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The Carbon Footprint Methodology in CFOOD Project

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Abstract—**In the paper, the research on the process of optimizing the carbon footprint to obtain the low-carbon products is presented. The optimization process and limits were analyzed based on the CFOOD project co-financed by the Polish Research and Development Agency. In the article, the carbon footprint (CF) testing methods with particular emphasis on product life cycle assessment (LCA) are discussed. The main problem is that the energy received from the energy-meters per the production stage is not directly represented in the raw data set obtained from the factory because many production line machines are connected to a single measurement point. In the paper, we show that in some energy-demanding production stages connected with cooling processes the energy used for the same stage and similar production can differ even 25-40%. That is why the energy optimization in the production can be very demanding.**

Keywords—**carbon footprint, greenhouse gas emission, LCA method, sustainable development, Prolog**

I. INTRODUCTION

SINCE the beginning of the 21st century, due to social development and the rapid development of industry, a series of environmental problems have appeared. One of the most worrying problems is the increase of greenhouse emissions to the atmosphere. An increase in their concentration causes a rapid increase in the average global temperature. Nowadays, climate change is considered as one of the biggest threats to our planet.

In this situation, many governments and non-governmental organizations take various initiatives [1]-[3] aimed at reducing greenhouse gas emissions and monitoring and optimizing processes affecting the volume of this emission, e.g. improving energy efficiency or increasing the share of renewable energy sources [4]-[5]. This applies to all areas of life and industries. The production of food, which we need more and more due to the growing population and excessive and less optimal consumption [6]-[9], has a particularly large impact on greenhouse gas emissions.

Due to the recommendations made by various institutions regarding greenhouse gas emissions, but also for economic reasons, producers are increasingly interested in optimizing the production process in terms of CO_2 emission [10]-[14].

The environmental impact of a process is often determined using a carbon footprint, which represents the total greenhouse gas emissions over the entire product life cycle [15]. The carbon footprint is a method of determining and measuring the carbon dioxide equivalent calculated as the total greenhouse gas emissions at each stage of the production and supply chain of each product or activity. It is expressed as carbon dioxide equivalent per product unit. Most methods used to calculate this value use ISO14040: 2006 [16] and ISO14064-1: 2018 [17], or the PAS2050 approach [18]. This method of determining CO_2 equivalent (equivCO_2) can be used in every industry. Taking into account the numerous activities of the European Commission and other institutions, it can be predicted that the calculation of the carbon footprint will become shortly a standard for all companies having an impact on the environment.

In the paper, we analyze the production stages of the frozen vegetables manufacturing. We discuss how different production stages contribute to the production as well as how they vary for similar processes. These variances of the production energy per unit measurements at the different stages make the optimization of the production difficult.

II. METHODOLOGY OF THE CARBON FOOTPRINT CALCULATING

The product's carbon footprint refers to the emissions of various greenhouse gases over the product's life cycle. These gases, as defined in IPCC 2007 [19], include: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and families of gases such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and fluorinated ethers.

The carbon footprint is usually calculated taking into account carbon emission factors and activity data that can be assessed using a Life Cycle Assessment (LCA). LCA is a method of assessing the environmental impact of a product's creation process associated with all stages of a product's life, from the extraction or production of raw materials to material processing, production, distribution, use, repair and maintenance, to disposal and / or recycling. Using this approach helps assess products for their harmful greenhouse gas emissions throughout their life cycle. LCA also helps to avoid a narrow view of the problem and analyse the actual environmental impact of the product.

LCA is based on the life cycle inventory (LCI), which takes into account data on resource and energy consumption and greenhouse gas emissions to the environment throughout the product's life cycle (Figure 1).

LCA is a widely used approach to assess the actual environmental impact of a product due to its production and use [20]-[23]. The product carbon footprint assessment

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standards in LCA are mainly PAS 2050 [18] and ISO / TS 14067 [24].

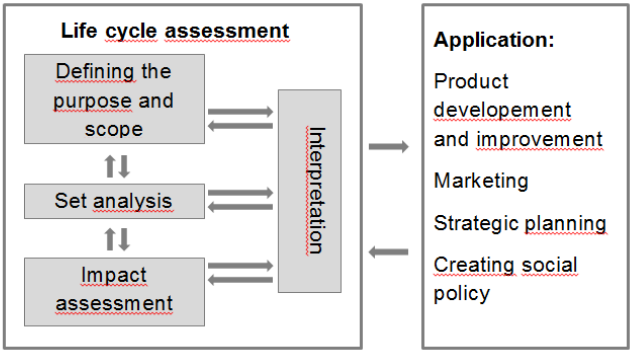

Fig. 1. Product Life Cycle Assessment (LCA).

Different approaches to the optimization problem are used for carbon footprint, e.g. expert systems, machine learning, or artificial intelligence. In [25] an approach based on mathematical sensitivity analysis was used. Examples of artificial intelligence and image recognition are shown in [26].

The carbon footprint of a product should be calculated taking into account all the stages necessary for its production, i.e. not only production but also transport, storage, utilization, etc. In some cases, e.g. when the relevant data is lacking, a smaller scope of analysis is allowed regarding e.g. only the production process. The wide scope of the carbon footprint analysis requires more work, but enables transparent presentation of the processes occurring throughout the product cycle as well as identification of the most emissive elements and, ultimately, reduction of their impact.

III. PRODUCT LIFE CYCLE ANALYSIS

We carry product life cycle analysis based on the real data from the company UNIFREEZE sp. z o.o., which represents the agri-food processing industry. It is a company that produces frozen fruit and vegetables (among other things). In the CFOOD project, as part of NCBiR Biostrateg III, we prepare an expert system that helps to assess the impact of individual stages of production on the total carbon footprint of the final product (frozen food). These studies will also be the foundation for UNIFREEZE's analysis of the entire production process in terms of the generated carbon footprint and its optimization in this respect. In the future, it will assist in reduction of CO_2 emissions.

According to the LCA methodology adopted, the product's carbon footprint consists of carbon footprints generated at individual stages of its production. According to the product life cycle definition and product carbon footprint analysis in PAS 2050 [18], the carbon footprint share is divided into five stages for the entire product life cycle: raw material sourcing, manufacturing, transport, use, recycling, and utilization. Hence the total CF for a given product or its unit value can be expressed by the following formula:

$$CF = \sum_{i=a}^{r} CF_i \qquad (1)$$

where: i is each of the stages of the product life cycle, $i = a$, m, t, u, and r, relate to the extraction of raw materials, production, transport, use as well as the recycling and disposal stage, respectively.

The product life cycle of UNIFREEZE consists of the following stages:

- production of raw material (agricultural production),
- transport from supplier to enterprise,
- production line,
- internal transport,
- storage,
- delivery to the recipient,
- sales,
- waste disposal.

Due to the lack of data for the sales stage (transport and storage of the product to/from the seller up to the sale of the product) and disposal, these stages will not be considered. The analysis will focus on processing from raw material production to delivery of the product to the wholesale recipient.

The calculation of the actual value of the product's carbon footprint is practically impossible due to the lack of reliable measurements at individual stages. For stages that are not or cannot be properly measured, average values are used. They can be obtained using literature data or LCA index databases of products and processes available in commercial (Ecoinvent) or free databases (JRC Ispra) [27].

The calculation of the carbon footprint for individual stages of the life cycle of the product produced in the company under consideration is as follows:

1. Stage of raw material production

Raw material suppliers (farmers) do not make any carbon footprint calculations for their production. The only way to determine the carbon footprint generated by this stage is to adopt literature data, which will be approximate, because they do not take into account the specificity of production on a given farm.

2. The transport stage from the supplier (farmer) to the enterprise

The company uses the services of a limited number of suppliers and keeps a record of deliveries. Hence, it is possible to determine the type of transport used by individual suppliers. This permits calculation of the carbon footprint generated by each supply.

3. Frozen food production stage

The production line at UNIFREEZE is well metered. Thanks to this, it’s possible to get accurate consumption values of individual components needed in the production process (mainly it is electricity consumption). It is therefore possible to precisely calculate the carbon footprint generated by each production line. In addition, it is possible to divide the production process into individual devices or groups of devices that make up the production line, because each of them is separately measured. Owing to this, it is possible to carry out a very detailed analysis of the impact of individual production stages on the total CF of the product.

4. Internal transport

Internal transport is the transport that takes place inside the enterprise in order to transport the raw material to the production line, collect waste and collection from the production line, place finished products in the cold store, etc. In this case, the type of means of transport used for this purpose is known. It’s possible to directly measure the fuel consumption or power consumption needed to charge the batteries, which allows us to calculate the exact carbon footprint at this stage.

5. Storage stage

UNIFREEZE is a frozen food factory. After freezing, the products are stored in cold stores. Cold stores, like the production line, are metered, which enables an accurate calculation of the energy consumption needed to cool products. UNIFREEZE also has data on the storage time of individual product packages in the cold store. However, the value of the carbon footprint generated at this stage by a single product packaging will be the average value for a given product or batch.

6. Delivery to recipient stage

As in the case of transporting the raw material to the company, records of deliveries to the recipient are kept as well as the means. This allows us to calculate the carbon footprint generated at this stage quite accurately.

7. Sales stage

For this stage, it is not possible to obtain reliable data on the pre-sale storage time and the amount of energy consumed by refrigerators or refrigerated counters. The entrepreneur (UNIFREEZE) does not have such data, and sellers are not obliged to provide it and do not keep accurate records. It is difficult to even estimate the value because it is not known how many times the product was transported at this stage and how long it was stored before it reached the final recipient.

8. Waste treatment stage

This stage is also difficult to describe. We have not obtained any data that would allow us to estimate the CF generated by the waste utilization process. It is known that all packaging must be disposed of. However, it cannot be determined what proportion of them went to recycling. In addition, it is impossible to determine what proportion of fruit and vegetables has been utilized, e.g. due to exceeding the best before date.

The production model we actually use can be described by the following formula:

$$CF = \sum_{i=a}^{r} CF_i \qquad (2)$$

where: i means the subsequent stages of the product life cycle, $i = pr, pz, m, tz,$ and tw relate to agricultural production, enterprise production, storage, internal transport, and external transport, respectively.

After performing a general life cycle analysis of the product, which in this case is frozen fruit or vegetables, the next step is to prepare models for each stage of the product life cycle. As mentioned earlier, such an analysis is not possible for all stages. For the first stage (agricultural production), due to the impossibility of obtaining more specific information, we will use statistical data only. Detailed analysis and preparation of the model will concern stages 2-6. These are stages that are controlled by the enterprise, and hence can be optimized.

For example, for intra-corporate transport, we consider two classes of warehouse trucks: diesel forklifts and electric forklifts.

The adopted model of internal transport takes into account two factors affecting the size of the generated carbon footprint: forklift truck operation time in different operating states and forklift energy consumption. Three main working conditions occurring during intra-company transport were taken into account:

- Unloaded condition - occurs when an unloaded forklift moves from the storage area to the storage area. The average speed is assumed for this condition and continuous operation is assumed.
- Lifting condition - this occurs when the forklift stops in the storage area to pick up the load. In this state, it is assumed that the trolley moves minimally.
- Moving condition - the loaded forklift moves from the storage area to the warehouse. Forklift speed in this case is influenced by two factors: the weight of the load being transferred and the power source of the forklift. When optimizing this stage, it should be taken into account that the safe maximum speed cannot be exceeded [26].

Energy E and time t needed for transporting loads from the storage area to the warehouse constitute the majority of the total energy and time consumed during internal transport. Thus, the carbon footprint for the internal transport process using forklifts can be determined by the relationship:

$$CF = EHR * t \qquad (3)$$

where: EHR - hourly CO_2 emission factor [$kgCO_2$ / h], t - total cycle time [h].

A similar analysis should be made of the remaining stages of the product's life cycle under consideration.

Product life cycle analysis and greenhouse gas emissions at each stage can detect those that generate the most significant carbon footprint. This in turn creates the basis for optimizing the production process in this respect. Unfortunately, the size of the carbon footprint is also influenced by external factors independent of the entrepreneur. The most significant is the cost (equivCO_2) of producing kWh of electricity in a given country. These indicators are very different in different countries. The carbon footprint generated in the electricity production process depends on the fuel mix used to generate that energy. Combustion of coal gives emissions of about 1000 g CO_2/kWh, oil about 800 g CO_2/kWh, natural gas about 500 g CO_2/kWh, and nuclear, water, wind, or solar energy less than 50 g CO_2/kWh. It is therefore obvious that the highest carbon footprint has those countries where electricity production is primarily based on coal combustion, with a small addition of other sources.

Figure 2 indicates the share of coal in electricity production for individual countries. It can be seen that Poland is in the group of countries where this share is high. This translates into electricity burdened with very high carbon dioxide emissions. It is evident that in Western Europe, the situation is much more favourable.

The data available for 2015/2016 shows that the average values of the carbon footprint for one kWh of electricity consumed in high voltage networks (defined as Carbon Intensity and measured according to equivCO_2/kWh) in selected European countries were: 100 in France, 45 in Sweden, 599 in Germany, 593 in Great Britain, 1110 in Latvia and 937 in Poland with the EU average EU28 of 428 g equiv CO_2/kWh [30].

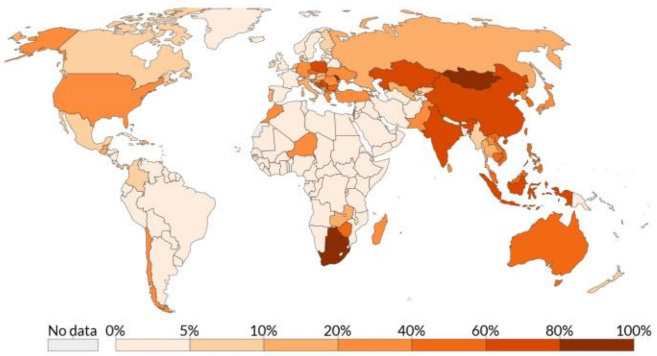

Fig. 2. Share of coal in electricity production [29].

In countries marked in dark green, such as Norway or Iceland, direct emissions from electricity production are lower than 20 g CO_2/kWh, due to the dominance of hydroelectricity or geothermal energy in Iceland. Other countries do not have such good results, but they are still much better than in Poland. Unfortunately, this may decrease competitiveness of Polish producers, if the important criterion is the carbon footprint produced in the production process, in which the main resource consumed is electricity, and not just the final price.

Analysing the carbon footprint for one of the UNIFREEZE production lines, for one of the products, after preliminary calculations (for stages 1-6), we obtained the results that the carbon footprint that arises over the entire production cycle of 1 kg of a given product is 50% dependent on electricity consumption (mainly in the cooling process). The remaining 50% of the carbon footprint is generated as a result of diesel consumption in plant production and external transport, as well as hard coal, gas, and water consumption [30]. If we assume that the cycle of production, processing and transport/logistics is similar in these countries and take into account the value of the carbon footprint in electricity production for various EU28 countries, then the calculated CF of electricity used in the industry [30] will constitute 55.3% of the value of CF in Poland (assumed as 100%) and respectively 52.4% in Sweden, 82% in Germany, 81.6% in Great Britain, 79.6% in Nederlands, 67.1% in Spain and 72.8% as EU28 average. This means that the task of optimizing the carbon footprint should take into account not only the total carbon footprint but also its components at the level of a given country.

IV. PRODUCTION STAGE LIFE CYCLE ANALYSIS

In the Tab. I below we can compare the results of average energy utilization in kWh per one tonne of product at seven subsequent process stages marked S1, S2, …, S7. Each of the process stages is connected to electric meter units. The measurements were taken from Feb till May 2020.

The process stages stand for:

- S1 – the raw material inception,
- S2 – initial cooling,
- S3 – raw material preprocessing,
- S4 – product freezing,
- S5 – product preparation to coldstore,
- S6 – storing in coldstore #1 (depending on the time in before B2B shipment),
- S7 – storing in coldstore #2 (depending on the time in before B2B shipment).

Each of the stages is consisting of one or more devices connected to the same measurement point, an electric meter. For example, stage S3 consists of a raw materials basket and two conveyors.

At the end of the process, we obtain the same or similar products. In our case, this is frozen onion cut in different size cubes. The product lines are the same. One of the line components, the shredder, is only set up into different cube sizes.

TABLE I
AVERAGE ENERGY UTILIZATION IN CHOSEN PROCESSES FOR THE SAME RAW MATERIAL PROCESS INTO SIMILAR FINAL PRODUCTS.

Process ID	**Average energy utilization at the process stage [kWh/t]**						
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
86	0.0885	6.2603	0.9627	27.4542	0.1015	74.5811	25.1826
88	0.1195	6.6663	1.0923	28.2903	0.3210	0.0000	29.9640
91	0.0896	6.1498	1.0894	26.3803	0.0224	80.0880	25.6895
94	0.0989	4.9022	0.9728	25.9552	0.0006	19.7335	24.5720
149	0.0640	7.9025	1.0417	29.5109	0.8790	90.5743	45.0136
150	0.0654	5.9003	0.9975	26.9711	0.6115	82.0181	39.3555
171	0.0628	6.0214	1.1490	26.2895	0.2104	0.0000	40.8242
172	0.0700	6.1365	0.9495	27.4685	0.1758	74.2249	41.8939
175	0.1018	9.0296	1.2319	33.5979	0.0151	74.5212	47.3627
Avg	**0.0845**	**6.5521**	**1.0541**	**27.9909**	**0.2597**	**55.0823**	**35.5398**
Var	**0.0201**	**1.2157**	**0.0952**	**2.3736**	**0.3018**	**37.1697**	**9.1384**

TABLE II.
THE ENERGY CONSUMPTION FOR THE VEGETABLE PROCESS

ID	**ET,** kWh	**M,** t	**EnS15,** kWh	**E15/M** kWh/t	**EnS67** kWh	**E67/M** kWh/t	**E/M** kWh/t
86	14033.9	104.24	3634.6	34.9	10399.4	99.8	134.6
88	836.6	12.59	459.4	36.5	459.4	36.5	66.5
91	6986.6	50.08	1689.3	33.7	5297.3	105.8	139.5
94	4183.0	54.87	1752.0	31.9	2431.0	44.3	76.2
149	7687.1	43.93	1730.8	39.4	5956.4	135.6	175.0
150	6957.1	44.62	1541.4	34.5	5415.7	121.4	155.9
171	3730.8	50.04	1688.0	33.7	2042.8	40.8	74.6
172	10673.0	70.72	2461.1	34.8	8211.9	116.1	150.9
175	13336.5	80.41	3536.0	44.0	9800.4	121.9	165.9
Avg	-	-	-	35.9	-	91.3	126.6
Var	-	-	-	3.7	-	39.5	42.5

In Tab. II the labels are as follows: ET – total energy used in the production process; M – the weight of the products in tons (t); En S15 – the energy used in the stages from S1 to S5 in kWh; E15/M – the energy used for the weight unit (kWh/t) in the stages S1-S5; En S67 – the energy used in the stages from S6 to S7 in kWh; E67/M – the energy used for the weight unit (kWh/t) in the stages S6-S7; E/W – total energy used in the stages S1-S7 per the weight unit in kWh/t.

It can be easily deducted from Tables I and II as well as from Fig. 3 that the final energy values (S6 and S7) depend mainly on the cooling/freezing substages as well as the time that the product is stored in the coldstore. Final carbon footprint depends on the electric energy consumption.

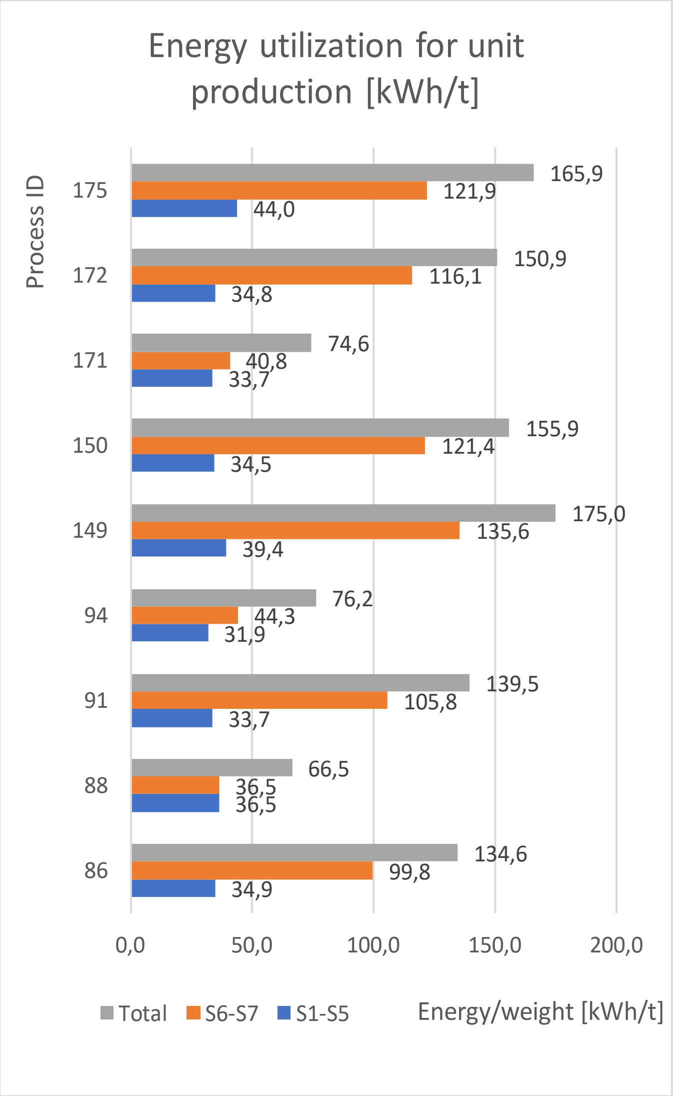

Fig. 3. Energy utilization in the example processes with the division into the processing (stages S1-S5), cold storing (stages S6-S7), and total value.

Another aim of the project is process optimization. But as it can be seen the problem solution is not straightforward. It needs to take into account many factors that can happen during the production process e.g. low-quality raw materials, weather conditions; the high or low season. Fig. 4 shows that the same product processing on the same production lines can lead to different energy consumption structure. Some stages show meaningful but stable energy consumption e.g. S1 and S3. In stage S5, the energy can be meaningful but can vary from almost 0 to 0.9 kWh/t. In the stages S2 and S4 connected with cooling processes the energy used for the same stage and similar production can differ even 25-40%. That is why the main goal of the project, that is energy optimization in the production, can be very demanding.

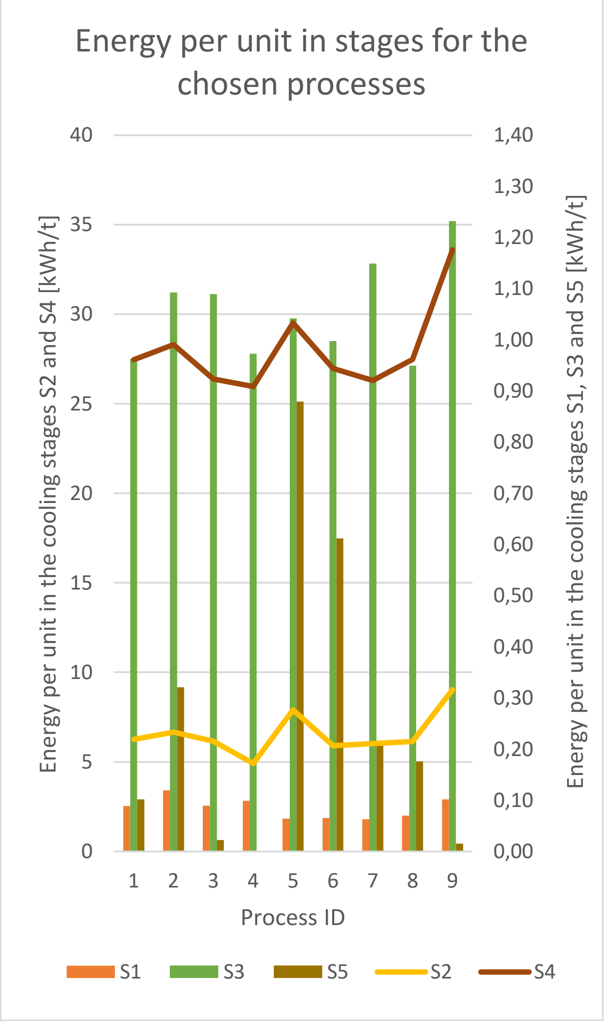

Fig. 4. Energy utilization in the processing stages S1-S5 for the processes from Tab. I, where process ID 1 refers to 86 and process ID 9 refers to 175.

CONCLUSIONS

The introduction of low-carbon economy assumptions, and in particular the corporate social responsibility strategy, is beginning to cause changes in the awareness of entrepreneurs. Providing the value of the carbon footprint of the product is not obligatory for entrepreneurs, but they are increasingly seeing the benefits of calculating it. They are forced to do so by the market. Increasingly, contractors, especially from Western Europe, send inquiries requiring the carbon footprint of a product to be provided. In this situation, for producers wishing to participate in the tender, the calculation of the carbon footprint becomes a necessity. Recently, there has also been a significant increase in the importance of the carbon footprint value for contractors. It is important not only to keep its low value, but it can be a decisive factor in choosing a given offer. The criterion of the minimum value of the carbon footprint is increasingly more important than the price of a product or service, e.g. for British companies [31].

Polish producers may often not be competitive compared to, e.g., French or German producers, because the electricity used in these countries has a significantly lower carbon footprint. The use of renewable energy sources can be an alternative.

The processes depend on many factors and even in the same conditions, the results can differ by around 25 % as it can be seen from Tables I and II. However, the energy consumption on different stages can be even eight times bigger for the production unit. In some energy-demanding stages (S2 and S4) connected with cooling processes the energy used for the same stage and similar production can differ even 25-40%. That is why the main goal of the project that is energy optimization in the production can be very demanding. In the analysed production stages the final carbon footprint depends on the level of the electricity consumption [32, 33].

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