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# Energy Inputs on the Production of Plastic Products

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**ABSTRACT**

The paper considers plastic products in terms of energy consumption at two stages of their life cycle, i.e. at the stage of production of virgin polymers and at the stage of processing polymers into a finished product. Energy intake places were indicated and energy needs related to the production of polymer products were assessed. This allowed to indicate which polymer production and processing processes into finished products are particularly energy-intensive. The research shows that the greater the amount of energy accumulated in the plastic during its production, the greater the importance of this plastic in the post-consumer phase as a recyclable material. Recycling of waste plastics allows the use of this energy and reduces the consumption of virgin raw materials. Primary polymers were compared in terms of the energy efficiency index of their production process. This indicator is the quotient of the calorific value of the polymer and the energy consumption in its production. It shows how much of the energy input during the production of primary plastic can be recovered from the thermal processing of the waste plastic. The highest indicator value was obtained for polyethylene and polypropylene. It was found shown that the total energy consumption (converted to primary energy) of the PET virgin polymer production process and its processing into packaging reaches the value of 109.2–115.2 MJ/kg. This is almost five times the calorific value of this polymer.

**Keywords:** energy consumption, primary polymers, plastics as energy storage, energy consumption in polymer processing.

## INTRODUCTION

The plastics industry currently uses mainly substances produced in the processing of crude oil [Wróbel et al. 2015, Ptak et al. 2016] and natural gas [Kaminsky 2021]. These processes require energy input, and the amount of energy consumption is influenced by, among others, the type of processing installations. The substances obtained in these processes constitute the raw material for the production of polymers. Energy is also needed to carry out this production. The processing of polymers for final plastic products also requires energy supply.

The economics of energy-intensive processes can be favourably influenced by access to cheap energy carriers. For example, in EU countries, gas prices for industrial customers in the first half of 2019 ranged from 0.02 EUR/kWh (Belgium) to 0.06 EUR/kWh (Finland) (EU average price: 0.03 EUR/kWh) [Natural gas Eurostat 2021]. For comparison, in the USA, the average price of natural gas for industrial customers is 130 USD/1000 Nm$^3$ (Nm$^3$ – normal cubic meter) (as of January 2020) [Natural gas, EIA 2022] – approx. 56% lower than the average price in the EU (0.03 EUR/kWh = 297 USD/1000 Nm$^3$; the calorific value of natural gas 33 MJ/Nm$^3$ and the exchange rate 1.08 USD/EUR were used for conversion). The fact that the USA has its own shale gas reserves and their development may affect the low level of natural gas prices in this country. According to Alsabri et al. (2021) access to 1/3 of the world's oil and natural gas resources in the Gulf Cooperation Council region has enabled and allows for the further development of the chemical and petrochemical industries in this region. As a consequence, the Gulf Cooperation Council is now the main producer and exporter of polypropylene in the world [Alsabri et al. 2020].

The results of the assessment of energy expenditure on the manufacture of plastic products will vary depending on the approach to the assessment. The comprehensive approach takes into account energy needs already at the stage of obtaining primary raw material (oil, natural gas), further at the stage of polymer production and then at the stage processing of polymers for final products.

The aim of the study is to present the impact of manufacturing plastic products on energy consumption and to learn how much energy was accumulated in these products. As part of the implementation of the aim of the study, the places of energy consumption at two stages of the life cycle of a plastic product (production of virgin polymers and processing of polymers into a finished product) were presented. Identifying these places can be important in reducing energy consumption. The considerations are to show that plastics are an energy store. The more energy is stored in the plastic during its production, the more important the plastic is in terms of the amount of energy that can be recovered in the recycling process.

Six polymers (polyethylene (PE), polypropylene (PP), polystyrene (PS), polycarbonate (PC), polyvinyl chloride (PVC), bottle-type polyethylene terephthalate (PET)) and typical polymer processing processes were adopted as the research area.

## RESEARCH METHOD

The method of analysing energy consumption at the stage of production of the considered primary polymers and at the stage of polymer processing using basic types of processing processes was used. Primary energy consumption was tested. The analysis was carried out on the basis of data from companies specialising in the production of polymers and plastic products. In addition, scientific publications, databases and studies of research centers were the source of the data.

## ENERGY NEEDS AT THE STAGE OF PRODUCTION OF VIRGIN POLYMERS

In the comprehensive approach to the assessment of energy consumption in the production of virgin polymers, the stage of obtaining virgin raw material (oil, natural gas) is already taken into account. The next stage is the production of polymers using this raw material.

At the virgin raw material acquisition stage, the energy consumption for exploration and preparation of the raw material deposit for exploitation, extraction, storage and transport of the raw material to processing plants is assessed [Ahsby 2012].

The polymer production stage includes processing (refining) processes of the primary raw material, resulting in components for the production of polymers, as well as the obtaining reactions and preparation of polymers to a form compatible with the requirements of the recipients.

For example, the base component for the production of polyethylene is ethylene. It is produced in the process of steam cracking of hydrocarbons, the main sources of which are naphtha (a product of crude oil distillation) and ethane (obtained from natural gas) [Vlachopoulos 2009, Ghanta et al. 2014]. As a result of the polymerization of ethylene, polyethylene is produced. There are several methods of polymerization depending on the type of product produced [Benchaita 2013].

Operations adapting polymers to the requirements of buyers consist in granulating polymers and mixing the granules with substances improving its properties.

In a narrower approach to assessing energy consumption, the starting point is the step of processing the primary raw material into intermediates needed subsequently in the chemical reactions of obtaining monomers. The next stages are the production of polymers and their preparation to the form compliant with the requirements of buyers. There is also an approach in which only two main steps are taken into account: production of monomers and production of polymers [Alsabri et al. 2021].

Table 1 shows the primary energy consumption for the production of typical petroleum-based polymers. These data, quoted by Engelbeen [Gervet 2007], are the result of a comprehensive approach to assessing energy inputs. The indicator “energy consumption from crude oil” involves the energy contained in the hydrocarbon fractions (obtained from crude oil), which are the raw material for the production of polymers. This energy is called the feedstock energy. In addition, it takes into account the energy from crude oil or its transformation products used as fuel in the processing processes in which monomers and, based on them, standardised plastics are produced. This energy is known as process energy. For example, the main processing processes for making polyethylene are steam cracking and polymerization.

The value of the indicator "energy consumption from energy carriers other than oil" (Table 1) consists of the consumption of energy obtained from fossil solid (coal) and gaseous fuels (natural gas) and renewable energy. These energy carriers are used to generate the heat and electricity needed in polymer production processes. The consumption of energy contained in these carriers was determined on the basis of the amount of electricity and heat consumed and assuming an average efficiency of mixed electricity production (based on various energy carriers) at the level of 40%. Increased efficiency of electricity generation means a lower value of the indicator "energy consumption from non-oil energy carriers". Total energy consumption (Table 1) is the sum of "energy consumption from crude oil" and "energy consumption from energy carriers other than oil".

In the calculations of raw material consumption (Table 1), petrol was considered and it was assumed that for the production of 1 $dm^3$ of petrol 0.9 kg of crude oil was needed [Engelbeen, Tamoor et al. 2022]. For example, the value of the index "energy consumption from crude oil" 55 MJ/kg PE (Table 1) was calculated as the product of the mass of oil (1.25 kg) and its calorific value (44 MJ/kg) – from this amount of oil it is possible to produce 1.06 kg of petrol (petrol density is assumed to be 0.76 $kg/dm^3$). In other words, to produce 1.06 kg of petrol, it takes 55 MJ of the energy contained in oil. On the other hand, the consumption of raw material (petrol) at the level of 1.35 kg/kg PE (Table 1) was obtained on the assumption that the energy needs of 70 MJ/kg PE will be covered only by energy from crude oil.

The values of energy consumption for the production of polymers reported in the literature show wide variation: PE-LD: 64.6–92 MJ/kg, PP: 64–111.5 MJ/kg, PS: 70.8–118 MJ/kg, PC: 78.2–117.4 MJ/kg, PVC: 52.4–79.5 MJ/kg [Thiriez et al. 2006, Vlachopoulos 2009, Iwko et al. 2019]. The discrepancy in values is influenced by the type of raw materials used for the production of polymers (naphtha or gas oil obtained from crude oil, ethane derived from natural gas), the final form of polymers (flakes, granules), process energy source and the efficiency of processing processes.

Ghanta et al. (2014) considered the impact of the type of raw material on energy consumption in the steam cracking process used to obtain, inter alia, ethylene and propylene. According to these authors, the energy consumption for steam cracking of naphtha is 20.1 MJ/kg of ethylene, and of ethane 13.7 MJ/kg. Natural gas was considered as the source of process energy.

The energy demand in the polymerization process to obtain PE-LD is 8.53 MJ/kg [Benchaita 2013], and PE-HD 5.43 MJ/kg [Vlachopoulos 2009]. These values are a weighted average in the European Union (EU).

According to Vlachopoulos (2009), the modernization of the steam cracking installation resulted in a reduction of energy consumption by about 50% compared to 1970.

The calorific value of the plastic (Table 1) expresses the amount of heat that is generated during the complete combustion of the plastic mass unit. The quotient of the calorific value of the plastic and the total energy consumption in the production of the plastic indicates how much of the energy input can be recovered as a result of the thermal treatment of the waste plastic. The highest quotient for the data in Table 1 was obtained for polyethylene and polypropylene (0.61 and 0.60, respectively). Marczak (2019) and Rashid et al. (2015) considered the energy

**Table 1.** Primary energy consumption in the production of selected plastics (based on [Engelbeen])

| Polymer | Energy consumption [MJ/kg] | | | Raw material consumption (petrol) [kg/kg] | Calorific value [MJ/kg] |
|---|---|---|---|---|---|
| | Total | From petroleum | From other sources of energy than petroleum | | |
| Polyethylene | 70 | 55 | 15 | 1.06-1.35 | 43 |
| Polypropylene | 73 | 58 | 15 | 1.11-1.40 | 44 |
| Polystyrene | 80 | 55 | 22 | 1.06-1.54 | 40 |
| Polycarbonate | 107 | 36 | 71 | 0.69-2.05 | 31[1)] |
| Polyvinyl chloride | 53 | 24 | 29 | 0.46-1.02 | 18 |

**Note:** [1)] [Castro-Aguirre et al. 2016].

**Table 2.** Production of selected plastics in the EU and Poland [Industry, trade, Eurostat 2022, Statistical Yearbook, GUS 2021]

| Product type | Production [thou. Mg] | | | | | |
|---|---|---|---|---|---|---|
| | EU | | | Poland | | |
| | Year | | | | | |
| | 2018 | 2019 | 2020 | 2018 | 2019 | 2020 |
| Plastic in primary forms of which: | 61800[1)] | 57900[1)] | 55000[1)] | 3456 | 3627 | 3682 |
| Polyethylene | 12310.1 | 11733.4 | 11643.2 | 346 | 383 | 348 |
| Polypropylene | 10755.5 | 10471.5 | 10090.7 | 287 | 351 | 351 |
| Polymers of styrene | 5590.0 | 5708.6 | 5121.1 | 146 | 175 | 168 |
| Polyvinyl chloride, not mixed with other substances | 5311.7 | 5160.1 | 4953.9 | 255 | 243 | 295 |
| Plasticised polyvinyl chloride mixed with any other substance | 917.9 | 880.6 | 726.5 | 108 | 107 | 94.2 |
| Polyamides | 2763.9 | 2580.8 | 2259.4 | 194 | 192 | 189 |

**Note:** [1)] [Plastic Europe 2021].

benefits of producing fuel fractions from waste polyethylene and polypropylene. Sahajwalla et al. (2012) and Sorek et al. (2012) presented the results of research indicating the suitability of plastic waste for energy use in metallurgical processes. The data presented in Table 2 show that polymers PE and PP occupy a dominant position in the production of plastics in the EU and Poland. The production of PE and PP also has a significant share (46%) in the global production of plastics [Kozera-Szałkowska 2019]. In 2020, the production of plastics in the world amounted to 367,000 thousand tons [Plastic Europe 2021]. The PE and PP polymers are formed by polymerisation of ethylene and propylene, respectively. Olefins are also a raw material for obtaining other plastic, including PVC, PS, PET. Literature data [Migdał et al. 2014] show that energy expenditure on oil extraction and on the processes of production of an intermediate product for the production of olefins from oil represents up to 20% of the total energy demand for the production of olefin-based plastic. Other places of energy expenditure are processing of the semi-finished product into monomers (olefins), chemical reactions leading to the formation of polymers and forming processes (e.g. granulation).

## ENERGY INPUTS AT THE STAGE IN THE PRODUCTION OF PRIMARY PET IN THE BOTTLE VARIANT

In European plants producing virgin bottled PET from raw materials derived from fossil fuels, the average primary energy demand (taking into account the upper calorific value of fuels) is 71.2 MJ/kg of polymer. These data relate to the method of producing PET directly from terephthalic acid and ethylene glycol. This method was gradually introduced from 1970 and is now the most widely used [Dias et al. 2021]. In the production of PET according to an older method, dimethyl terephthalate is used instead of terephthalic acid [Benavides et al. 2018]. The main fossil fuels on the basis of which the raw materials for the production of PET are made are crude oil and natural gas. In practice, there are installations for the production of PET that rely on raw materials obtained exclusively from the processing of crude oil [Singh et al. 2021, Tamoor et al. 2022] and those in which the source of raw materials is both crude oil and natural gas [Franklin Associates 2010].

Energy needs (71.2 MJ/kg on average) are covered mainly with energy from non-renewable energy sources (69.6 MJ/kg on average) and, to a small extent, with renewable energy (1.6 MJ/kg on average) (Table 3).

Energy from non-renewable sources is the sum of feedstock energy and energy used to implement the PET production process (Table 3). The energy used in the production process consists of the energy of the fuel used in the extraction of minerals (crude oil and natural gas), in the transport of these minerals to petrochemical plants, in the processing of crude oil and natural gas, in the synthesis reaction (esterification) of monomers and in the polymerization reaction (polycondensation) of monomers, as well as to transport of materials and raw materials in all phases of the PET production process (Figure 1).

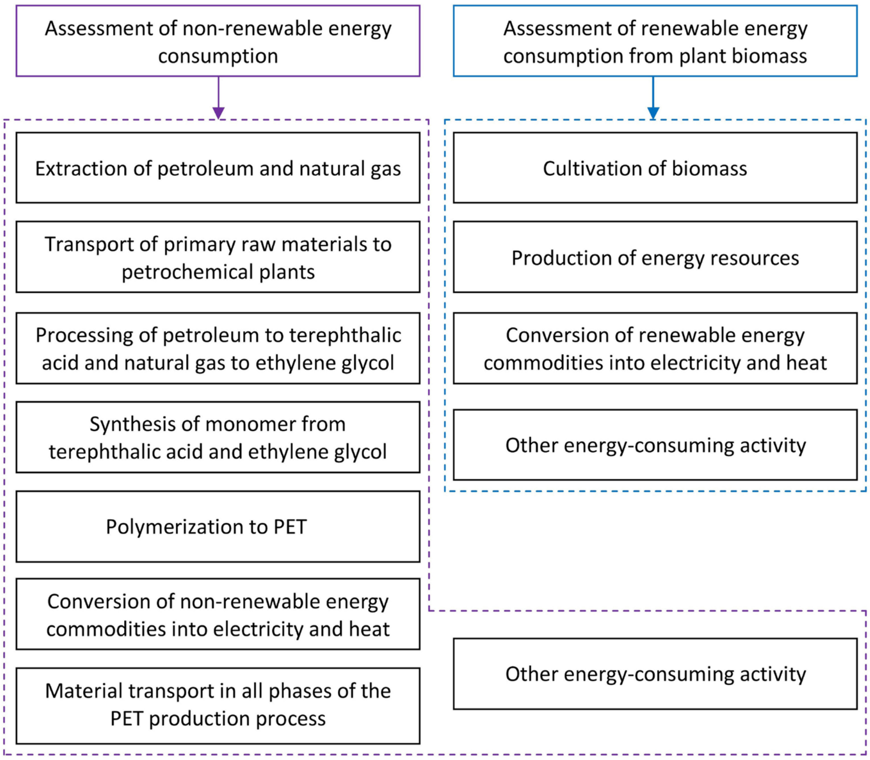


**Figure 1.** Elements taken into account in the assessment of energy consumption at the stage of producing virgin PET polymer in the bottle variety

The process of crude oil processing includes many energy-consuming processes: atmospheric distillation, hydrotreating, catalytic reforming, vacuum distillation, hydrocracking, catalytic cracking, steam cracking. The purpose of these processes is to obtain first para-xylene from crude oil and then (by oxidation of the para-xylene) crude terephthalic acid. Purified terephthalic acid (as powder) is one of the intermediates product to obtain PET.

The natural gas treatment process consists of a steam cracking process which products ethylene, which is a substrate for obtaining the ethylene glycol needed to produce PET.

Polymerization takes place in two stages. In the first stage, the polymerization takes place in the molten state, and its result is an amorphous PET used for the production of films and fibres. In the second stage, solid-state polymerization is carried out, in which PET of the bottle type (partially crystalline resin) is obtained. Solid-state polymerization enables PET with a higher molecular weight to be obtained.

The implementation of each process in the production of PET requires the use of a certain amount of electricity and heat. These energies are obtained from both non-renewable and renewable energy resources (plant biomass). Non-renewable energy used to generate electricity and heat includes chemical energy contained in fossil fuels and energy used in the chain of activities from fuel extraction, through processing, storage, to transport to combustion installations. On the other hand, the consumption of renewable energy from plant biomass consists of the chemical energy of biomass and the consumption of energy for the production of biomass (Figure 1).

Considering the demand for primary energy (as the sum of energy from fuels and raw material energy) at the PET production stage show that in European plants the average demand for fuel energy is 37.1 MJ/kg, and for raw material energy: 34.1 MJ/kg (Table 3).

In the structure of the consumption of primary energy carriers for the production of 1 kg of PET, the largest share is taken by energy from crude oil – approximately 66.1% (47.07 MJ), a smaller share is taken by energy from natural gas (23.4%), from hard coal (2.33%), lignite (1.52%), other sources (6.57%).

Figure 2 shows the consumption structure in the mass unit (kg) of primary energy carriers in the PET production process.

The steps of the PET production process can be ranked in descending order in terms of unit energy consumption (MJ/kg) as follows: production of para-xylene (54% of Total primary energy

**Table 3.** Primary energy consumption at the production stage of bottle-type primary PET (based on [Polyethylene, CPME 2017])

| Energy carriers | Consumption of energy contained in energy carriers [MJ/kg] | | |
|---|---|---|---|
| | Total | As a raw material for production | As a fuel |
| Petroleum | 47.07 | 32.41 | 14.66 |
| Natural gas | 16.74 | 1.73 | 15.01 |
| Hard coal | 1.66 | | 1.66 |
| Lignite | 1.08 | | 1.08 |
| Nuclear energy | 3.04 | | 3.04 |
| Renewable energy | 1.6 | | 1.6 |
| Total | 71.19 | 34.14 | 37.05 |

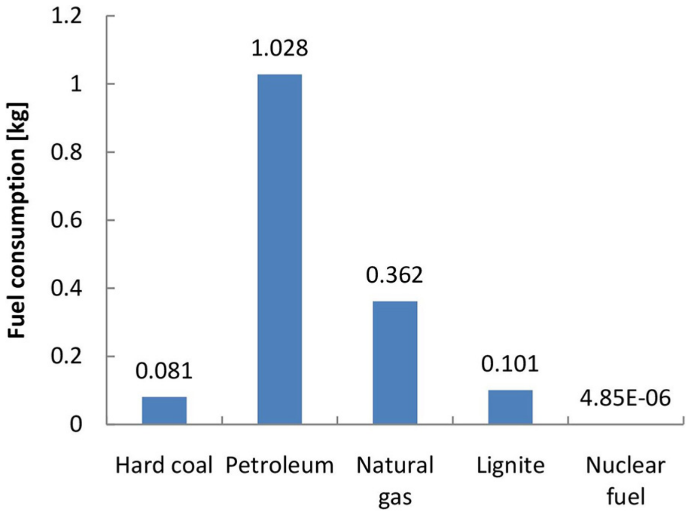


**Figure 2.** Consumption of primary energy carriers (expressed in kg/kg of product) at the stage of PET production in the bottle variety (based on [Polyethylene, CPME 2017])

demand), production of ethylene glycol (23.8%), production of terephthalic acid from para-xylene (13.6%), production of PET from semi-finished products: terephthalic acid and ethylene glycol (8%), transport of materials directly used in PET production (0.5%), other activities (0.1%).

The energy requirements at each stage take into account all activities. For example, energy consumption at the stage of para-xylene production is the sum of energy consumption in the chain of operations starting from the extraction of the necessary raw materials. At the stage ”production of PET from semi-finished products”, the value of energy consumption is the sum of energy consumption in the production process, as well as for the production of heat, compressed air and electricity, and for the preparation of water.

The energy content of PET plastic is 24 MJ/kg [Polyethylene, CPME 2017] (24.7 MJ/kg according to Franklin Associates (2010)). This parameter indicates how much energy can be recovered from 1 kg of waste PET. The value of the difference between the total contribution of primary energy to the production of PET and the calorific value of PET is a measure of the process energy (lost energy) that is converted into waste heat. The use waste heat is currently an important research issue.

## ENERGY INTENSITY OF IRON AND STEEL AND ALUMINIUM PRODUCTION

According to IEA [Iron and Steel, IEA 2021] data, the energy intensity of global iron and steel production in 2020 was 19.4 MJ/kg. Electricity covers approximately 13.4% of the final energy demand, and coal approximately 75%.

Martelaro (2016) reports that in the US, energy consumption for steel production (including pig iron production) using an oxygen furnace is 24.5 MJ per kilogram of steel produced (13.5 MJ per kilogram of pig iron). Steel production (starting with pig iron production) using an electric arc furnace requires an energy consumption of 15.75 MJ per kilogram of steel produced. The energy source for pig iron production is coking coal. Mainly coal or natural gas is used to power oxygen furnaces. Arc furnaces require electricity.

The global average unit electricity consumption in primary aluminium production in 2020 was 14.28 kWh/Mg (Table 4) [International Aluminium Institute 2021]. This value relates to the energy consumption of the Hall-Heroult process electrowinning of aluminium from alumina [Obaidat et al. 2018]. Electricity is mainly generated from coal, water and natural gas. According to Leisegang (2019), 9 to 12 kWh of electricity is needed to produce 1 kg of aluminium, with a process efficiency of 85 to 95%. In 2020, the average word energy consumption in the world of alumina production from bauxite (for the needs of aluminium production) was at the level of 10.522 MJ/kg of alumina (Table 5). To produce alumina, energy is needed mainly in the form of heat and steam. An important source of energy is the combustion of fuels, in particular coal and natural gas (Table 5). Approximately 0.5 Mg of primary aluminium is produced from 1 Mg of alumina [Tressaud 2019]. In view of the above world data, for 2020 the combined energy consumption in the production of alumina and primary aluminium in the world was average around 72.45 MJ per kilogram of aluminium (approx. 73.2% of this value is electricity). Converting to primary energy sources (efficiency of thermal power plants approx. 40%), this value is 152 MJ/kg of aluminium. The energy consumption of plastics production (Tables 1 and 3) expressed in primary energy is much lower than this value.

**Table 4.** Energy consumption of primary aluminium production (based on [International Aluminium Institute 2021])

| Parameter | Unit of measure | 2020 | |
|---|---|---|---|
| | | World | Europe |
| Electricity consumption | [kWh/kg] | 14.280 | 15.499 |
| | [MJ/kg] | 51.408 | 55.796 |

The production process of secondary aluminium consumes approximately 5% of the energy needed to produce primary aluminium [Kossakowski 2013].

## ENERGY EXPENDITURES IN THE PROCESSING OF POLYMERS FOR THE FINAL PRODUCT

The comprehensive assessment of energy consumption at the stage of polymer processing should take into account the energy expenditure on the transport of polymers to the processing plant, the processing of polymers into final products and the transport of finished products to packaging plants (Figure 3).

In the processing processes of polymers, only electricity is consumed, or both electricity and fuel energy. The amount of energy consumption is fundamentally influenced by the type (complexity) of the process and processed material, the characteristics of the final product (shape, form and size), as well as the type and specification of the machines and devices used (hydraulic, all-electric). In the processing, injection moulding, thermal moulding, pressure moulding, rotating moulding and extrusion moulding processes are used. The cycle of each moulding process consists of specific unit operations, e.g. drying, mixing, heating, melting, injection moulding, blowing, cooling of the finished product. These operations are carried out with the use of devices powered by electricity or systems and elements powered by a medium (air, gas, oil, emulsion) under appropriate pressure. Equipment (compressors, pumps) powered by current or fuel (equipment with internal

**Table 5.** Energy consumption of alumina production (based on [International Aluminium Institute 2021])

| Parameter | | 2020 | |
|---|---|---|---|
| | | World | Europe |
| Energy consumption [MJ/kg] | | 10.522 | 13.707 |
| Share of energy from energy sources [%] | Coal | 52.7 | 0 |
| | Natural gas | 29.5 | 92.2 |
| | Oil | 7.8 | 0.12 |
| | Elektricity | 7.4 | 3.7 |
| | Other | 2.5 | 4.0 |

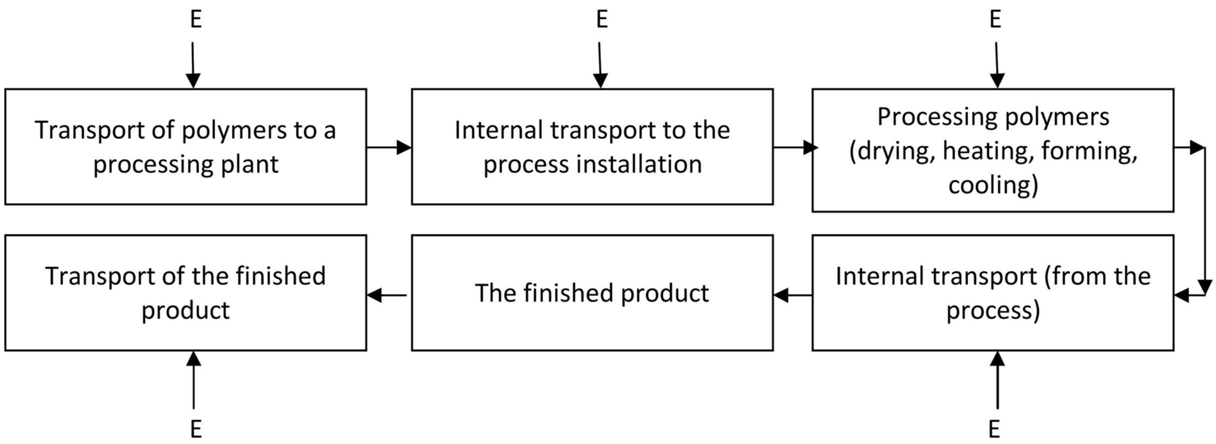


**Figure 3.** Places of energy consumption (E) at the stage of plastics processing

combustion engine) are used to generate the pressure of the working medium in hydraulic and pneumatic systems.

The assessment of energy consumption for the entire processing plant includes energy consumption by devices (process and auxiliary) and to meet other energy needs.

For example, in the extrusion blow molding process, the extruder (as a process equipment) consume the most energy, and essentially its drive system, the plasticizing unit with heating elements (plasticizes the plastic and injects it into the mold), the assembly forming the material into the required form, and the process control and regulation system. Auxiliaries consuming energy include compressors designed to increase the pressure of the air used for blowing the material, fans used to cool the product after removal from the mold, water coolers used to cool the material in the mould, pumps supplying hydraulic systems for closing and opening the mold.

In the injection molding method, energy is needed to melt the polymer, create a pressure enabling the polymer to be injected into the mold that gives the product shape, to open and close the mold, to maintain the required pressure on the mold during molding and cooling, and to operate auxiliaries such as dispensers, dryers, mills, belt conveyors.

In the processing plants, electricity is also used for heating, ventilation and lighting of production halls and office rooms, cooling of machines, as well as for storage and internal transport. The research of the European plastics processing sector (surveys included 165 processors) [Low Energy, RECIPE 2006, Schepp et al. 2006] shows that the average unit electricity consumption reaches the lowest value for mixing (0.64 kWh/kg = 2.29 MJ/kg of processed polymer), and the highest value for vacuum thermoforming (6.23 kWh/kg = 22.42 MJ/kg).

Values of electricity consumption for other processing processes are shown in Figure 4. The extrusion of products (foils, fibres, pipes and

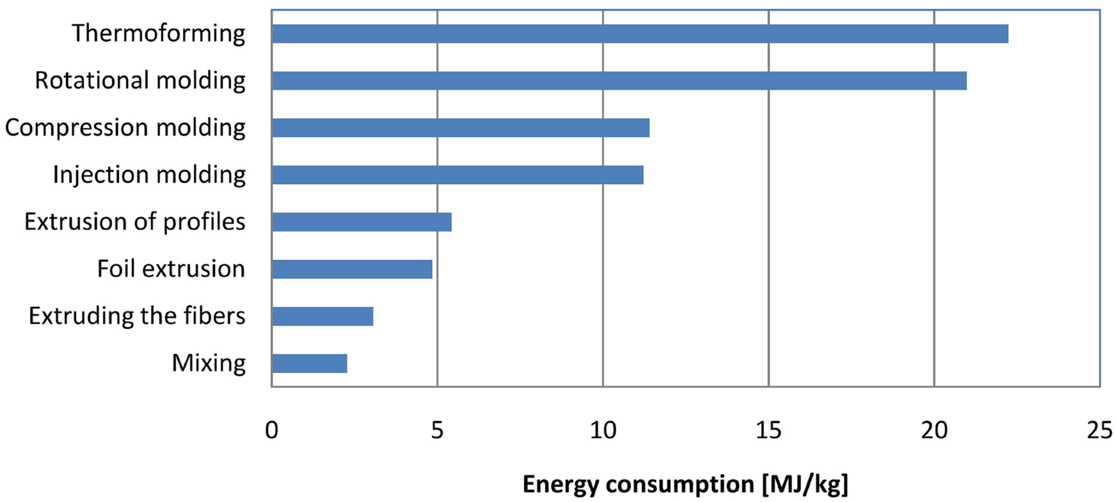


**Figure 4.** Average unit electricity consumption in plastics processing (based on [Polyethylene, CPME 2017])

profiles) is characterized by a noticeably low level of energy consumption.

In a typical injection moulding plant, the injection moulding machine accounts for the largest share of electricity consumption (approx. 60% of the total energy consumed). Lighting, heating, ventilation and air conditioning of the rooms account for 21% of energy consumption, cooling units for 9%, and compressors for approximately 3%.

According to Thieriez (2006), the average energy consumption per kilogram of polymer processed by injection method depends on the type of machines used – for fully electric injection molding machines it is 4.8 MJ, while for hydraulic and hybrid injection molding machines – 11.3 and 5.5 MJ, respectively. The energy consumption increases when the energy consumption of other devices is additionally taken into account. The average total energy consumption of injection molding machines, auxiliary equipment, for internal transport, heating and lighting of production rooms is 12.9 MJ/kg when fully electric machines are used, 19.3 or 13.6 MJ/kg for machines respectively hydraulic or hybrid. After adding the energy requirements for the production of polymers, the energy consumption increases to about 94 MJ/kg.

According to the literature data [Migdał et al. 2014] the total energy needs (including transport) for PET processing into packaging are around 20 MJ/kg. In order to express this value in terms of primary energy, you need to know the share of electricity in the total energy consumption in PET processing. Assuming that the share of electricity is 60–80%, the share of primary energy 20–40% and the efficiency of the power plant at 40%, the energy consumption of PET processing will be 38–44 MJ/kg converted to primary energy. Taking the above into account, the total energy consumption (converted into primary energy) of the PET production and PET processing stage in order to obtain packaging is 109.2–115.2 MJ/kg. This is almost five times higher than the PET calorific value (24 MJ/kg).

## CONCLUSIONS

Total energy consumption in the production and processing of polymers lasts at a significant level. There is therefore a need to look for solutions to reduce energy consumption in the abovementioned stages of its existence of plastic products. This need results from rising energy costs and the negative environmental impact of energy consumption. Reducing energy consumption may increase economic benefits for enterprises and improve the energy and environmental characteristics of products.

High priority should be given to activities that enable the implementation of circular economy principles. An example of such activities is recycling. Recycling technologies should be continuously developed also due to the suitability of plastics for recycling.

In polymer processing, process equipment consumes the most electricity. Therefore, the right course of action for reducing energy consumption is to increase the use of energy-efficient processing machines of the new generation. Research on a group of European injection moulding companies shows that the use of fully electric rather than hydraulic machines saves more energy.

The development and implementation of technologies leading to a reduction in the consumption of polymers per unit mass of a plastic product will reduce the unit energy consumption (per unit mass of the product).

The reduction of the consumption of primary polymers will be significantly influenced by the development of design of plastic products in terms of extending their use time (by reusing, regenerating) and the possibility of using waste from these products as secondary raw materials (in the recycling process).

The recycling of plastic waste eliminates the use of raw materials natural used in the production of virgin polymers. It is therefore an action for the quantitative protection of environmental resources. The lower demand for natural raw materials translates into a reduction in the intensity of exploration, extraction and transport of raw materials, and as a result into a reduction in energy expenditure in these activities. The use of recycled polymers in the manufacture of plastic products is also important for reducing energy consumption and makes such products environmentally friendly.

Material recycling is recommended for plastic waste with undamaged internal structure. It should be supported especially when the total energy expenditure on recovering full-value polymers from waste and carrying them to the form required by the recipients does not exceed the energy expenditure on the production of primary polymers. In general, the polymers contained in the waste are converted into flakes or granules.

Whole-value polymers from waste can have the same function as virgin polymers.

Recycling makes it possible to reuse waste materials in the economy. The practical application of recycling plastic should be considered if recycling saves more energy than the incineration of plastic waste.

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