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The use of algae as carbon dioxide absorber in heat production industry

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Abstract: There are approximately 15 million users of system heat in Poland, but unfortunately nearly 70% of the fuel used in heat production is fossil fuel. Therefore, the CO_2 emission reduction in the heat production industry is becoming one of the key challenges. City Heat Distribution Enterprise Ltd. in Nowy Sącz (Miejskie Przedsiębiorstwo Energetyki Cieplnej sp. z o.o.) has been conducting a self-financed research and development project entitled *The use of algae as carbon dioxide absorbers at MPEC Nowy Sącz*. The project deals with post-combustion CO_2 capture using *Chlorella vulgaris* algae. As a result of tests conducted in a 1000 l hermetic container under optimal temperature and light conditions, the recovery of biomass can be performed in weekly cycles, yielding approximately 25 kilograms of biomass per year. Assuming that half of the dry mass of the algae is carbon, it can be said that 240 grams of carbon is bound in one cycle, which, converted to CO_2, gives 880 grams of this gas. Our results showed that around 45.8 kilograms of CO_2 per year was absorbed. Additionally, it is possible to use waste materials and by-products of technological processes as a nutrient medium for algae.

Introduction

CO_2 emissions continue to increase annually. Therefore, to reach the goals set in the Paris Climate Agreement, it is necessary to reduce emissions and to implement methods of CO_2 capture (Kammerer et al., 2023). The necessity to reduce CO_2 emissions is required by a number of international laws, including the Fit For 55 package (Brożyna et al. 2023) and the revision of the Emissions Trading System (EU ETS) (Bordignon and Gamannossi degl'Innocenti, 2023, Rogulj et al. 2023).

In 2022, in the global emission of CO_2 by sectors, the largest emissions were observed in the electric energy and heat generation sectors, amounting to 39.7% of the total emissions (International Energy Agency, 2023). In Poland, system heat is used by approximately 15 million people, and regulated heat accounts for 42% of the market in households (Izba Gospodarcza Ciepłownictwo Polskie 2023). The diversification of fuels used in heat production is progressing slowly. The Polish market is still dominated by fossil fuels, which in 2021 accounted for 69.5% of all fuels used in heat sources (in 2020 – 68.9%, in 2019 – 71%, in 2018 – 72.5%, and in 2017 – 74.0%). In 2021, 14,089 thousand tons of this raw material were used for licensed heat engineering needs (Urząd Regulacji Energetyki 2022). It must be pointed out that apart from the combustion process, the excavation of coal poses a serious burden on the environment (Chłopek et al. 2021).

The above data show that the reduction of CO_2 emissions constitutes a serious challenge. Four ways of decreasing the carbon dioxide emission level can be distinguished: reducing the use of fossil fuels (including the use of renewable energy sources and green hydrogen, reducing energy demand, improving the efficiency of energy conversion processes), replacing coal-based technologies, reducing deforestation processes and, as a result, storing larger amounts of CO_2 in biomass, capturing CO_2 from burning fuels, and storing it in appropriate geological structures (Erdiwansyah et al. 2023, Nord and Bolland 2020). These methods of capture of carbon dioxide in power stations and heat and power stations are vital due to the scale of the phenomenon and the slowly progressing process of decarbonization of Polish heat engineering. Potential methods and techniques of CO_2 capture in power stations and heat and power stations include:

- CO_2 capture before the carbon combustion process: in this method, the fuel undergoes oxidation in the gasification process, resulting in the production of synthetic gas composed of hydrogen and carbon monoxide (Faizal et al. 2021, Madejski et al. 2022).
- CO_2 capture during the combustion process in an oxygen atmosphere involves separating the CO_2 generated during the combustion process in oxygen. This method includes capturing and storing CO_2 in geological structures deep below the earth's surface (Madejski et al. 2022, Sifat and Haseli,2019).
- post-combustion CO_2 capture involves removing carbon dioxide from the combustion gas. The capture unit is placed after the cleaning installations such as desulfurization,

denitration, and dust removal. Technologies include chemical absorption, physical absorption (Schwister and Leven 2020), and adsorption.
– physical separation (Osman et al. 2021), membrane separation (Xie et al. 2019), combustion in a chemical loop (Sifat and Haseli 2019), cryogenic method (Font-Palma et al. 2021), and natural inclusion (utilizing plants, bacteria, algae) (Valdovinos-García et al. 2020).

The problem of reducing CO_2 emission also affects MPEC Nowy Sącz. The company, which produces heat, has an installed capacity of 80 MW. In 2019, in the main heat-generating plants, which accounted for 95% of heat production, namely Millenium (the largest boiler plant in MPEC, consisting of 7 coal-fired boilers with a total capacity of 70 MW) and Sikorskiego (MPEC's second largest boiler plant, which includes 4 coal-fired boilers with a total capacity of 13 MW), produced 100% of heat from coal. Despite significant expenditure and diversification of heat sources, approximately 40-49% of heat is still generated from coal (Kupczak 2021, 2022). Consequently, the company has undertaken a self-financed research and development project entitled *The use of algae as carbon dioxide absorbers at MPEC Nowy Sącz.* The main objective of the project was to assess the carbon dioxide absorption capacity of the installation in question under industrial conditions. The project focuses on post-combustion CO_2 capture using *Chlorella vulgaris* algae. The primary advantage of algae is their capability to assimilate large quantities of CO_2, ranging between 1.65 kg and 1.83 kg of CO_2 per kilo of generated biomass (Skompski et al. 2023).

The carbon content of algae dry matter was estimated based on information from the work of W. Kozieł and T. Włodarczyk (2011). The literature highlights numerous benefits resulting from using algae in CO_2 capture to reduce carbon dioxide emissions (Iglina et al. 2022). The reduction of CO_2 emissions will contribute to improving air quality in the city of Nowy Sącz and also the Kotlina Sądecka region, which has a significant impact on the health of residents and tourists. Recently, there has been a growing recognition of challenges related to algae and carbon sequestration. Algae have the potential to offer long-term solutions to critical global issues such as the energy crisis and climate change. It is worth noting that carbon dioxide contributes to global warming, accounting for 68% of total greenhouse gas emissions (Sarwer et al. 2022). Algae, being photosynthetic organisms, utilize their photosynthetic machinery to sequester carbon dioxide from the environment, exhibiting an increased photosynthetic efficiency 10 to 15 times higher than that of traditional plants (Zhou et al. 2017).

Material and methods

In industry tests, a preparation containing live *Chlorella vulgaris* algae culture was used. In laboratory scale, a 10 dm^3 bioreactor with constant mixing at 250 rpm was used. A synthetic nutrient medium was used, the composition of which is presented in Table 1 below.

Table 1. Ingredients of synthetic nutrient medium.

Ingredient	Concentration
Nitrogen (NH_4NO_3)	250 mg/l
Phosphorus (KH_2PO_4)	3 mg/l
Potassium (KNO_3)	30 mg/l

The culture developed under the following conditions: an airflow of 2.5 dm^3/minute and an ambient temperature of 23°C (±1°C). The tests were conducted in natural light. The concentration of algae in the reaction mixture was determined using the weight method, separating the biomass on the micro-filter. Samples of 150 cm^3 were taken for analysis. The first measurement was taken on the 4th day of algae growth, followed by further measurements every two days. The culture grew for 30 days. Due to the sedimentation of algae layers on the vessel walls, mechanical cleaning with a brush made from non-reactive plastic was performed every 3 days, starting from the 7th day of the process.

The experimental development work was conducted in a sealed 1000 l container, with the volume of the mixture being 800 l. To determine the concentration of biomass, samples with a volume of 0.5 l were taken. Instead of air, as was the case in the laboratory test, combustion gases taken from the channel leading to the chimney were used. Gases were administered from the bottom using the compressor with the flow rate of 10 l per minute in 30 minutes/2 hour cycles. Gases from above the surface of the mixture were returned to the combustion gas channel. Because the bioreactor had walls that did not transmit sunlight, an external source of artificial light located in the upper part of the container was used to provide light to the culture.

This LED lamp (AQUALED, model 5050-1P31-70) had a power of 9W and was designed for effective plant cultivation. The application of properly selected wavelengths (around 450÷470 nm and around 630÷660 nm) corresponded to the demand for chlorophyll present in *Chlorella vulgaris* (Matejczyk et al. 2023). The lamp consisted of red and blue light diodes in a repeated combination of colors 3R:1B. The algae proliferation process was conducted under conditions of periodic lighting, alternating between 18 h of light phase and 6

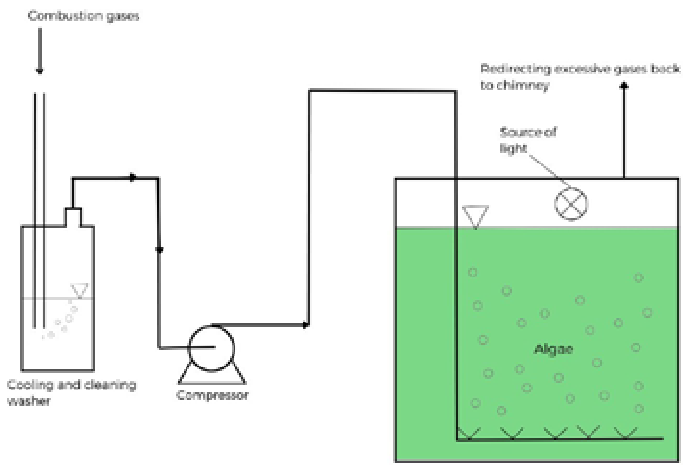

Figure 1. The installation diagram.

h of dark phase. The installation diagram is presented in Figure 1 below.

In the subject installation, the reactive liquid was mixed by bubbling, ensuring the inflow of combustion gases rich in carbon dioxide. The cultivation period was 45 days. Gases were extracted from the channel leading the combustion gases to the chimney via a 1/8" diameter gas pipe. The gas temperature was approximately 100°C, necessitating the use of a cooling and cleaning washer placed before the compressor. A sodium carbonate solution was employed in the cleaning washer to remove sulfur oxides and nitrogen oxides while preserving carbon dioxide. The average CO_2concentration in the entering gases was 13.3%, assessed using a "MADUR GA-21 plus" flue gas analyzer during a 3-hour measuring session with 10-second counting of the measured values. The CO_2 concentration in the exiting gases was not measured due to varying measurement error limits. The reaction of carbon dioxide fixation by algae was too slow to detect changes in CO_2 concentration under process conditions. Initially, the solution absorbed CO_2 until saturation, but in later phases, this saturation did not result in carbon dioxide absorption while neutralizing sulfur and nitrogen oxides. Periodic pH testing of the solution was conducted to monitor exhaustion, as it is known that H_2SO_3 inhibits the process of CO_2 absorption by algae (Dyachok et al. 2020).

The liquid in the washer had a pH in the range of 8-10. The absorbing liquid from the washer, containing nitrogen and sulfur from combustion gases, served as a carrier of mineral elements for the algae culture. The bioreactor was placed near the boiler house building, ensuring proximity to relevant water and electricity connections. The research post's location facilitated research continuity during winter months by relocating the bioreactor to the boiler hall, where the heat production installation using forest biomass (wood chips) was situated.

Ultimately, during the stable operation phase, half of the volume of the reaction fluid would be removed from the reactor for biomass recovery, after which it would be returned to the bioreactor and supplemented with minerals. The recovered biomass in the form of *Chlorella vulgaris* algae can be used as fertilizer, biomass for energy purposes, or further processed, e.g., torrefied for longer storage, for energy production. The use of a 1000-liter container is practical because of its easy availability, resistance to process conditions, and adaptability to different configurations – including additional lighting, mixing, or connection to other containers. This makes it possible to expand the system and make it practical on a larger scale.

Results and discussion

At the stage of industrial research, the optimal concentration of biomass was obtained between the 22nd and 26th day, which is presented in Figure 2 below. The constant supply of air which contains carbon dioxide allowed for intense growth of the biomass.

The greatest growth of biomass, averaging 100 mg/l per day, was observed between the 22nd and 26th day of culture growth. At this stage, it was concluded that biomass separation might pose challenges on an industrial scale. Various separation methods were explored, with coagulation using $Fe_2SO_4 \cdot 7H_2O$

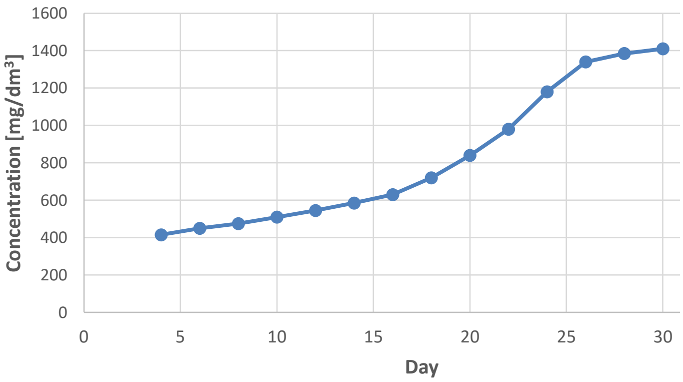

Figure 2. Changes to the biomass concentration.

followed by flocculation and filtration proving most efficient. SUPERFLOC 492 HMW was utilized as the flocculant, but other positive ion polyelectrolytes could also be considered, necessitating testing the whole range of preparations available on the market. Depending on the initial concentration of biomass in the culture and the conditions of the process, the time needed to reach the maximum growth of biomass and its optimal concentration may vary. This has already been proven, as can be seen from the results of available research (Dziosa and Makowska 2015, Szatyłowicz et al. 2017).

In their papers, researchers indicated the influence of temperature, mineral elements or light on the speed of biomass growth (Metsoviti et al. 2019). An important issue affecting the algae growth speed is the presence of mineral elements, such as compounds of nitrogen and phosphorus, whose sources may also be found in sewage (Tleukeyeva et al. 2021; Urbina-Suarez et al. 2021, Yu et al., 2023) without atrazine and heavy metals, which may be absorbed by algae (Liu et al., 2021, Matejczyk et al. 2023). The rate of algae growth is also influenced by the by-products of the reactions, as well as waste, which additionally affects the pro-ecological nature of such installations (Urbina-Suarez et al. 2022). The use of gases with increased CO_2content was in line with the direction adopted by other authors (Dyachok et al. 2019), who described the possibility of absorbing carbon dioxide by microalgae synthesizing chlorophyll. It was demonstrated that both CO_2 and sulfur oxides, nitrogen oxides and phosphorus oxides are absorbed by the stems of microalgae. A control experiment conducted in an open tank under similar light and temperature conditions showed 5.3 times slower biomass growth.

In the experimental development work, reactions were conducted in a pilot installation presented in Figure 3, resulting in similar biomass concentrations. The bioreactor, constructed from high-density polyethylene, offered the advantage of translucency, enabling observation of the fluid in the tank. A compressor, visible on the tank, injected exhaust gases through a pipe located on the left side of the green cap, facilitating mixing of the reaction liquid. Inside the tank, a light source was attached to its upper wall. Excess gases were discharged through a pipe attached to the green cap on the right side. The green hue of the liquid in the tank was attributed to the presence of *Chlorella vulgaris* algae.

In the initial period of culture growth, before the 12th day, a gradual intensification of the green color of the reactive liquid was observed, indicative of algae proliferation. Subsequently,

Figure 3. Installation for absorbing carbon dioxide using Chlorella vulgaris algae in industrial conditions.

after the 12th day, we noted the sedimentation of algae on the container walls, primarily at the liquid level. Due to the substantial flow rate of combusted gases relative to the rate of CO_2 absorption by the algae, there were differences in the concentration of CO_2 in the gases at the inlet and outlet of the reactor within the measurement uncertainty limits. As a result, we determined the amount of CO_2 absorbed by examining changes in the concentration of algae in the solution, as depicted in Figure 4 illustrating the changes in biomass concentration over time.

After reaching an algae concentration of 1200 mg/l, half of the 800 l of the reactive mixture underwent filtration, yielding 480 grams of biomass. The experimental setup utilized a container with a liquid height of approximately 80 cm, a specificity noted in the experimental design. According to available literature, the optimal depth or height of the liquid in a photobioreactor for the cultivation of *Chlorella vulgaris*

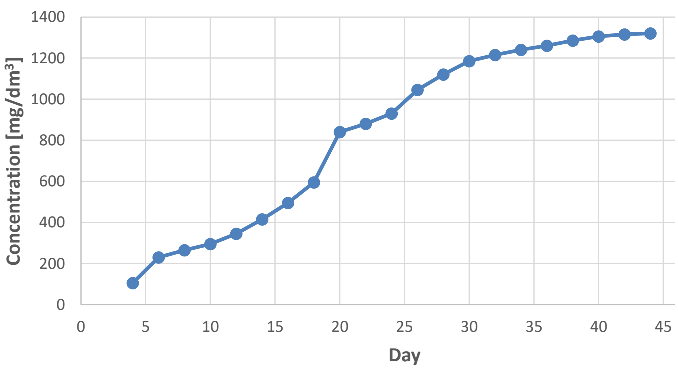

Figure 4. Changes in the concentration of alga at the stage of experimental development work.

algae ranges from 15 to 50 cm (Daliry et al. 2017). Despite this, vigorous mixing of the container's contents aimed to enhance light accessibility for the algal cells within. Consequently, the fluctuating biomass growth could be attributed to variable conditions such as lighting and temperature, especially as the process was conducted outside the boiler house. Unlike other researchers (Yerizam et al. 2023), who relied more on natural light in their investigations, our approach employed a closed container.

It was determined that under optimal temperature and light conditions, the recovery of biomass can be conducted in weekly cycles, yielding around 25 kilograms of biomass per year. Assuming that half of the dry mass of algae is carbon, it can be assumed that in one cycle 240 grams of carbon is bound, which corresponds to 880 grams of CO_2. Assuming weekly biomass recovery, this yields 52 cycles per year of 0.24 kg, or 12.48 kg of bound carbon. Thus, it is possible to absorb around 45.8 kilograms of CO_2 per year. The cost of such an installation amount to around USD 650. The installation consumes approximately 0.5 kWh/day, and this energy can be obtained from renewable sources. The total energy consumed by the installation is 943 kJ/day, while the energy stored in the carbon absorbed in the biomass is approximately 1695 kJ. Therefore, the energy balance is positive, totaling approximately 752 kJ/day.

Biomass recovery from CO_2-absorbing algae colonies represents an innovative approach to efficiently treat the carbon dioxide contained in flue gases. This process facilitates the conversion of CO_2 gas into solid and dry organic biomass, thereby contributing significantly to the mitigation of greenhouse gas emissions. Algae colonies, serving as natural filters, not only absorb pollutants but also enable the recovery of a valuable raw material in the form of biomass.

The method described differs from others in the literature (Fawzy et al. 2022) in several ways. Firstly, biomass growth is induced by providing specific conditions, primarily aimed at absorbing carbon dioxide. Additionally, it serves as the raw material for the biocarbon production process outlined in the description.

To implement the described method of CO_2 sequestration, only minor modifications were required, such as the construction of an intake point and flue gas discharge, as well as the purchase of individual components of the installation. The advantage of the described solution lies in the simplicity of implementation and the relative ease of the process. However, achieving significant capacities exceeding 50 kg of absorbed CO_2 per year in an installation with the given parameters requires careful control of the conditions and operation of the system. Based on the results obtained, scalability can be achieved by multiplying the number of individual tanks (reactors). Increasing the volume could result in zones of negligible light penetration in a larger volume of reaction liquid (Skawińska et al. 2014). The main advantage is speed, as optimal conditions for the process are reached in just a few days, while trees need many years to do so. In terms of the number of trees, the project's 1000-liter container can absorb about 45.8 kg of CO_2 per year, which is equivalent to the amount absorbed by 8 trees.

To assess the feasibility of implementing the proposed solution on a larger scale in thermal power plants, the application for 100% CO_2 absorption during year-round operation of a 5 MW coal-fired boiler will be analyzed. The calculations consider the combustion of 650 kg of coal dust per hour with a calorific value of 23 MJ/kg, an ash content of 15.5% and a total moisture content of 9.8%. With these parameters, the CO_2 capture installation would need to have a volume of 340,000 m^3, equivalent to a cube with a side of 70 meters. The estimated cost of such an installation would be USD 221 million, which is not economically justified. In addition, there is uncertainty about the linearity of the results as the volume increases. Additionally, heating costs would need to be considered for such an installation. In the current project, excess heat from the plant is wasted, but with full utilization, there would be additional heating costs during the periods of temperatures below $+25^0$C.

Conclusions

1. The micro-installation for CO_2 capture from coal-fired boilers in heat and power stations leads to the reduction of CO_2 emissions.
2. The significant tolerance of *Chlorella vulgaris* algae to growth conditions enables their industrial use in CO_2 absorption plants.
3. In a sealed 1000 l container, under optimal temperature and light conditions, the recovery of biomass can be conducted in weekly cycles, yielding approximately 25 kilograms of biomass per year. Assuming that half of the dry mass of algae is carbon, it can be inferred that in one cycle, 240 grams of carbon is bound, which, in terms of CO_2, equates to 880 grams of this gas. Therefore, around 45.8 kilograms of CO_2 can be absorbed per year.
4. Waste products and by-products can be used as a source of mineral elements needed for algae growth, thus reducing the burden on the natural environment.
5. Eight trees can absorb the same amount of CO_2 in that time. However, it should be noted that trees consume almost no energy during their growth. The efficiency of trees in terms of CO_2 absorption is very high.
6. The solution resulting from the project *The use of algae as carbon dioxide absorbers at MPEC Nowy Sącz* is not suitable for application and scalability in thermal power plants due to economic reasons and a lack of confirmation of the linearity of the results. Nevertheless, given the success of the project and the promising results, cheaper solutions should be sought.
7. It seems reasonable to continue the research considering two main directions – first, intensification of the process; and second, research in other systems using cascade reactors and process studies in different container dimensions.

References

Bordignon, M. & Gamannossi degl'Innocenti, D. (2023). Third Time's a Charm? As-sessing the Impact of the Third Phase of the EU ETS on CO2 Emissions and Performance. *Sustainability*, 15 (8), 6394. DOI:10.3390/su15086394

Brożyna, J., Strielkowski, W. & Zpěvák, A. (2023). Evaluating the Chances of Implementing the "Fit for 55" Green Transition Package in the V4 Countries. *Energies,* 16 (6), 2764. DOI:10.3390/en16062764

Chłopek, Z., Lasocki, J., Melka, K. & Szczepański, K. (2021). Equivalent Carbon Dioxide Emission in Useful Energy Generation in the Heat-generating Plant – Application of the Carbon Footprint Methodology. *Journal of Ecological Engineering*, 22 (2), pp. 144–154. DOI:10.12911/22998993/130891

Daliry, S., Hallajisani, A., Mohammadi Roshandeh, J., Nouri, H. & Golzary, A. (2017). Investigation of optimal condition for Chlorella vulgaris microalgae growth. Global *Journal of Environmental Science and Management,* 3 (2), pp. 217–230. DOI:10.22034/gjesm.2017.03.02.010

Dyachok, V., Mandryk, S., Huhlych, S. & Slyvka, M. (2020). Study of the Impact of Activators in the Presence of an Inhibitor on the Dynamics of Carbon Dioxide Absorption by Chlorophyll-Synthesizing Microalgae. *Journal of Ecological Engineering*, 21 (5), pp. 189–196. DOI:10.12911/22998993/122674

Dyachok, V., Mandryk, S., Katysheva, V. & Huhlych, S. (2019). Effect of Fuel Combustion Products on Carbon Dioxide Uptake Dynamics of Chlorophyll Synthesizing Microalgae. *Journal of Ecological Engineering*, 20 (6), pp.18–24. DOI:10.12911/22998993/108695

Dziosa, K. & Makowska, M. (2015). The influence of temperature on the growth of biomass of freshwater micro-algae grown in laboratory. *Inżynieria i Aparatura Chemiczna*, 54 (4), pp.152–153. (in Polish)

Erdiwansyah, E., Gani, A., Mamat, R., Mahidin, M., Sudhakar, K., Rosdi, S. M. & Husin, H. (2022). Biomass and wind energy as sources of renewable energy for a more sustainable environment in Indonesia: A review. *Archives of Environmental Protec*tion, 48 (3), pp. 57–69. DOI:10.24425/aep.2022.142690

Faizal, M., Said, M., Nurisman, E. & Aprianti, N. (2021). Purification of Synthetic Gas from Fine Coal Waste Gasification as a Clean Fuel. *Journal of Ecological Engineering*, 22 (5), pp. 114–120. DOI:10.12911/22998993/135862

Fawzy, S., Osman, A. I., Mehta, N., Moran, D., Al-Muhtaseb, A. H. & Rooney, D. W. (2022). Atmospheric carbon removal via industrial biochar systems: A techno-economic-environmental study. *Journal of Cleaner Production*, 371, 133660. DOI:10.1016/j.jclepro.2022.133660

Font-Palma, C., Cann, D. & Udemu, C. (2021). Review of cryogenic carbon capture innovations and their potential applications. *C - Journal of Carbon Research,* 7 (3), 58. DOI:10.3390/c7030058

Iglina, T., Iglin, P. & Pashchenko, D. (2022). Industrial CO2 Capture by Algae: A Review and Recent Advances. *Sustainability,* 14 (7), 3801. DOI:10.3390/su14073801

International Energy Agency. (2023). CO2 Emissions in 2022. https://www.iea.org/reports/co2-emissions-in-2022

Izba Gospodarcza Ciepłownictwo Polskie. (2023). Transformacja i rozwój ciepłownictwa systemowego w Polsce. Raport 2023.

Kammerer, S., Borho, I., Jung, J. & Schmidt, M. S. (2023). Review: CO2 capturing methods of the last two decades. *International Journal of Environmental Science and Technology*, 20 (7), pp. 8087–8104. DOI:10.1007/s13762-022-04680-0

Kozieł, W. & Włodarczyk, T. (2011). Algae – biomass production (a reviev). *Acta Agrophysica,* 17 (1), pp. 105–116. http://www.acta-agrophysica.org/Algae-biomass-production-a-reviev,107203,0,2.html

Kupczak, P. (2021). Energy transformation of medium-sized PECs. *Energety-ka Cieplna i Zawodowa,* 2, pp. 24–27. https://issuu.com/marfi1976/docs/2_2021_energetyka_issuu (in Polish)

Kupczak, P. (2022). How to save energy resources in times of their shortage? *Nowa Energia*, 85 (4), pp. 30–35. (in Polish)

Liu, L., Xia, M., Hao, J., Xu, H. & Song, W. (2021). Biosorption of Pb (II) by the resistant Enterobacter sp.: Investigated by kinetics, equilibriumand thermodynamics. *Archives of Environmental Protection*, 47 (3), pp. 28–36. DOI:10.24425/aep.2021.138461

Madejski, P., Chmiel, K., Subramanian, N. & Kuś, T. (2022). Methods and Techniques for CO2 Capture: Review of Potential Solutions and Applications in Modern Energy Technologies. *Energies*, 15 (3), 887. DOI:10.3390/en15030887

Matejczyk, M., Kondzior, P., Ofman, P., Juszczuk-Kubiak, E., Świsłocka, R., Łaska, G., Wiater, J. & Lewandowski, W. (2023). Atrazine toxicity in marine algae *Chlorella vulgaris* and in *E. coli* lux and gfp biosensor tests. *Archives of Environmental Protection,* 49 (3), 87–99. DOI:10.24425/aep.2023.147331

Metsoviti, M. N., Papapolymerou, G., Karapanagiotidis, I. T. & Katsoulas, N. (2019). Effect of Light Intensity and Quality on Growth Rate and Composition of *Chlorella vulgaris*. *Plants*, 9 (1), 31. DOI:10.3390/plants9010031

Nord, L. O. & Bolland, O. (2020). Carbon dioxide emission management in power generation. John Wiley & Sons.

Osman, A. I., Hefny, M., Abdel Maksoud, M. I. A., Elgarahy, A. M. & Rooney, D. W. (2021). Recent advances in carbon capture storage and utilisation technologies: a review. *Environmental Chemistry Letters*, 19 (2), pp. 797–849. DOI:10.1007/s10311-020-01133-3

Rogulj, I., Peretto, M., Oikonomou, V., Ebrahimigharehbaghi, S. & Tourkolias, C. (2023). Decarbonisation Policies in the Residential Sector and Energy Poverty: Mitigation Strategies and Impacts in Central and Southern Eastern Europe. *Energies*, 16 (14), 5443. DOI:10.3390/en16145443

Sarwer, A., Hamed, S. M., Osman, A. I., Jamil, F., Al-Muhtaseb, A. H., Alhajeri, N. S. & Rooney, D. W. (2022). Algal biomass valorization for biofuel production and car-bon sequestration: a review. *Environmental Chemistry Letters*, 20 (5), pp. 2797–2851. DOI:10.1007/s10311-022-01458-1

Schwister, K. & Leven, V. (2020). Verfahrenstechnik für Ingenieure: Ein Lehrund Übungsbuch (mit umfangreichem Zusatzmaterial). Carl Hanser Verlag GmbH Co KG.

Sifat, N. S. & Haseli, Y. (2019). A Critical Review of CO2 Capture Technologies and Prospects for Clean Power Generation. *Energies,* 12 (21), 4143. DOI:10.3390/en12214143

Skawińska, A., Lasek, J. & Adamczyk, M. (2014). Study of CO_2 removal processes using microalgae. *Inżynieria i Aparatura Chemiczna*, 53 (4), pp. 292–293. (in Polish)

Skompski, S., Kozłowska, A., Kozłowski, W. & Łuczyńsko, P. (2023). Coexistence of algae and a graptolite-like problematical: a case study from the late Silurian of Podolia (Ukraine). *Acta Geologica Polonica*, 73 (2), pp. 115–133. DOI:10.24425/agp.2022.143599

Szatyłowicz, E., Patyna, A., Biłos, Ł., Płaczek, M. & Witczak, S. (2017). Productivity of microalgae *Chlorella vulgaris* in laboratory condition. *Inżynieria Ekologiczna*, 18 (3), pp. 99–105. DOI:10.12912/23920629/70264

Tleukeyeva, A., Pankiewicz, R., Issayeva, A., Alibayev, N. & Tleukeyev, Z. (2021). Green Algae as a Way to Utilize Phosphorus Waste. *Journal of Ecological Engineering*, 22 (10), pp. 235–240. DOI:10.12911/22998993/142451

Urbina-Suarez, N. A., Barajas-Solano, A. F., Garcia-Martinez, J. B., Lopez-Barrera, G. L. & Gonzalez-Delgado, A. D. (2021). Cultivation of Chlorella sp. for biodiesel production using two farming wastewaters in eastern Colombia. *Journal of Water and Land Development*, 50. DOI:10.24425/jwld.2021.138169

Urbina-Suarez, N. A., Barajas-Solano, A. F., Garcia-Martinez, J. B., Lopez-Barrera, G. L. & Gonzalez-Delgado, A. D. (2022). Prospects for using wastewater from a farm for algae cultivation: The case of Eastern Colombia. *Journal of Water and Land Development*, 52, pp. 172–179. DOI:10.24425/jwld.2022.140387

Urząd Regulacji Energetyki. (2022). Thermal energy in numbers. 2021. (in Polish)

Valdovinos-García, E. M., Barajas-Fernández, J., Olán-Acosta, M. de los Á., Petriz-Prieto, M. A., Guzmán-López, A. & Bravo-Sánchez, M. G. (2020). Techno-Economic Study of CO2 Capture of a Thermoelectric Plant Using Microalgae (*Chlorella vulgaris*) for Production of Feedstock for Bioenergy. *Energies,* 13 (2), 413. DOI:10.3390/en13020413

Xie, K., Fu, Q., Qiao, G. G. & Webley, P. A. (2019). Recent progress on fabrication methods of polymeric thin film gas separation membranes for CO2 capture. *Journal of Membrane Science,* 572, pp. 38–60. DOI:10.1016/j.memsci.2018.10.049

Yerizam, M., Jannah, A. & Aprianti, N. (2023). Bioethanol Production from *Chlorella Pyrenoidosa* by Using Enzymatic Hydrolysis and Fermentation Method. *Journal of Ecological Engineering*, 24 (1), pp. 34–40. DOI:10.12911/22998993/156000

Yu, Y., Fang, X., Li, L. & Xu, Y. (2023). Performance and mechanism of Carrousel oxidation ditch and water Spinach wetland combined process in treating water hyacinth (*Pontederia crassipes*) biogas slurry. *Archives of Environmental Protection*, 49 (1), pp. 39–46. DOI:10.24425/aep.2023.144735

Zhou, W., Wang, J., Chen, P., Ji, C., Kang, Q., Lu, B., Li, K., Liu, J. & Ruan, R. (2017). Biomitigation of carbon dioxide using microalgal systems: Advances and perspectives. *Renewable and Sustainable Energy Reviews*, 76, pp. 1163–1175. DOI:10.1016/j.rser.2017.03.065

Zastosowanie alg jako absorbera dwutlenku węgla w ciepłownictwie

Streszczenie. W Polsce z ciepła systemowego korzysta ok. 15 mln osób, lecz niestety blisko 70 proc. paliw zużywanych do produkcji ciepła to paliwa węglowe. Zatem redukcja emisji CO2 w ciepłownictwie staje się jednym z kluczowych wyzwań. Miejskie Przedsiębiorstwo Energetyki Cieplnej sp. z o.o. w Nowym Sączu realizuje projekt badawczo-rozwojowy finansowany ze środków własnych pn. Zastosowanie alg jako absorbera dwutlenku węgla w MPEC Nowy Sącz. Projekt związany jest z wychwytywaniem CO2 po spalaniu z wykorzystaniem alg Chlorella vulgaris. W wyniku przeprowadzonych badań w szczelnym zbiorniku o pojemności 1000 l w optymalnych warunkach temperatury i oświetlenia odzysk biomasy można prowadzić w cyklach cotygodniowych, uzyskując ok. 25 kg biomasy rocznie. Przyjmując, że połowa suchej masy alg to węgiel, można przyjąć, że w jednym cyklu związane zostaje 240 g węgla, co w przełożeniu na CO2 daje 880 g tego gazu. W skali roku można zatem zaabsorbować ok. 45,8 kg CO2. Dodatkowo jako pożywkę dla alg można stosować materiały odpadowe i produkty uboczne z procesów technologicznych.