reforming to increase the proportion of hydrogen in the mixture. The next step is to use one of three hydrogen purification and separation methods. These methods are PSA (Pressure Swing Adsorption), cryogenic distillation, and membrane techniques. Depending on needs, the hydrogen energy carrier can also be further purified using specialized equipment [2].

Among the methods mentioned, membrane separation methods are particularly noteworthy. The main division of membranes is the composition of their structure. Thus, we can distinguish between organic, inorganic and composite membranes. The advantage of their use is the absence of waste, as they are a physical barrier. Other advantages of such methods include the ease of operation of the hydrogen separation plant or the possibility of producing hydrogen in a continuous process. This is very important in the context of building a gasification plant with the possibility of continuous batching on a process scale. The sequestration of hydrogen in a continuous process allows the possibility of continuous production to be maintained, and thus gasification can be a stable process that does not destabilize the energy system or hydrogen-based transportation systems [2].

In the separation of hydrogen from syngas, it is also possible to use so-called chemical loops. The first step, as with the previous methods, is hydrogen enrichment by water reforming. The water reforming process is responsible for the conversion of carbon monoxide into carbon dioxide, which is automatically absorbed by the calcium oxide sorbent. Then, in the regeneration stage, the gas with oxygen is fed into the gasification reactor. The gas is designed to oxidize the iron-based catalyst. During this time, the sorbent that previously absorbed the carbon dioxide is decomposed by the acting heat and releases the previously stored compound. Thus, the separation process contains two chemical loops, one involving the activity in the catalyst reactor, the other involving the action of the sorbent [10].

6. Gasification of electronic waste

The gasification of electronic waste was performed according to the scheme shown earlier in Fig. 4. The substrate in the gasification process was RAM memory. The experimental system is divided into a gasification zone, where the feedstock lands, and a catalyst zone, which in the case of the study conducted was dolomite. The gasification agent was steam. Two survey samples were conducted. The table below summarizes the parameters of the two test samples.

Table 1. Results of the gasification process

Process components	Experiment 1	Experiment 2	Units
Mass of the charge before the process	120.54	194.56	[g]
Mass of the charge after the process	92.6	156.15	[g]
Mass loss	27.94	38.41	[g]
Mass loss	23.18	19.74	[%]
Mass of water placed in the steam feeding flask	398.21	279.35	[g]
Mass of water remaining in the steam feeding flask	18.37	194.74	[g]
Mass of water given in the process	379.84	84.61	[g]
Steam feeding time	295	293	[min]
Average steam output	1.29	0.29	[g/min]
Condensate mass	267.15	35.1	[g]
Steam/water loss	112.69	49.51	[g]

As can be seen in Table 1, samples containing RAM had different weights. In the case of the first experiment, a higher proportion of the gasification medium was also evident, with a consequent increased amount of condensate. Figure 5 and 6 show the gasification process waveforms.

Figure 5 and 6 show that gasification in experiment two took less time than in example one. The reactor heating rate was the same for both experiments. The maximum reactor and catalyst temperatures for both experiments were the same. We can also deduce from Fig. 5 and 6 that the steam feeding started 28 minutes earlier in experiment 2 than in experiment 1. In the case of experiment 1, there were spikes in the temperature of the catalyst, while in experiment two the temperature course was harmonic. The P1 sample for experiment 1 was taken 88 minutes after the start of steam injection, while the P1 sample for experiment 2 was taken 53 minutes after the start of steam injection. Despite this difference, the samples have similar compositions. Table 2 shows the composition of the gases that are the product of the gasification process.

Table 2. The results of the analysis of gases produced from the gasification process

	Experiment 1		Experiment 2			Units
Gas analysis	Sample P1	Sample P2	Sample P1	Sample P2	Sample P3	
CO	17.32	1.33	17.51	12.66	11.05	[%Vol]
CO_2	50.62	28.1	57.24	58.2	60.74	[%Vol]
0_2	5.96	7.09	3.44	4.13	3.74	[%Vol]
HC	667	26	1050	402	142	[ppm Vol]
NO	–34*	–8*	7	9	–21*	[ppm Vol]
Lambda	0.939	1.144	0.918	0.957	0.966	–
Gas flow rate	2.0	0.9	–	1.4	1.4	[dm^3/min]
Estimated share of H_2	27.71	2.13	28.02	20.26	17.68	[%Vol]

*The minus results are due to the measuring range of the instrument.

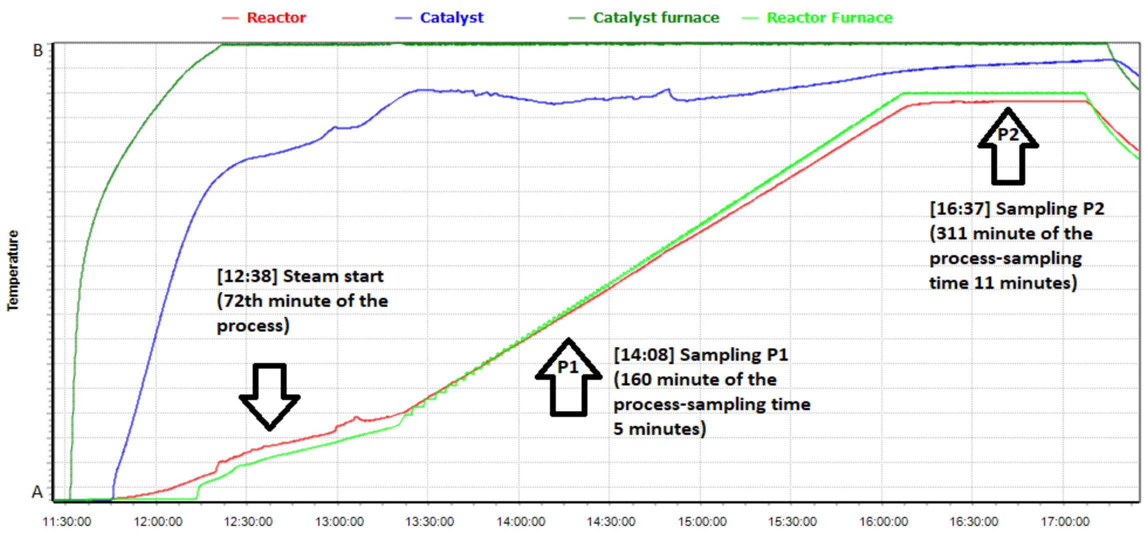

Fig. 5. The course of the gasification of the first experiment

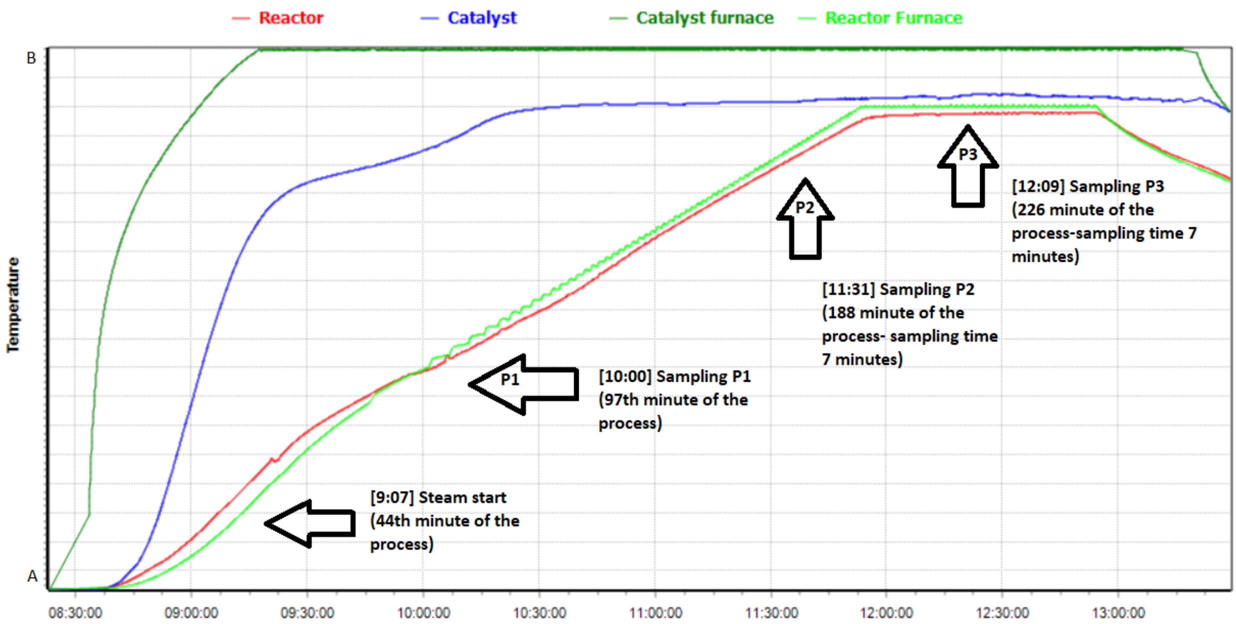

Fig. 6. The course of the gasification of the second experiment

The first gas samples were taken while the catalyst was heating up, when its performance was at a high level. This can be seen in the higher gas flux values. Once the catalyst reaches heating, its efficiency decreases over time, as does the gas flow rate. The initial phases of gasification also release the most hydrocarbons, which are the source of our interest. Over time, the presence of carbon oxides in the mixture also decreases. The highest flow rate is about 2 dm^3/min, which would yield about 0.55 dm^3 of hydrogen per minute. The estimated proportion of hydrogen was calculated by knowing the ratio of H_2 to CO. According to the literature, this ratio is 1.6 [12]. These values should be considered indicative, taking into account possible measurement errors when examining the gas composition and the potential inaccuracy of the method.

The materials lost between 19–23% of their mass after the gasification process. The remaining materials were characterized by a black color, visible copper layer of RAM. Behind the catalyst, chromium precipitated as a yellow precipitate. The material is recyclable, and the plastics have mostly oxidized to form syngas.

7. Summary and conclusions

Waste gasification technologies are a very important step towards sustainable and low-emission transport, especially since most of the hydrogen is produced in the process of reforming fossil resources [11]. Using waste, especially electronic waste, as a source of hydrogen for vehicles seems to be a solution with many advantages. In particular, we manage waste, a thing unnecessary for the environment, and get the opportunity to recover important raw materials from the waste, and as a gaseous product, a fuel that can power vehicles.

The use of purely hydrogen-powered engines is an object of further research and requires a lot of money, while the use of engines combining hydrogen with diesel fuel is already a possible implementation. Such engines can achieve peak efficiencies of up to 50%, which compares very well with internal combustion engines powered by conventional fuels. The use of such a fuel mix also reduces emissions in the city, which is crucial in the context of sustainable urban development and low-carbon transportation systems, especially urban transportation [1]. In addition, hydrogen blended with biogas can further reduce the share of hydrocarbons in emissions and this is also one potential avenue for development [21].

Electronic waste as a process input is characterized by a high flux, and thus a high level of availability. The gasification process is an ideal solution for both the energy use of this waste and its disposal, thus offsetting its environmental impact. Plastic materials or epoxy resins used in electronic products are a very important part of the syngas that is formed afterwards. By combining the gasification process with renewable energy sources, the cost of the process is reduced and the emission burden will be even lower. The ecological process of producing hydrogen, as well as the characteristics of this energy carrier, make the application of the process a future-proof solution worthy of further study, and hydrogen is a great element for application in both the professional energy and automotive markets.

Nomenclature

WEEE	Waste of Electrical and Electronic Equipment
PSA	pressure swing adsorption
IT	information technology
RAM	random-access memory
E-waste	electronic and electrical waste

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