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Research article

Evaluation of pulse-jet baghouse dust collectors' contribution to CO_2 emissions

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ABSTRACT

Dust cleaning systems are mandatory for use almost in any manufacturing process. Their market size is expected at US$10.77 billion by 2030 growing from US$7.28 billion in 2022. Removing dust particles is the main purpose of these systems and they make an invaluable contribution to environmental safety. However, while cleaning the air from solid particles, industrial pulse-jet baghouse collectors have an additional impact on the environment that usually is not considered. An analysis of energy consumption at the manufacturing and operation stages of the baghouse dust collectors allows for the evaluation of CO_2 emissions. The analysis shows that, given the current state of affairs in the industry, by 2030 manufacturing and operation of baghouse dust collectors over the world will emit 70+ million tons of carbon dioxide additionally to the levels of 2021. To reduce the CO_2-related environmental impact of industrial pulse-jet baghouse collectors, among all scientific and technical measures, it is recommended to simply scale up the dust collection system, which involves replacing several low-capacity collectors with one general-capacity collector within one industrial enterprise. This allows for a reduction in energy consumption at the collector manufacturing stage from 3 to 10 times and also ensures a significant reduction in operation energy consumption of the dust collector during its service life.

1. Introduction

The first mention of a dust collection facility dates back to the 1880s. The first patent dates back to September 1, 1885, when John M. Finch invented his cyclone dust collector and assigned it to the Knickerbocker Company [1]. Since that time a lot of different types of dust removal systems were developed, and have become mandatory for almost all industrial applications.

Researchers developed different types of dust collection technology and facilities that can be divided into a few large groups: inertial separators, fabric filter baghouses, electrostatic precipitators, and wet scrubbers. Each type has advantages and weaknesses. Fabric filter baghouses have one of the largest shares among all dust removal systems. And, in turn, pulse-jet bag filters are most widespread among other sub-types of fabric filter baghouses.

Pulse-jet baghouse dust collectors are important for environmental protection and mitigating climate change. These systems are essential for reducing the emission of harmful particulate matter and pollutants into the atmosphere, which can have detrimental effects on air quality and human health. By efficiently capturing dust particles from industrial processes, pulse-jet baghouse collectors

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help to prevent the release of harmful substances into the air, thereby minimizing the environmental impact.

Moreover, pulse-jet baghouse dust collectors support sustainable industrial practices by promoting cleaner production processes and reducing environmental pollution. By improving air quality and reducing emissions, these systems contribute to creating a healthier and more sustainable environment for both current and future generations.

Pulse-jet baghouse dust collectors require a significant amount of energy for their operation, primarily in the fan (or blower), which organizes dirty airflow to the filter and clean air flow from it, and the pulse-jet cleaning system, which utilizes compressed air to clean the filter bags by pulsing bursts of air to dislodge accumulated dust particles. Additionally, the control system, including sensors, switches, and electronic controls, also consumes energy to monitor and regulate parameters such as airflow, pressure, and cleaning cycles.

To date, much research has been carried out to improve the efficiency of dust removal, and/or to increase those systems' energy efficiency. Since the 1980s researchers have studied the nature of the pulse-jet cleaning phenomenon to improve its efficiency [2,3]. The use of specially developed materials allows us to improve the dust-collecting properties and capture fine particles up to PM 2.5 [4–6].

Many other pieces of research can be listed here. Great reviews [7–9] can be recommended for a complete reading. We do not make a detailed analysis of all these papers since achievements in filtration technologies and processes are not a subject of the present research.

In recent years, the energy-saving issue has become one of the frontlines in scientific research. And, fabric filter baghouses and related areas are also involved in this competition. Compressed air is used in many industrial processes, and is also one of the important subsystems in pulse-jet cleaning baghouses. Authors of [10,11] made a comprehensive analysis of the compressed air system efficiency and came to the conclusion that it is often very low. As Nehler rightly notes [10], the efficiency of the installations driven by compressed air is typically only 10–15 %. The authors of [11] agree with Nehler and have proposed a 6-step approach for improving the use of industrial compressed air systems. The approach is based on the classical methodology of energy management and audit. However, the efficiency of a pulse-jet baghouse dust removal system depends on many different subsystems, including, for example, suction fans, collected dust unload facility and many others.

Krammer et al. [12] conducted an experimental study to examine the relationship between filtration time for one regeneration pulse and the lower pressure drop. They discovered that there exists a specific lower pressure drop value, corresponding to a constant upper pressure drop, at which the filtration time per pulse reaches its maximum value. Therefore, for a given combination of upper and lower pressure drops, there exists an optimal configuration to maximize the efficiency of the cleaning operation.

The authors of [13] investigated the efficiency of the compressed air system for filter regeneration, considering various factors. In their study, they demonstrated that a combination of compressed air pressure and cleaning pulse duration can optimize energy consumption by the compressed air system. According to the authors, when combined with an appropriate compressed air system and specialized fabric materials for the filter media, energy consumption by the regeneration system can be reduced by 40 %.

An interesting approach to optimizing the design of pulse-jet baghouse collectors was proposed in Ref. [14], presenting an economically sound criterion. The authors introduced a discounted total annual cost function that considers various design parameters of the baghouse. This function aims to minimize overall costs, which are influenced by factors such as the number of filter bags, total pressure drop, and filtration time. These parameters affect different cost components, including capital and bag replacement costs, operating costs, and cleaning and maintenance costs. According to the authors, the minimum total cost determines the optimal combination of penetration rate (total baghouse filter area), pressure drop, and number of cleaning cycles (filtration time) for a given fabric material. Their model is recommended for use during the preliminary design phase, providing insights into how design choices impact the overall cost of the system as the plant layout is determined.

While the last two factors influencing the developed function, namely pressure drop and filtration time, directly affect energy consumption during operation, and the number of bag filters is linked to energy costs during manufacture, the authors [14] do not specifically address the associated CO_2 emissions.

Ho et al. [15] also studied economical-based ways for the optimization of fabric filter baghouse systems with the help of MATLAB modeling. They found that the effectiveness of a pulse-jet filtration system depends on the filter material, the type of dust, the parameters of the pulse-jet system, and the filtration speed. The authors selected the cost of operating a bag filter as an optimization criterion and conducted the optimization procedure. The optimization results indicate that, from a cost perspective, a pulse interval of 10 s is the optimal parameter, and the pulse duration time does not significantly affect the overall cost of the filter. However, from an energy-saving standpoint, the optimal value is a pulse duration of 0.1 s. Thus, as evident from the analysis of the last two literature sources, optimizing economic parameters appears to be an intriguing approach to reducing energy consumption. Nevertheless, the results of the research are applicable to the only design of the pulse-jet baghouse system considered by the authors. Besides, the economic optimization criterion does not always coincide with the environmental criteria.

The authors of [16] investigated additional measures to improve dust collection efficiency by the use of electrically pre-charged by corona discharge bag filters and discovered an increase in dust collection efficiency. Another issue is that additional equipment for pre-charging requires additional energy anyway. However, the authors did not consider this "side of the medal".

In [17], as in Ref. [16], the authors investigated the pre-charging bag filter in the pulse-jet baghouse. However, unlike research [16], this time the authors focused on power consumption rather than on dust collection efficiency. The results showed that as the pre-charge voltage increases, the energy consumption of the system decreases significantly. It should be noted, that the bag filter pre-charging requires the incorporation of the additional high-voltage tool. Also, the authors did not analyze the possible impact of the dust collection system on carbon dioxide emissions and focused only on the estimation of power consumption.

Papers [18,19] directly discuss the issue of the energy demand of the baghouse dust collectors. The authors investigate the influence of various fabric materials, dust air velocity, dust concentration, compressed air pressure, and regeneration cycle time from the perspective of energy demand and dust removal efficiency. Enhancing the efficiency of dust cleaning inevitably leads to higher energy costs, primarily due to the necessity of increasing the pressure drop across the filter material. This is particularly notable for low concentrations of dust and/or fine particles. A special test procedure is developed and recommended for use in Ref. [18] that allows for the classification of the various dust filter media from the point of view of energy consumption for specified separation efficiency. The authors of [19] demonstrated the significance of considering energy criteria when evaluating filter performance. A rise in raw gas concentration leads to more frequent regenerations, thereby increasing overall energy consumption. Lower gas flow rates through the filter are advantageous from an energy standpoint and enable the handling of higher dust concentrations. If there is a need to maintain the total exhaust gas flow rate in the technological process, this can be achieved by enlarging the filtration area. Additionally, it was observed that while increased compressed air pressure in the regeneration system reduces overall energy consumption for fan operation, it also compromises the degree of purification, which is unacceptable. Surprisingly, the authors did not mention the fact that maintaining elevated pressure in the system increases the energy consumption of the compressed air compressor.

As clearly seen, much research is focused on the energy efficiency of the dust removal system itself and does not deal with the estimation of such systems' hidden impact on CO_2 emissions. On the other hand, greenhouse gas emissions are an important factor currently drawing close attention from researchers, policymakers, and environmental activists. Climate change is an urgent issue that has required a lot of attention during the last decades. Government programs to prevent climate warming include all possible sources of human activity that affect the environment.

There are some controversial opinions on the sources of global warming. For example, a recently published manuscript [20] discusses the possible way to influence the dust directly to climate change. The authors show that the presence of dust in the air led to slower global warming than would have occurred if the air had been completely free of dust. Dust reflects part of the infrared radiation from the Sun back to space. However, the undeniable importance of particulate removal is beyond the scope of this article. At the same time, dust protection is the main goal of dust removal systems, which make a great contribution to environmental protection and human health.

The authors of the present manuscript leave out the discussion of the essence of the climate change problem but consider the potential impact of dust removal systems on energy spending and CO_2 emissions and possible ways to eliminate this impact.

To date, the subject of the environmental impact of pulse-jet baghouse dust removal systems is discussed weakly in the scientific periodical. Several researches devoted to this area. In Ref. [21] the authors consider the synergistic effect of air pollution removal and associated climate benefits. The authors state that improvement of the energy efficiency of the air pollution control and reduction system allows us to decrease dust emissions as well as SO_2, NO_x, and CO_2. Also, two additional interventions for China's industries can help with this: structural change, i.e., transfer from small-size enterprises to large ones; and change energy sources from fossil fuels to renewable ones. Obviously, such arrangements effect is expected. However, in the manuscript, the authors consider all possible air pollutants as a whole but do not pay special attention to dust removal systems and their contribution to carbon dioxide emissions.

The recent research [22] devoted to coal-fired plant pollution is very close to the subject raised in the present manuscript. The authors studied the contribution of different air pollution control devices (APCD) used in China's coal-fired power plants to carbon dioxide emissions. They rightly point out that all types of APCDs use electricity for their operation, and this electricity production is accompanied by CO_2 emissions. The results of the research show that the contribution of the clearing systems to CO_2 emissions in 2020 was 1.19 % of the total carbon dioxide emissions from China's power plants. In absolute value, the emissions of CO_2 are estimated as 2000 Mt in 2020.

Carbon dioxide emissions from coal-fired power plants primarily result from coal combustion and the subsequent release of carbon dioxide into the atmosphere. However, there are several other contributors to CO_2 emissions from coal-fired plants. The extraction of coal from mines and its transportation to power plants also contributes to CO_2 emissions. This includes emissions from mining machinery, transportation vehicles, and associated infrastructure. The transportation and disposal of ash and slag waste also contribute to CO_2 emissions. Plant operations, including repairs, inspections, and general upkeep, also require energy and resources, leading to additional CO_2 emissions. Coal combustion directly contributes up to 70–80 % of carbon dioxide emissions, while indirect CO_2 emissions are generated by other activities.

Unfortunately, detailed data on direct (combustion) and indirect (all other activities) CO_2 emissions generated by coal-fired power plants are not readily available. While coal combustion is the largest contributor to carbon dioxide emissions – serving as a source of direct emissions – other activities contribute indirectly. These include.

- Mining and transportation of coal: these activities may contribute around 5–10 % of CO_2 emissions, depending on factors such as the distance the coal needs to be transported and the methods used for extraction.
- Waste disposal: while the contribution of waste disposal to CO_2 emissions may be relatively small compared to other sources, it can still account for around 1–5% of total emissions, depending on factors such as the volume of waste produced and the methods used for disposal.
- Maintenance and operation: the energy and resources required for the maintenance and operation of coal-fired power plants may contribute around 1–5% of CO_2 emissions, depending on factors such as the size of the plant and the frequency of maintenance activities.

At the same time, it is worth noting that the authors of [22] analyzed only the operational stages of desulfurization, dust removal, and denitrification of coal-fired power plant equipment and did not include the production of this equipment and consumables. However, the manufacturing of all component systems also has its own equivalent of CO_2 emissions.

Thus, research into the potential impact of manufacturing and operation of the dust removal facility on carbon dioxide emissions is rare and a major gap exists in this area. This article evaluates the contribution of pulse-jet baghouse dust removal systems to energy consumption and CO_2 emissions.

2. Materials and methods

The estimation of energy consumption and carbon dioxide emissions are based on the Life Cycle Assessment (LCA) procedure. The LCA algorithm of the environmental impact of any system requires determining energy spent at all stages of the production and operation of all the components of the system [23]. It includes raw source mining, treatment, transportation, etc.

Defining and unifying some of these links in the chain is a complex task. Moreover, in many cases, the energy consumption of the same operation varies significantly from one provider to another. For example, the energy costs (and emissions) of transportation vary from one supplier to another. This was perfectly demonstrated in a study [24]. There, the energy demand for transporting disposable natural leaf plates to points of sale makes the smallest contribution to the total life cycle energy requirement, in contrast to the study [25], where transporting disposable leaf plates makes the largest contribution to the same cycle. Similar considerations apply to the raw material extraction stage, i.e., in different mines, raw material miners expend different amounts of energy in their work cycles, etc.

Therefore, in the present research, we deliberately excluded all stages of transportation, as well as the extraction of raw materials from the consideration.

Additionally, we are not considering the contribution of disposal of the filter elements at the end of their service life to emissions of carbon dioxide. There are various methods for disposing of filter bags, which depend on factors such as the filter material, the type of dust separated by the dust removal system, etc. Each disposal method makes a different contribution to CO_2 emissions, and not all stages of the disposal procedure can be easily assessed in terms of CO_2 emissions. As this research represents an initial approach, we have temporarily excluded such a detailed analysis. Future research will incorporate this stage.

2.1. Pulse-jet baghouse dust collector components

In general, a pulse-jet industrial baghouse dust collector consists of a metal body and fabric filter bags and is accompanied by a suction system based on a fan, and a pulse-cleaning system. The latter uses compressed air from the existing production line in the enterprise structure. Fig. 1 presents a typical layout of the collector.

The suction fan is attached to the "Clean gas" duct and is not shown in the figure.

There, the metal body considered in this research includes (see Fig. 1 for references).

- main housing;
- hopper;
- tube sheet;
- baffle plate;
- compressed air manifold;
- Venturi nozzles.

Fabric filter bags are made from various textile materials. Plastic-based (i.e., polyethylene terephthalate – PET, polypropylene – PP, polyester – PE, and their modifications) filter bags are the most efficient in terms of dust catching and life cycle duration [4,17,26]. Therefore, we consider plastic-based filter bags in further analysis.

Special support cages for bags prevent the bag from collapsing and maintain its shape. They are usually made of steel wire.

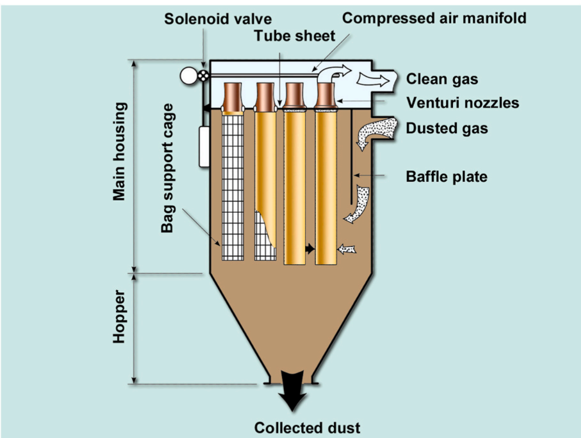

Fig. 1. Pulse-jet baghouse dust collector layout.

Therefore, for energy consumption assessment, this component of the bag filters was included in the metal body of the entire pulse-jet baghouse collector.

2.2. Simplifications

There are many different models of pulse-jet baghouse dust collectors of various capacities, sizes, and purposes. Each manufacturer uses different metal and plastic processing technologies and tools to produce specific baghouse collectors manifold components and assemble the final product. Authors of [27] clearly show that different types of metal processing (conventional drilling and laser-based cutting/grooving) have different values of energy consumption and as a result – different carbon emissions of the operation. Since the main idea of this research is the evaluation of the impact of the entire set of baghouses on the environment, we have made the following assumptions.

- All the metal details are made from rolled steel as the raw source.
- All the textile details are made from PE plastic as the raw source.
- Energy costs for the manufacture of elements were taken as an additional 30 % of the costs of rolled steel and raw plastic for the collector body and fabric bags, respectively.

2.3. Data sources

The energy demand for the production of various types of rolled steel was analyzed by different authors [28,29]. The book [29] (in Russian) was published by the State Enterprise "Ukrainian Scientific Technical Center UkrSTC Energostal [30]. It contains comprehensive data on energy costs for the production of rolled steel, calculated per Ton of Coal Equivalent (TCE – Russian unit of energy). 1 TCE = 29.3 GJ. We used data from this book for the evaluation.

For data on energy consumption for the manufacturing of fabric filter bags (Cloth) made from plastic of various origins, we carried out an analysis of manuscripts [31,32], and accepted data obtained by Dr. Eng. Halina Marczak from the Lublin University of Technology, Poland [31].

For research we use statistical data on the fabric filter bags production, entire baghouse systems production, and operation production. State Enterprise "Ukrainian Scientific Technical Center UkrSTC Energostal [30] develops, produces, and installs industrial pulse-jet baghouse dust collectors of wide nomenclature. The data of developed dust collectors as well as the industrial test results of these baghouses were used in this research. In addition, to increase statistical representativeness, available open data from the Internet from other manufacturers of industrial baghouse dust collectors was used.

Thus, for the energy spending and emissions analysis, the following parameters of the pulse-jet baghouse dust collectors were collected and processed.

- Capacity [m^3/hour];
- Cloth area [m^2];
- Baghouse weight (except bags) [kg];
- Pulse-jet air rate [m^3/hour];

Baghouse manufacturers and suppliers included in the analysis are the following.

- UkrSTC Energostal [30] – main applications are metalworking and foundries
- Assorted brands from AM Industrial Group, LLC [33].
- C&W DustTech [34] – asphalt plants, concrete production facilities, and woodworking shops.
- Controlled Air Design [35] – specializes in providing baghouse dust collectors for various industries including asphalt plants, concrete production facilities, woodworking shops
- DMC [36] – food processing, grain handling, cement production, and power generation
- Donaldson Company, Inc [37]. – heavy-duty and light industrial applications, including mining, agriculture, automotive, and aerospace.
- Sternvent [38] – woodworking shops, metal fabrication facilities.
- U.S. Air Filtration, Inc [39]. – pharmaceuticals, food processing, plastics manufacturing, and chemical processing.

As is seen, pulse-jet baghouse collectors are used in various industries such as cement manufacturing, foundry, metal processing, mining, food processing, energy, chemical processing, wood processing, and many more. On the one hand, the size of a baghouse depends on the volume of dust generated, the airflow rate, the type of particulate matter collected, and the baghouse manufacturer's internal regulations and specifications. On the other hand, although larger capacity bag filters are often used in industries that produce large volumes of dust, such as cement plants, they are not limited to these applications exclusively. Baghouse collectors for large volumes of dust are usually assembled from several collectors of smaller capacities.

3. Results and discussion

As the first step, the comparative qualitative-quantitative analysis was carried out of the pulse-jet baghouse dust collectors' basic parameters. We consider parameters that affect energy consumption at the manufacturing and operational stages.

The main independent parameter of the baghouse collector is its productivity or Capacity [m^3/hour] – the maximal volumetric flow rate of dirty air that can be passed through the collector for cleaning. Cloth area, or filtration area (i.e., the area of the working surface through which gas is filtered) is the next important parameter that determines filter bags' nomenclature and number. This, consequently, influences baghouse dimensions, weight, fan productivity, etc.

3.1. Cloth area

Cloth area is available for most of the baghouse models. This parameter can help to evaluate the efficiency of the dust collector. Obviously, the larger the capacity of the dust collector the larger should be its Cloth area. Figs. 2 and 3 present data on all considered pulse-jet baghouse dust collectors. As can be seen, the data in Fig. 2 overlap in the range of small capacity equipment, and the analysis in this representation is difficult, while Fig. 3 allows us to make it due to the logarithmic axes. Therefore, hereinafter in some of the figures, we use logarithmic axes that provide clearer representations.

Any additional symbols are described in text near the figure where they are used.

It follows from Fig. 3 that the filtration area almost linearly depends on the collector's capacity. However, this parameter varies between producers. As seen, the equipment of UkrSTC Energostal has a maximal specific filtration area (cloth area divided by baghouse capacity) in comparison with others, while DMC collectors have a minimal specific filtration area. The reverse parameter – air-to-cloth ratio – is widely used in industry applications for the characterization of dust removal systems. It is calculated by dividing the capacity [m^3/min] by the filtration area [m^2]. Usually, it is in the range of 1.2–3.5 [m/min]. However, we intentionally use the ***Cloth area*** in our analysis rather than the air-to-cloth ratio because it allows us to determine energy spending, as shown further.

Cloth area has a controversial effect on life cycle energy analysis results. From the point of view of the filter bag production (*manufacturing*) stage, a larger filtration area requires a larger mass of feedstock (in our case, plastic). This fact leads to increased manufacturing costs, including the energy required to produce and process plastic. On the other hand, a smaller filtration area leads to faster filter contamination and the need for more frequent cleaning during the *operation stage*. The latter issue is confirmed by the results presented in Fig. 4.

It is clearly seen from the figure that DMC collectors, which have a smaller specific filtration area, require a much higher pulse-jet air rate than UkrSTC Energostal dust cleaning systems that have a larger specific filtration area. As a result, a larger pulse-jet air rate leads to an increase in energy demand for the compressed air sub-system during the operation of the pulse-jet baghouse dust collection system.

Another feature can be found in the figure. Obviously, the dust concentration in the inlet (dirty) airflow also affects the frequency of cleaning during operation and, as a result, the pulse-jet air rate. In Fig. 4, there are different symbols corresponding to the facility of UkrSTC Energostal that allows dust concentrations up to 10 g/m^3 and 20 g/m^3 in the inlet dirty gas flow. It is seen that an increase in the dust concentration leads to an increase in the rate of the compressed air required for cleaning.

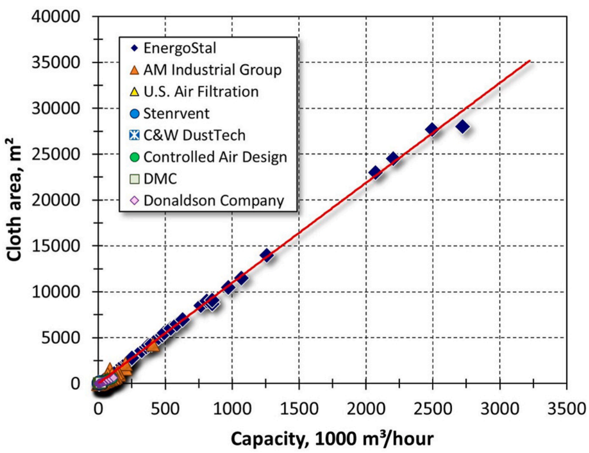

Fig. 2. Cloth area vs Capacity for all the analyzed baghouse collectors.

- Markers of various colors and shapes represent data declared by manufacturers, or calculated on their basis
- Solid and dotted curves correspond to generalization by trend lines. These curves are provided to improve the perception and analysis of the general behavior of the parameters, as well as for the approximated forecasting of the impact of baghouse collectors on the environment, given at the end of the research.

In Fig. 2 and 3, and all the figures further in the text of the manuscript, the following conventions are used.

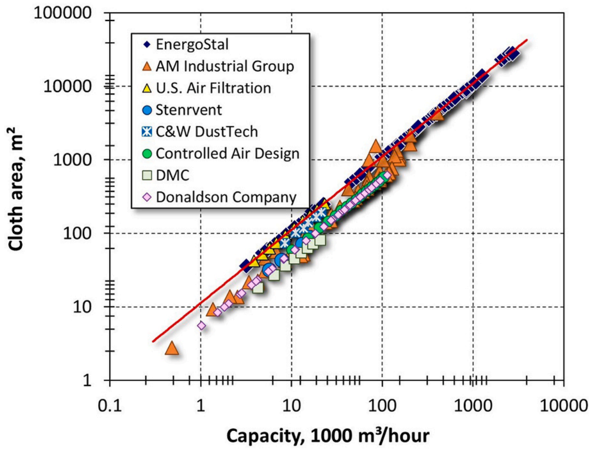

Fig. 3. Cloth area vs Capacity for all the analyzed baghouse collectors. Logarithmic axes.

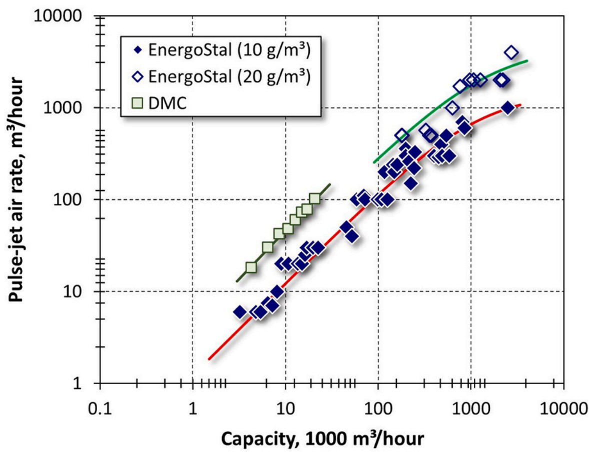

Fig. 4. Pulse-jet (Compressed) air rate vs Capacity.

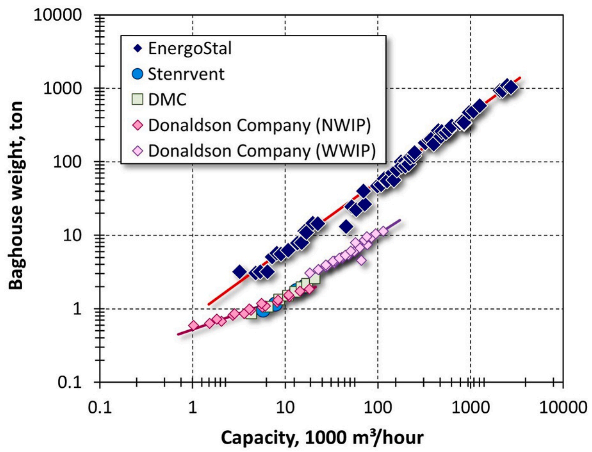

Fig. 5. Weight of the baghouse dust collector vs Capacity.

3.2. Weight of the baghouse

Although the ***weight of the equipment*** does not directly affect the quality of the cleaning process or the energy efficiency of the dust collector, it becomes important if the Life Cycle Assessment procedure is applied for the evaluation of the energy/environmental efficiency of the production. So, the weight of the baghouse dust collector – is important for our analysis, although it is not so important for customers.

Fig. 5 presents data for this parameter for pulse-jet baghouse dust collectors.

As expected, the weight of the collector increases with increasing purified airflow. From the compared brands, it follows that the UkrSTC Energostal collectors have the largest weight, while Donaldson Company's, Sternvent, and DMC baghouse collectors weigh less, for the Capacity being equal.

Donaldson Company's models with a capacity larger than 18,000 cubic meters per hour can be supplied with a walk-in clean air plenum design providing protection during inclement weather. It is for this reason that there are two "separated" groups in the figure.

- NWIP – none walk-in-plenum;
- WWIP – equipment with walk-in-plenum.

3.3. Manufacturing energy

Knowing the baghouse and cloth weights, it is possible to carry out a simplified calculation of ***energy*** that is required for the manufacturing of the end-user product. To do this we use data from the book [29] where a detailed analysis of the metallurgical processes is given. Data on plastic production was taken from Ref. [31] as was mentioned earlier. Data, collected and used for the calculation, are presented in Table 1.

Calculation of the manufacturing energy consumption (E_m) for the exact pulse-jet baghouse collector model is made by formula (1):

$$E_m = E_b + E_c = SE_s \times Weight_{collector} + SE_p \times \rho_s \times Cloth_{area} \tag{1}$$

Here,
E_m – manufacturing energy consumption, [J];
E_b – energy consumption for metal baghouse ***body*** production, [J];
E_c – energy consumption for filter bags production, [J];
SE_s – specific energy for rolled steel production, [J/kg];
$Weight_{collector}$ – mass of baghouse collector body, [kg];
SE_p – specific energy for raw plastic production;
ρ_s – surface density of filter bag fabric, [kg/m^2];
$Cloth_{area}$ – total Cloth area of filter bags, [m^2].

Unfortunately, all the data necessary for calculations of energy consumption is available only for bag filters of UkrSTC Energostal. Therefore, further results were obtained only for the production of this manufacturer.

Limiting the energy consumption assessment of baghouse collectors to only one manufacturer does introduce some limitations to the analysis. This may affect the reliability and generalizability of the results. The energy consumption of baghouse collectors varies significantly between manufacturers due to differences in design, materials, technology, and operating parameters. On the other hand, this limitation affects the exact quantitative parameters, but should not affect the general behavior of the dependencies. Understanding the nature of phenomena, which is the main scientific goal of any research, allows us to critically perceive the results and avoid incorrect conclusions. Of course, future research is needed to study a wider range of manufacturers and compare their products to obtain a more accurate quantification of energy needs. Nevertheless, the basic correlations apply to any pulse-jet baghouse dust collector and their qualitative behavior is similar.

Fig. 6 presents the dependencies of the energies required for metal body and filter material manufacturing, as well as their ratio to the baghouse capacity. In addition to the expected obvious relationships: energy costs for the production of bag filter components increase with increasing productivity of the pulse-jet baghouse dust collector, a few important remarks could be given as the result of the figure analysis.

Firstly, the correlation between the manufacturing energy needed for the production of baghouse metal body is not linear but exponential with the order of degree less than 1 – a solid curve that approximates data for "Body" is not a straight line. This means that the larger the productivity of the baghouse the less its specific weight (weight of baghouse divided by capacity).

Secondly, the crossed circles in Fig. 6 present the Body/Cloth ratio of manufacturing energies of the baghouse collectors. Despite the quite high dispersion of the data at the range of low capacities, a general trend of this ratio is also decreasing.

Table 1
Input data for manufacturing energy calculation.

Parameter	Units	Value	Elements' manufacturing	Total
Specific energy for rolled steel production [29],	MJ/kg	41.02	+30 %	53.33
Specific energy for raw plastic production [31],	MJ/kg	112.2	+30 %	145.86
Plastic filter bag surface density, ρ_s	kg/m^2	0.5	–	–

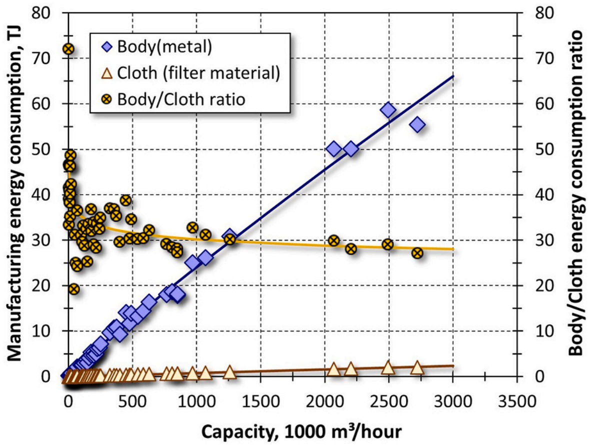

Fig. 6. Energy consumption for the manufacturing stage.

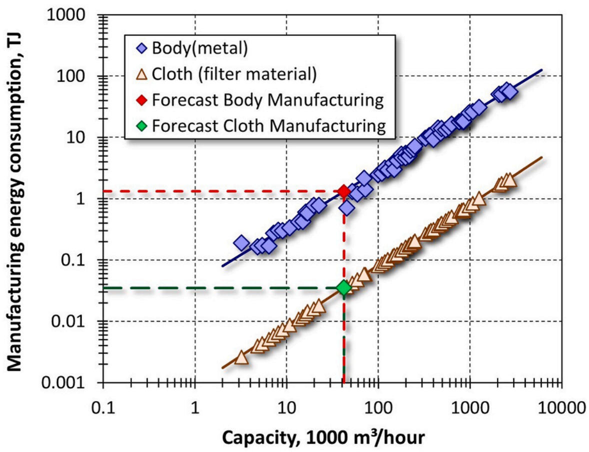

Fig. 7. Energy consumption for the manufacturing stage. Logarithmic axes.

Finally, as followed from the logarithmic representation data in Fig. 7, the manufacturing energy required for filter bags' production also exponentially depends on baghouse capacity – the approximation curve is a straight line in logarithmic axes. The order of degree is also less than 1.

Exponential correlations with both (Body and Cloth) manufacturing energies with the orders of degree less than 1 is an important result that provides an interesting opportunity for controlling the environmental impact of the dust collectors.

In simple words, by making one pulse-jet baghouse dust collector of large capacity instead of several smaller ones, we decrease the manufacturing energy consumption and, consequently, reduce the environmental load of the dust cleaning system for the same productivity of the baghouse collector.

3.4. Operation energy

During the operation phase, a pulse-jet bag dust collector consumes energy to operate a *suction fan*, which moves contaminated air from the dust source into the environment through the filter material. Also, periodic cleaning of bag filters from dust deposits requires energy generated by the *compressed air system*.

Power consumed by the ***suction fan*** depends on the overall baghouse hydraulic resistance and the fan efficiency. Formula (2) was used for the calculation of the operational energy of the suction fan:

$$E_{fan} = H_{filter} \times Capacity \times t / \eta_{fan} \tag{2}$$

Here,

E_{fan} – Energy consumption by suction fan operation [J];

H_{filter} – Hydraulic resistance of baghouse dust collectors [Pa];

Capacity – Baghouse productivity, [m^3/s];

t – Time of operation, [s];
η_{fan} – Fan efficiency.

The energy, required for bag filter cleaning by pulses of ***compressed air***, is the work of the air compressor to compensate for the pressure drop during the cleaning pulse. Assuming the polytropic process of the compression air in the compressor, the following formula was used for the calculation (3):

$$E_{comp\_air} = \frac{\Delta P \times q_{comp\_air} \times t}{k-1} \times \frac{1}{\eta_{comp}} \tag{3}$$

Here,

E_{comp_air} – Energy of air compressor operation, [J];
ΔP – Pressure difference between compressed air and ambient air, [Pa];
q_{comr_air} – Compressed air rate, [m^3/s];
t – Time of operation, [s];
k – Exponent of polytropic process, 1.33 [17];
η_{comp} – Compressor's efficiency.

- Compressed air rate – q_{comr_air}, obviously, depends on the baghouse collector Capacity.
- Operational energy consumption depends on the operational lifetime.

Using the formulas above and data of UkrSTC Energostal baghouse collectors [30] the operational energy consumption for a one-year duration was calculated. The results are presented in Fig. 8.

Interestingly, for the considered pulse-jet baghouse dust collectors, the energy consumption at the manufacturing stage is very close to the operational energy consumption during a year of operation (i.e., both data sets look like they match in Fig. 8, as do the trend lines describing their approximations).

From this latest observation, an intriguing new insight emerges regarding the impact of filter bag cloth area on energy consumption and CO_2 emissions. Typically, filter bags boast a service life exceeding one year. The extensive cloth area of filter bags facilitates less frequent cleaning, consequently extending their lifespan. This prolonged lifespan of the baghouse translates to reduced replacement frequency, thereby diminishing the proportion of energy expended on bag production in the overall energy demand and CO_2 emissions contribution over its extended lifespan. Consequently, over the long term, the additional filter area proves advantageous from an energy efficiency standpoint.

Fig. 9 presents the sum of manufacturing and operational energy consumption. Since operational energy consumption depends on the duration of the baghouse's operational life, we have conducted calculations for different durations ranging from 1 to 10 years for the UkrSTC Energostal baghouse collectors. As expected, the longer the operational life of the baghouse, the higher the total energy consumption. It is worth noting that this figure includes only the one-time manufacturing energy consumption for filter bags. In real conditions, filter bags are replaced periodically. However, the frequency of replacement is a highly specific parameter that cannot be predicted, as it depends on numerous factors.

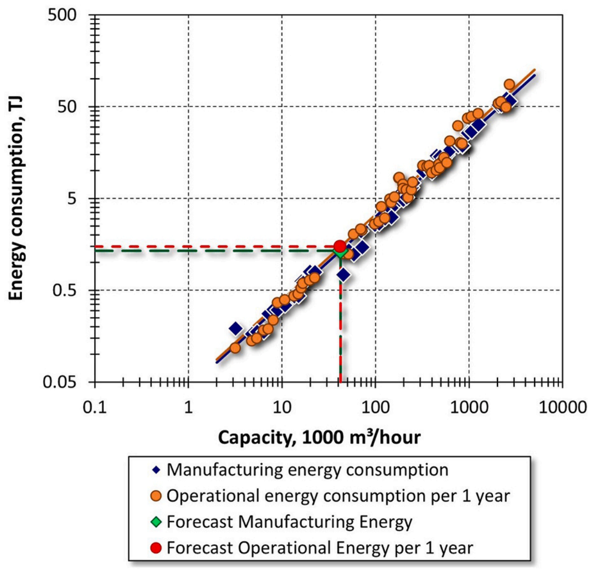

Fig. 8. Comparison of energy consumption at the production stage and during 1 year of operation.

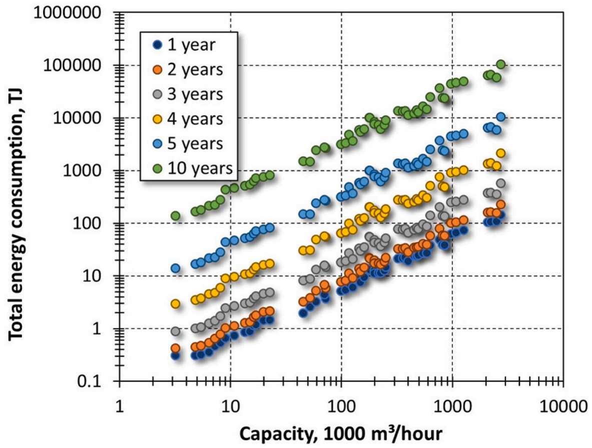

Fig. 9. Total energy consumption by the baghouse dust collectors.

3.5. Forecast of the impact of dust collection system on the environment

We are interested in assessing the impact of pulse-jet baghouse collectors on CO_2 emissions, so the service life was taken from 2022 to 2030 years. The total market of industrial dust-collecting systems is expected at US$10.77 billion by 2030 [40]. The total market size of those systems in 2022 and 2023 was estimated at US$7.28 billion and US$7.60 billion, respectively. As of 2022, the share of industrial baghouse dust collectors was 32 % of the total market [40].

Following the graphical presentation of these data in Fig. 10, the expected growth in the industrial baghouse dust collectors market is exponential. The solid curve in the figure reflects the approximation of the forecast data and can be used to calculate intermediate results.

If we know the average baghouse collector price, using data from Fig. 10 we can guess the number of baghouse dust collectors produced over the world by years. Then the energy consumption at the manufacturing and operation stages can be estimated, after which we can calculate the equivalent of CO_2 emissions.

However, there are many different models of industrial pulse-jet bag dust collectors of varying capacities, and, accordingly, their price varies widely. Although the price of the dust collector is usually calculated individually by project, averaged estimations from Ref. [41] can be accepted as the basis. There are only data for three points in Ref. [41].

- Capacity of 1000 cubic feet per minute (CFM) (1699 m^3/h) – US$5000;
- Capacity of 2000 CFM (3398 m^3/h) – US$10,000;
- and Capacity of 10,000 CFM (16,990 m^3/h) – US$80,000

If putting these data on the graph, it is seen that the correlation between the price and baghouse capacity is not linear but exponential (Fig. 11). Of course, as can be seen from the figure, in the case under consideration, the linear approximation provides a fairly good match with the coefficient of determination R^2 equal to 0.9934. However, the detailed analysis of the insertion at the left

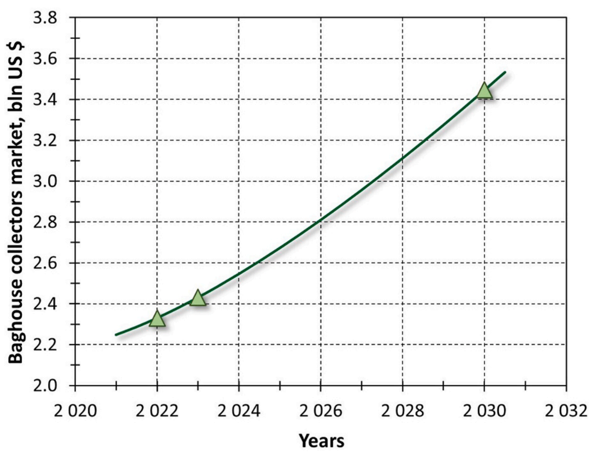

Fig. 10. Baghouse industrial dust collectors market size by years.

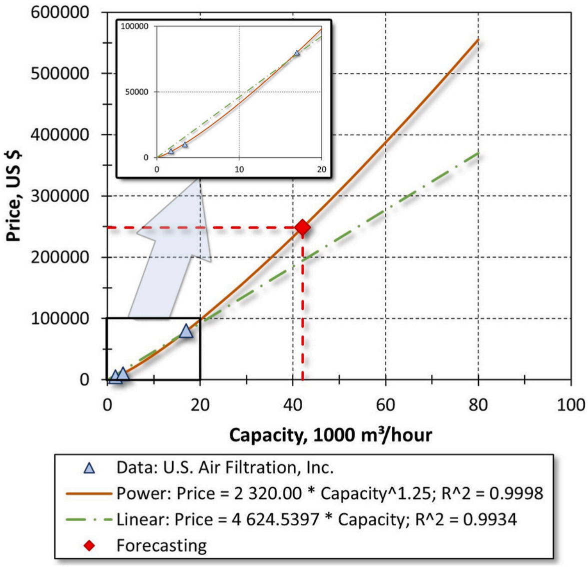

Fig. 11. Price of pulse-jet baghouse dust collector on Capacity.

upper corner of Fig. 11 shows that the linear approximation is wrong.

The approximation of any data in any field must meet some "boundary conditions" or reference points. In this case, one of these conditions is the zero-point condition. In the case under consideration, if the capacity of the bag filter is 0, then the price should be zero. As can be seen, the linear approximation, which must pass the required [0; 0] point, does not correspond to the behavior of the trend, while the exponential approximation follows the overall trend much better. Thus, for predictive calculations, exponential (power) approximation should be used.

So, calculating the average price of a baghouse collector requires knowing the average capacity of baghouse collectors. Using the example of the sample under consideration we can estimate the average capacity by the use of statistical treatment. The simplest approach for this is the calculation of the arithmetic median, which gives us the result of 162,000 m^3/h. However, the analysis of the data for example from Fig. 2 shows that most of the manufactured pulse-jet baghouse collectors have a capacity of less than 250,000 m^3/h, whereas collectors of higher capacity are quite rare. This is confirmed by the normal distribution curve of collectors by capacity (Fig. 12a), as well as data on the frequency distribution (Fig. 12b) that were calculated by use of Microsoft Excel Data Analysis Toolpak.

Fig. 12 shows that 85 % of the manufactured pulse-jet baghouse collectors of the sample are concentrated in the capacity range of 1–200,000 m^3/h. Each of all other capacities has a frequency distribution value of less than 3 %. Following these results, we calculated the average capacity by the limited sample of less than 200,000 m^3/h. Thus, the resulting average capacity of industrial pulse-jet baghouse dust collectors is 42,093 m^3/h. This value was used to calculate and forecast the total energy consumption of industrial baghouse dust collectors worldwide from 2022 to 2030. These calculations correspond to the points labeled "Forecast" in Figs. 7, 8 and 10.

The general procedure of the calculation is as follows.

1. Based on the data of UkrSTC Energostal baghouse dust collectors (Figs. 2 and 3) the parameters of fabric bags and their number were determined:

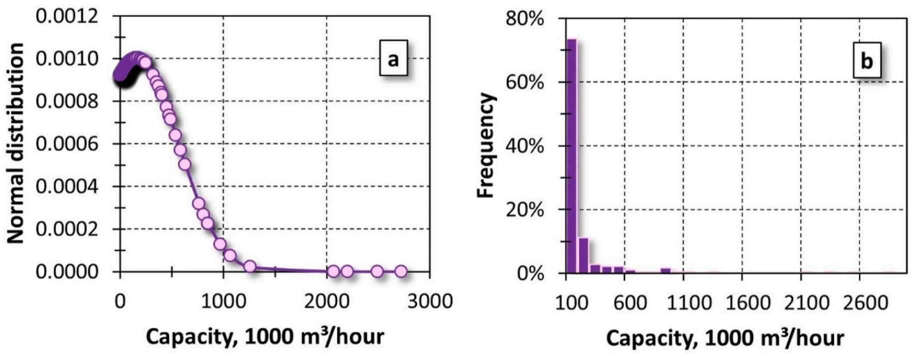

Fig. 12. Normal distribution (a) and frequency distribution (b) of baghouse dust collectors by capacity.

2. For Capacity 42′093 m^3/h Cloth area is ∼468 m^2;
3. UkrSTC Energostal provides filter bags ranging in length from 1.6 to 8 m, with an average length of 5.32527 m. So, let the filter bag size is 5 m in length and 130 mm in diameter, so, 230 filter bags are needed for the baghouse dust collector manufacturing;
4. The approximate price of one filter bag of 5 m in length and 130 mm in diameter is ∼ US$50. (Cloth example link: https://remix.in.ua/ua/p504892428-rukav-filtrovalnyj-rtsi.html; Support frame example link: https://remix.in.ua/ua/p1800449226-karkas-rukava-filtrovalnogo.html). Thus, US$ 11,500 is the cost of 230 filter bags. Using the power trendline data from Fig. 11, the cost of the entire baghouse dust collector is to be ∼ US$250,000, where US$11,500 – is the cost of the fabric filters (∼4.62 %)
5. By dividing the market size minus the share of filters (4.62 %) for the corresponding year by the cost of one collector, we obtain the number of collectors produced per year (Fig. 13). By dividing the share of filter market size (4.62 %) for the corresponding year by the cost of one filter bag, we obtain the number of filter bags produced per year (Fig. 13).
6. Using the dependences of cloth area – Fig. 3, manufacturing energy consumption of filter bag and manufacturing energy consumption of metal body of the baghouse collector – Fig. 7 – all these one-time per year, and operation energy consumption of baghouse collector Fig. 8 – cumulative, the total energy consumption at manufacturing and operational stages of the industrial baghouse dust collectors worldwide can be calculated.
7. Finally, using the recommendation of [42] the calculated energy consumption is converted to CO_2 emissions using emission factors.

Fig. 14 presents the results of the forecast of the cumulative CO_2 emissions generated by industrial baghouse dust collectors worldwide. It is worth noting, that these emissions should be added to the existing 2021 CO_2 emissions level.

Thus, as follows from the assessment, industrial dust collectors will add more than 70 million tons of additional carbon dioxide emissions by 2030.

3.6. *Possible strategy for emission reduction*

Among all the arrangements that could be used for a decrease in CO_2 emissions, there is one that has already been mentioned earlier in the subchapter devoted to the discussion of manufacturing energy – Fig. 7. The proposed solution is quite simple: just by paying attention to the correct layout of dust collection pipelines at an industrial enterprise and combining them into one large baghouse collector, the specific weight of the dust collector can be reduced by 3–10 times. Fig. 15 demonstrates this result.

The next important observation that was made during the analysis is related to the peculiarity of the compressor operation for pulse cleaning. An increase in the baghouse collector capacity leads to an increase in the rate of the compressed air. However, from Fig. 4 it is seen that the latter increases slower than capacity. So, we have a similar phenomenon to the specific weight: specific compressed air rate (air rate divided by capacity) decreases with the growth of the baghouse capacity. In terms of energy, this means a decrease in operation energy consumption.

Fig. 16 allows us to compare the operation power (energy per hour) of the suction fan and the compressor for pulse-jet cleaning of fabric filter bags. As expected, the energy consumption of the suction fan increases linearly with the increase in the capacity of the bag collector. However, the energy consumption of the compressor of a pulse-jet cleaning system depends on the capacity of the power-law relationship. The larger the baghouse collector capacity, the slower the energy consumption of the cleaning system increases.

Moreover, from Fig. 16 follows that at a small baghouse collector capacity, as well as at a high level of dust concentration, the energy consumption of the pulse-jet cleaning system is equal to or greater than the energy consumption of the exhaust fan. The longer the service life of the dust collector, the greater the energy consumption during its operation. In this way, it is feasible to scale up the dust collection facility to reduce both manufacturing and energy consumption. This will result in a reduction in associated CO_2 emissions.

To estimate the potential decrease in CO_2 emissions achievable by this approach, we conducted a simplified calculation based on the approximate data on energy consumption for UkrSTC Energostal baghouse collectors. Fig. 17 allows for evaluating the results.

From the figure, it can be observed that replacing, for example, three individual dust collectors of smaller capacity (X) with one large baghouse collector of increased capacity equal to $3 \times X$ can lead to a decrease in carbon dioxide emissions by approximately 8.4 % during the baghouse manufacturing stage and by approximately 7.3–7.5 % during the operational stage. Interestingly, with an increase in the operational life of the collectors, the benefit of this approach seems to decrease. However, this aspect should be clarified in future detailed analyses.

The greater the number of baghouses that can be combined, the more CO_2 emissions can be reduced.

Nevertheless, there are a lot of various factors and specifics of the exact production lines where baghouse collectors are used. It is necessary to determine how many processes actually rely on the use of multiple baghouses and whether the proposed solution is applicable. For example, from a process and safety perspective, the chemical industry would rather not combine different gas streams, potentially carrying different dust and chemical compositions, into one large baghouse rather than using several smaller ones. This consideration goes beyond mere logistical convenience and encompasses broader implications for operational efficiency, environmental impact, and occupational safety.

Moreover, it is important to realize that in certain scenarios, the choice of filter materials must account for their chemical resistance to specific gas components, such as hydrolysis, environmental aggressiveness, specific dust substances, and more. There is no universally applicable filter material suitable for installation in a large bag filter covering all possible production processes. This underscores the importance of a detailed and context-specific approach to materials selection, considering the unique chemical environment and operational requirements of each process.

Additionally, detecting and diagnosing leaks and bag defects pose greater challenges in larger baghouses, making troubleshooting

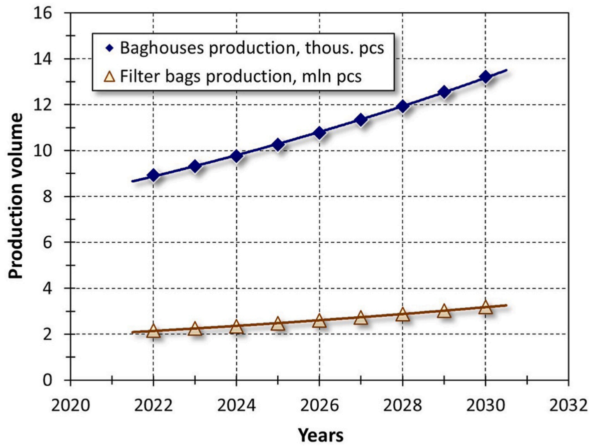

Fig. 13. Forecast of baghouse collectors and filter bags production per year, pcs.

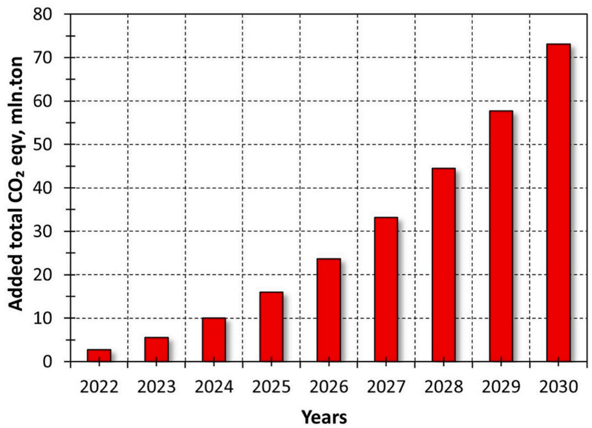

Fig. 14. Cumulative CO_2 emissions from industrial baghouse dust collectors (as an addition to the 2021 level).

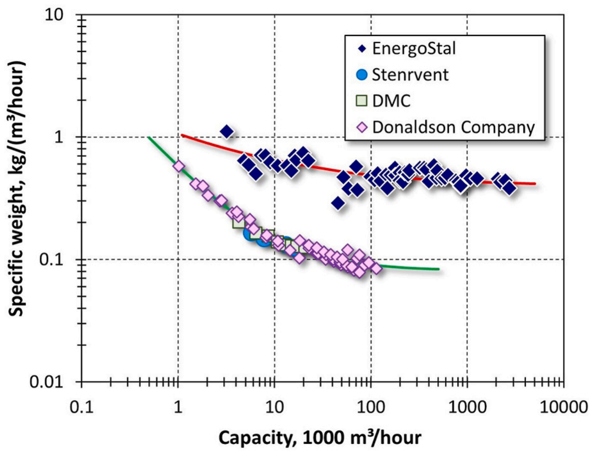

Fig. 15. Specific weight vs baghouse dust collector Capacity.

much more difficult. This not only complicates regular maintenance and repairs but also increases the risk of extended downtime and potential safety hazards. Therefore, careful consideration must be given to the design and implementation of monitoring systems and maintenance protocols to effectively address these issues.

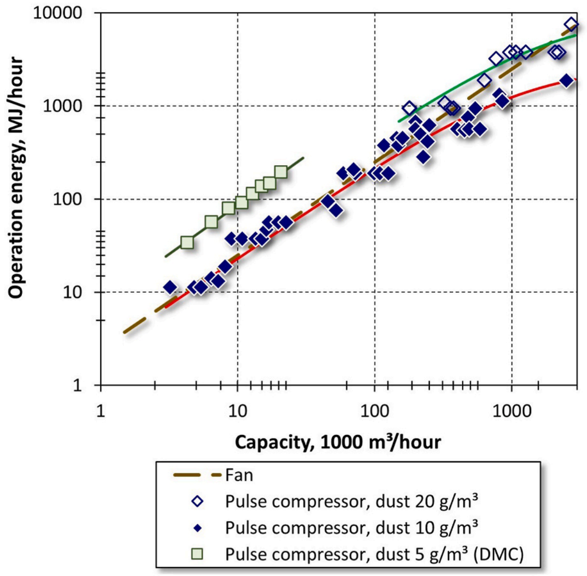

Fig. 16. Operational energy consumption per 1 h for suction fan and compressed air system.

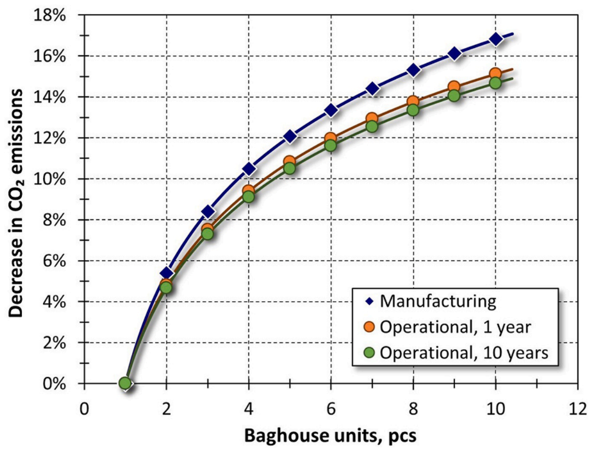

Fig. 17. CO_2 emission reduction by the replacing of N baghouse collectors of X capacity with one baghouse collector of $N \times X$ capacity.

The main goal of the study was to assess the contribution of the production of bag dust collectors and their operation to carbon dioxide emissions. The proposed solution can be considered as one of the ways to reduce such a contribution, but it should not be considered the only correct one.

4. Conclusions

Despite dust collection systems improving air quality by removing particulate matter, their manufacturing and operation influence CO_2 emissions. According to the research findings, cumulative CO_2 emissions from industrial baghouse dust collectors worldwide are expected to exceed 70 million tonnes, in addition to the 2021 level of emissions.

The specific weight of industrial baghouse dust collectors (weight divided by the collector's capacity) decreases as the capacity increases. Consequently, energy consumption during the manufacturing stage of these collectors is also reduced. Additionally, the specific compressed air rate used for pulse-jet cleaning of the fabric filter bags decreases with an increase in the capacity of the baghouse collector.

Consolidating dust collection pipelines at industrial enterprises into a single large baghouse dust collector instead of multiple smaller baghouse dust collectors helps reduce CO_2 emissions during the baghouse collector's manufacturing and operational stages. While this approach appears promising, its feasibility should be carefully analyzed before implementation.

Availability of data and materials

Data associated with the study has not been deposited into a publicly available repository. Data are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Andrey Skoromny: Validation, Resources, Methodology, Formal analysis, Data curation. **Valeriya Pinchuk:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrey Kuzmin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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