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Life Cycle Assessment of an Innovative Microalgae Cultivation System in the Baltic Region: Results from SMORP Project

Francesco ROMAGNOLI[1*], Alessandro THEDY[2], Baiba IEVINA[3], Maksims FEOFILOVS[4]

[1,3,4]*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV-1048, Latvia*

[2]*Universitá degli studi di Brescia, Via Branze 38, Brescia, 25123, Italy*

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***Abstract* – Microalgae cultivation at biogas plants creates joint benefits for using liquid digestate and exhaust gas from the CHP unit as nutrient and carbon sources for microalgae growing. This circular approach increases biogas production's sustainability towards a bioeconomy and zero-waste perspective. This study aims to evaluate the potential environmental impacts in connection to a novel microalgae growing technology named Stacked Modular Open Raceway Pond (SMORP) as a side-stream process coupled with centrate and exhaust gases from a biogas plant. A comparative LCA according to ISO 14044 is performed between the innovative SMORP concept at the pilot level and a hypothetical scaled-up system. Primary data for the inventory are directly gathered from the microalgae growing test performed at the biosystems laboratory of the Institute of Energy Systems and Environment of the Riga Technical University. Secondary data are collected from literature mostly in terms of mass and energy balances considering the SMORP pilot project design. The results of the LCA include the main findings both at mid and endpoint categories according to the IMPACT 2002+ method. In addition, a sensitivity analysis for several different parameters has been investigated. Results show the feasibility of the coupled system and the possibility of having benefits once the system is scaled up. Nevertheless, the results show a critical dependency of the environmental performance on the local conditions, potentially affecting too high cultivation costs.**

***Keywords* – Biogas plant; environmental impact assessment; LCA, microalgae, sustainability.**

1. INTRODUCTION

Microalgae are unicellular aquatic organisms with an average diameter of 2 μm, which float in the oceans [1]. These organisms are responsible for approximately half of the oxygen in the atmosphere by converting solar energy, carbon dioxide, and other nutrients into biomass which, after mechanical and chemical processes, can be used as energy, food, or feed source [2]. Microalgae are a promising source of biomass for the future compared to terrestrial plants. They have greater photosynthetic efficiency, yield, higher CO_2 fixation, and a growth rate about 100 times faster [3]. In fact, microalgae can double their biomass in less than a day.

* Corresponding author.
E-mail address: francesco.romagnoli@rtu.lv

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About 40 000 different known species of microalgae exist, but less than 10 % [4] are currently cultivated and maintained in culture media for study or commercial purposes. Studies on microalgae culturing techniques started already in the nineteenth century [5], but the first step for commercialization was made during the middle of the twentieth century by Spoehr and Milner [6], followed by Cook [7], and Pirson [8]. However, despite all research efforts and development, the commercial exploitation of microalgae did not fully reach economic viability due to: the high capital cost required, combined with sometimes relatively low and inconstant yields, and the need to manage and optimize a bio-based industrial system [9]. Nevertheless, the necessity to increase the yield and stabilize the production for commercial purposes has led to exploring new solutions for microalgae cultivation and use and looking towards integrated approaches.

Microalgae potentially represent a valuable feedstock for renewable energy production [10]. Microalgae biomass can be converted to heat by direct combustion or by producing biofuels such as biodiesel, biomethane, or biohydrogen. Transformation into biomethane has shown great potential [11]. However, to make this transformation feasible, it is necessary to link the production with secondary high-value co-products or to integrate a microalgae culture with an existing biogas plant to overcome problems such as nutrient supply and high production costs [12]. The main challenge is to integrate the cultivation process to use the side-stream waste from biogas plants, such as the excess heat and flue gases available from the biogas combustion and digestate from anaerobic digestor (AD) respectively, for the algal growth while maintaining biomass production at low costs.

Despite the knowledge gap in sustainability assessments through Life Cycle Assessment (LCA), biogas-coupled systems are reported to be one of the promising pathways to tackle current environmental impacts [13]. Therefore, this study aims to assess the performance of an innovative open raceway pond cultivation system for microalgae called *Stacked Modular Open Raceway Pond* (SMORP) integrated within a biogas plant system to understand the potential environmental benefits and drawbacks. In this study biomass production and energy consumption refer to the constructive characteristics of a realized pilot stand at specific Baltic climate conditions within the Latvian context.

First, the investigated pilot system is analyzed through LCA to quantitatively assess the impacts of biomass production over the plant's life cycle by identifying flows of materials, emissions, energy, and waste released into the environment. Later, the pilot scenario's results are compared with hypothetical pre-commercial and scaled-up commercial scenarios. The comparison between these different systems accounted for the variation of key parameters depending on a specific scaling-up formulation for identifying possible areas for future improvements and implementation.

2. LITERATURE REVIEW

A fundamental characteristic of microalgae is the ability to capture and sequester carbon dioxide, which is responsible for global warming [14], [15]. Therefore, using microalgae as a biological means to deal with carbon dioxide emissions is very promising. Furthermore, compared to terrestrial plants, microalgae have a 10 to 50 times higher photosynthetic efficiency [16]. This leads to a regeneration time usually less than 8 hours [17] and consequently to a higher biomass production through carbon dioxide fixation.

Laboratory studies conclude that using optimal parameters and conditions allows obtaining the theoretical yield of around 280 tons dry weight (DW) biomass ha^{-1} y^{-1} while consuming about 513 tons of carbon dioxide, 14 tons of nitrogen, and 3 tons of phosphorus [18], [19].

However, the actual yields are around 20–50 tons DW biomass ha^{-1} y^{-1} showing great potential for improvements.

The capacity to assimilate other nutrients necessary for their growth is another reason behind the commercial use of microalgae in treating municipal or other industrial or side-stream wastewaters [20].

Microalgae constitute a biological filter reducing nitrogen and phosphorus levels, the main elements that cause the phenomenon of eutrophication of aquatic environments [21]. Moreover, microalgae cultivation can be placed on non-arable land, abandoned industrial sites, and unproductive or remote areas, avoiding the food-vs-fuel dilemma [22].

The harvesting of microalgae biomass can be performed in natural and artificial ponds. Natural ponds are natural ecosystems in a cultivation basin mainly used for wastewater treatment and water purification. The major drawback of such a system is the difficulty in managing algal growth conditions, which can also be linked to the limited capacity of carbon dioxide-liquid mass transfer [23]. There are two basic types of cultivation systems for experimental and commercial applications: open and closed systems.

Open cultivation systems are mainly characterized by direct contact with the atmosphere, a low surface-to-volume ratio, technical simplicity, and not long lifespan. In most cases, they are shallow ponds with a depth of about 30–40 cm fed by industrial or municipal wastewater, which is mixed using rotating systems, propellers, or natural circulation, and have a biomass harvesting system at the end of the circulation cycle. This configuration is known as a raceway pond [24]. Such ponds can be dug directly into the ground and lined with impermeable material to prevent water leaks or built above the ground using construction material for walls and floors. Open systems can have a variety of configurations depending on their size, materials, mixing, inclination, algal species, the climate of the region, and other key aspects [25]. Raceway ponds are the most common type of open cultivation system, shaped as oblongs shallow ponds with semi-circular ends, mixed by slow rotating mechanisms or propellers, with suspended biomass concentration generally about 0.3 g L^{-1} [26]. Commercial cultivation of microalgae in open ponds is generally cheaper than culture in closed photobioreactors but, given the difficulties of controlling all the parameters, is also limited to a relatively small number of species, and usually restricted to temperate regions. Studies have shown that open systems present lower environmental and operating costs thanks to their constructive simplicity than closed cultivation systems known as photobioreactors (PBRs) [27].

Closed systems typically present a higher surface-to-volume ratio, allowing better light penetration and, thus higher productivity. Depending on the configuration for the specific chosen application, they are proposed in a wide range of sizes, technology, and shapes, from tubular to inclined, horizontal, flat, or spiral [28]. Within the PBRs there is no direct contact between the medium and the atmosphere. A transparent material separates the culture from the external environment allowing better control of external factors compared to open ponds.

There is no better configuration suitable for all cases because only the final product determines the necessary specific parameters of the system. Conventional commercial-size plants use open systems because they are economically feasible to produce a low-value product, such as biofuels, which requires the production of hundreds of tons of biomass per year and thus have a large cultivation area [29]. As for PBRs, the technical complexity of closed systems does not allow them to reach those values. PBRs are known to present a greater yield because of a greater surface-to-volume ratio of about 1.7 g L^{-1} for tubular PBR and 2.1 g L^{-1} for flat panel PBR [30], but having higher capital and maintenance costs, mostly due to system complexity and pipes cleaning procedures. The main problem of closed systems is fouling, as microalgae cells attach to the wall of the system and gradually reduce light

penetration, consequentially reducing microalgae productivity and, if not properly treated, leading to the collapse of the culture. Another significant drawback of the closed systems is that temperatures inside the PBR can reach critical values for microalgae survival in the summer months. This requires a cooling system that is difficult to, feasibly and efficiently, scale up to a commercial level [31]. PBRs can be suitable for the cultivation of moderate quantities of high-value-added products, such as those in the pharmaceutical and cosmetics sectors, while biomass cultivation of low-value commodity products, such as biofuels, is more suitable in open pond systems [32].

Besides the selected type of microalgae cultivation system, microalgae's harvesting and dewatering procedures are recognized as the most critical factors in the scaling-up process from pilot to commercial scale. During microalgae harvesting the need to process large quantities of water can result in high capital and production costs [33]. Natural sedimentation has low capital and operating costs but often requires considerable space, and the efficiency is usually moderate-low. On the contrary, a special microalgae filtration system can be very efficient but requires specific equipment that increases capital and maintenance costs [34]. The parameters of the sedimentation procedure vary depending on the algal species and the specific system characteristics. This technique allows for the production of an initial slurry with an approximate concentration of 1–2 % wet weight (WW). In secondary treatment, centrifugation or filtration as dewatering techniques is used to obtain a concentrated biomass of 20–25 % WW, sufficient for biogas production through anaerobic digestion.

Microalgae cultivation is economically feasible only in case of high and constant biomass productivity combined with low capital, maintenance, and harvesting costs [35]. A potential solution to overcome these barriers could be integrating a microalgae cultivation system with existing industrial plants. One of the most promising is CHP plants that operate with biogas produced via anaerobic digestion (AD) [36]. AD is one of the most diffused sources to produce renewable energy based on numerous bacteria' oxygen-free decomposition of organic substances. During the process of oxygen-free decomposition, the energy contained in the chemical bonds of organic substances is released mainly in the form of methane (50–70 %) and carbon dioxide. This decomposition process takes place in four main steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The growth rate of methanogens bacteria is low compared to previous phases, and thus long retention times, order of 20–25 days, is required for adequate digestion [37]. The four phases can take place in two ranges of temperature. For mesophilic bacteria (30–42 °C), and for thermophilic bacteria (43–55 °C). Working at a higher temperature, the latter allows the elimination of pathogens, recommended from substrates derived from wastewater treatment [13].

Within the integrated microalgae cultivation and CHP plant system, the waste products of the CHP plant can be used as a feedstock for microalgae cultivation and the harvested algal biomass can be used for biogas production for the CHP plant, making the system a sustainable production circle. Carbon dioxide for microalgae growth can be obtained from flue gases produced by the combustion process in a biogas plant. Research has shown that cultivation productivity can be even higher when using exhaust gases rather than pure carbon dioxide [38], contributing to the system reduction of production costs and environmental footprint. In addition, the fermentation residue of the anaerobic digestion known as digestate is a very high agronomic value liquid that contains inorganic substances, such as nitrogen and phosphorus, and can be used as the primary source of nutrients necessary for microalgae growth.

Currently, the level of algal cultivation and harvesting technologies used for energy production cannot compete with fossil fuels. Several authors reported differences in production costs, from 12.52 € kg^{-1} DW to 35.92 € kg^{-1} DW for non-processed algal biomass in 2014, [30] around 80 € for a barrel of microalgae oil in 2004 [39], 4.95 € kg^{-1} DW for open

ponds system, 4.16 € kg^{-1} DW for tubular PBR and 5.96 € kg^{-1} DW for flat panel PBR non-processed biomass in 2010. [40] The difference in price range can be attributed to the uniqueness of each study, differences in technologies considered, specific parameters, weather conditions, assumptions, risk analysis, and others.

Despite all favorable aspects, such as carbon dioxide fixation, wastewater purification, and renewable energy production, the commercial exploitation of microalgae cultivation is still a problem due to the high amount of energy required in the cultivation and harvesting phase. However, the environmental benefits of such a system compared to fossil fuels can have momentum for commercial-scale plant development in the future [41]. LCA studies about microalgae cultivation show a wide range of results mainly due to the heterogeneity of the underlying hypotheses and boundaries (e.g. including or excluding infrastructures production, final disposal, water, and carbon dioxide losses, type of fertilizer, algae-specific composition, and others [42]). Currently, there is a lack of a comprehensive sustainability assessment through the LCA approach applied to the microalgae cultivation at biogas CHP plant that can demonstrate and prove a substantial competitive advantage of the integrated microalgae cultivation and CHP plant system.

3. METHODOLOGY

3.1. Case study

This study focuses on innovative microalgae open raceway pond, named as SMORP, which combines the best aspects of actual open and closed systems in a hybrid approach. A built SMORP pilot (i.e. 3 pyramidally stacked ponds with a leght of 3.0 m and width of 1.0 m) has been integrated within a biogas plant to evaluate the feasibility of applying a sort of microalgae-based biofilter process as a treatment and management method for the liquid digestate and flue gases from a CHP unit [43]. The additional positive effect is about transforming environmental externalities as added-value products. This aspect is specifically addressed to the use of digestate, carbon dioxide from flue gases and excess heat to feed the growing algal system, reducing biomass production costs and, simultaneously, the environmental impact.

3.1.1. Design of SMORP

Compared to the closed system, open ponds have evident drawbacks in land occupation and low surface-to-volume ratio, which means low yields while using large spaces. The SMORP system coupled with biogas production and CHP plant deepens the problem even more. A solution, in this case, is stacking several ponds to obtain a land occupation reduction of up to 40 % [43]. The original project design, still at a pre-commercial scale, is intended to stack 5 ponds (see Fig. 1) with a length of 10.0 m and a width of 1.0 m.

The usual practice for open pond systems is digging them into the ground or constructing them with concrete or brick walls with an HDPE separation layer to prevent leaks [44]. This means a low surface-to-volume ratio and lower productivity compared to closed systems. The SMORP project's novelty consists of building the pond using a transparent material with high light transmission, resistance to chemical compounds, durability, excellent mechanical properties, and easy shaping for rounded geometry. According to those characteristics, polymethylmethacrylate (PMMA), an acrylic material, has been selected for the pilot pond.

For the SMORP pilot, the mechanism for maintaining water flow through the SMORP growing modules consists of paddle wheels with flat blades. Since power consumption is greatly affected by the intensity of water flow, it is necessary to maintain the minimum

turbulence required in terms of the system's energy efficiency. Paddle wheels are less energy-intensive compared to stirring pumps, but on the other hand, deeper layers are poorly mixed than surface layers due to laminar flow conditions.

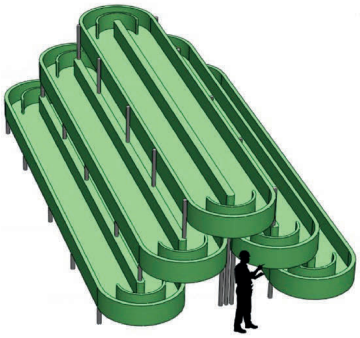


Fig. 1. Concept system of stacked ponds at the pre-commercial stage.

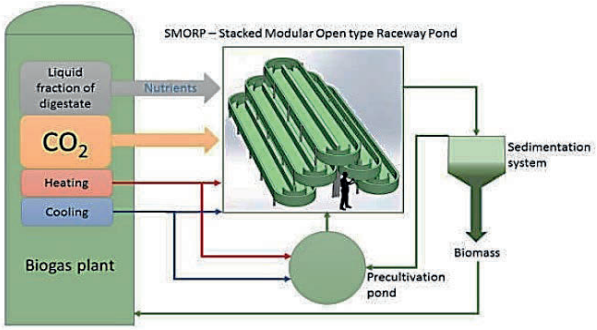


Fig. 2. SMORP pilot plant coupled with a biogas plant.

Given the cold Baltic temperatures during the winter months, a greenhouse was installed to guarantee a constant annual production yield. This greenhouse can positively protect the cultivation site from external weather conditions and culture contamination. A pilot pond built in similar climatic conditions has recorded an average temperature inside the greenhouse higher than 10 degrees compared to the external one [45]. Fig. 2 shows the overall scheme as an integrated system between existing biogas plants and the SMORP concept.

3.1.2. Nutrient source

Some studies have already shown that microalgae could grow using digestate as a nutrient source [46], [47]. Still, there are also some drawbacks, mainly due to the dark colour of the digestate, the presence of organic matter, and ammonia content [48]. Organic solids have a problem with the heavy metals and pathogens content that must be monitored and maintained under threshold levels if part of the biomass is used as animal feed. Ammonia content alkalizes the pH level and leads to inhibitory effects on microalgae growth. The dark colour and the presence of organic solids decrease the light transmission in the culture medium and the algal growth. In this case, pre-treatment in the form of separation of the liquid and solid fraction of digestate is a suggested solution, by using the liquid fraction on a dilution of about 0.5–1 % not to affect the algal growth [49]. The liquid fraction of the digestate of the biogas plant is stored in a continuously stirred mixing tank and can be fed into the pond as a nutrient source after dilution to avoid light limitations.

3.1.3. Carbon source

Flue gases released from the biomethane combustion in the biogas plant are used as a carbon source for the SMORP pilot plant. The absorption of carbon dioxide from flue gas into water is slower than absorption from pure carbon dioxide, and the loss to the atmosphere is expected to be above 80 % [44]. Therefore, a simple flue gas sparging method is used. The sparging system consists of perforated pipes placed on the bottom of the pond. Flue gas sensors are

installed to monitor temperature, composition, and the presence of unwanted elements like heavy metals.

3.1.4. Light source

The SMORP pilot plant is realized and tested under Baltic climate conditions, which present a strong seasonality in the lighting conditions from 1 hour of average sunlight per day in January up to 10 hours in July. To maintain a constant growth rate and biomass harvesting yield, it is thus fundamental to use solar light coupled with a low-consumption LED system. Using a combined light source allows for optimizing daily and annual lighting cycles, hence increasing biomass production. LED lights are installed considering the appropriate light frequency and colour for maximal photosynthesis rate.

3.1.5. Specie selection

A wide variety of algae differ in the growth parameters such as the salinity of the medium, adaptability to the climate conditions, potential growth rate, pH needed, the number of nutrients, light necessary, optimal temperature range, and others. The selection of the specific microalgae strain is site-specific and dependent on the desired characteristics of the final product. Different studies present pilot plants best practices using different microalgae species such as *Chlorella* spp., *Scendesmus* spp., *Nannochlopsis* spp., *Phaeodactylum* spp., *Chlamidomonas* spp. [50] or *Dunaliella salina*, *Arthospira* spp. and *Chlorella* spp. [51]. The most used species in other pilot plants with similar conditions were *Chlorella* spp. and *Scendesmus* spp.

Literature about the growing test and output of *Chlorella* spp. in laboratory conditions shows that *Chlorella* spp. can grow in extreme and aggressive environments, and this is highlighted by the extensive use of this species for both open and closed systems. [52, 53] Thus, the selected species for the SMORP pilot plant is *Chlorella vulgaris,* which main characteristics as productivity or lipid content can vary significantly for different strains according to Table 1.

TABLE 1. *CHLORELLA VULGARIS* MAIN CHARACTERISTICS, ADAPTED FROM [54]

Species	Environment	Lipid content, % DW	Lipid production, mg L^{-1} d^{-1}	Volume production, g L^{-1} d^{-1}
Chlorella vulgaris	Freshwater	5.0–58.0	11.2–40.0	0.02–0.25

3.2. Data analysis for SMORP

An empirical model describing the yield of biomass production and the related energy consumption for the integrated SMORP in the biogas CHP plant system has been developed to obtain values to be used in the subsequent LCA study. The empirical model describes several aspects related to the pilot plant, climate data specific to the Baltic region, heat parameters regarding heat balance, pumps and flue sparging energy consumption, and scale-up factors. In addition, specific assumptions and simplifications have been made regarding the construction input data for the construction stage. The empirical model for these assumptions is inspired by the work carried out in the *EnAlgae project* [55], which collected contributions from different pilot plants installed in Belgium, Germany, the UK, and the Netherlands.

3.2.1. SMORP size and energy consumption

The calculations of the total area of microalgae cultivation and the total volume of microalgae culture calculation are reported in Annex A. The total energy needed for the LED lighting to reach the requested photosynthetic active radiation (PAR) is calculated using a conversion factor of an approximated value of 2.1 Watt, considering the original conversion factor of 4.57 [56] and only 45 % of the solar radiation in the 400–700 nm range, useful for photosynthesis. The equation used for this calculation is reported in Annex A.

3.2.2. Climate data

The Baltic region has a humid continental climate with severe winter, no dry season, warm summer, and strong seasonality, which is classified as a humid continental climate (i.e. Dfb) on the Köppen-Geiger scale. The data on climate conditions includes heating balance and algae production estimation. Global radiation statistics, expressed in MJ $(m^2\ day)^{-1}$, are collected in a detailed study about solar irradiation in Latvia [57], assuming a 40 % decrease in solar radiation that reaches the surface of the pond due to the effect of the greenhouse [45]. The rest of the data were selected from the literature (i.e., *climatemps.com* website), which provides information about daily temperature (i.e., mean temperature, average minimum, and average maximum), daily humidity percentage (at noon), sunlight hours (average hours of sun per day, average daylight hours per day, and monthly cloud coverage). Data on average wind speed and monthly rainfall were not considered as the pilot will be built under a greenhouse.

3.2.3. Temperature-Algae growth relationship

The optimal temperature for microalgae growth is species-dependent and decreases according to factors for non-optimal conditions when moving away from this optimal value. Therefore, a pond temperature of 20 °C throughout the whole year has been used in the estimates assuming for the *Chlorella vulgaris* an optimal growth temperature of 25 °C. The curve trend for the temperature factor used in this study is represented in Fig. 3 [49].

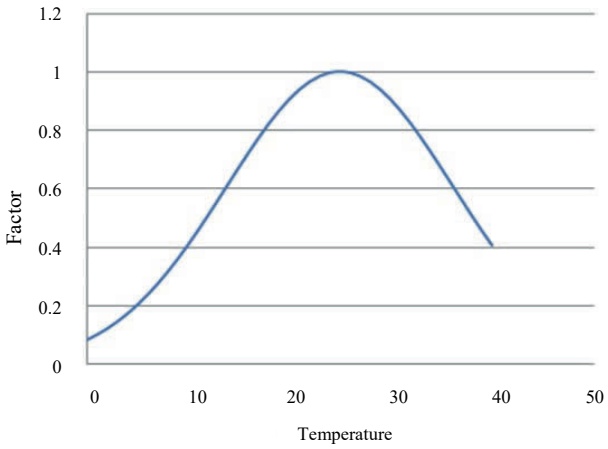


Fig. 3. Temperature factor for non-optimal temperatures [49].

3.2.4. Heat balance in SMORP

Heat balance in the pond is affected by different factors that change the temperature of the medium in which the microalgae grow. In this study a model is used with the contribution of five different factors to the heat balance, also considering heat lost during crashes of the cultivation ponds: heat loss through evaporation, convection on the pond surface, heat loss through water recirculation, solar radiation, and heat dispersion through pond walls (see Annex B).

Assumptions for heat balance calculation considered that the greenhouse ensured +10 °C compared to ambient air temperature, based on the experimental data obtained in another open pond in the Netherlands [58], and assuming water temperature in the pond equal to air temperature in the greenhouse. It was assumed that when the air temperature inside the greenhouse is lower than 20 °C, the heating system is activated to reach such a temperature. The calculation of the five contributions considered was carried out using five assumptions [59] (see Annex A), specifically for: evaporation, the number of crushes, heat convection and dispersion, and solar radiation.

3.2.5. Pumps and CO_2 injector

The SMORP pilot pond uses six main hydraulic pumps. Specifically, the first pump injects the water from the pond to the settler tank, the second pump is connected to the supernatant water from the settler tank back to the pond, the third pump injects the slurry from the settler tank to the centrifuge, the fourth ones return the supernatant water from the centrifuge back to the pond, the fifth refills the water lost by evaporation, and the sixth one pumps the liquid digestate to the pond. In addition, one air pump is used for sparging flue gases from the CHP plant into the SMORP pilot. Electricity consumption values found in the literature have been used as indicated in Life Cycle Inventory (LCI) tables in Annex C and D.

The SMORP pilot pond has relatively small dimensions compared to other ponds found in literature and, therefore, can have comparatively lower efficiency and, consequently, greater energy consumption. The equations used for calculations are reported in Annex A. Estimates have shown that the pumps that process the lower daily flow rates have negligible consumption and therefore have not been considered in this study. In this way, two out of six hydraulic pumps and the air pump for the flue gases are considered in this study.

Each pump has a total daily operating time of 30 minutes, composed of 3 sessions of 10 minutes, to respect the microalgae growth rate assuming an 8 hours retention period. Flowrate is calculated scaling data related to another study [60]. According to estimates, hydraulic pumps have a lower consumption compared, for instance, to mixing or artificial lighting.

The electricity needed for sparging flue gas inside the pond has been taken from the literature [61]. As this value is expressed in kWh kg^{-1} of flue gases, it is necessary to know the number of flue gases needed by knowing the amount of algae biomass related to CO_2 consumption. The equation is proposed in Annex A [62]. The flue gases flowing through the pond represent the amount that must be conveyed from the CHP plant to the SMORP pilot to support microalgae growth. This value has been selected from the literature [63], [64]; nevertheless, there is still an uncertainty if the use of flue gas will have detrimental effects on the algae culture of the presence of heavy metals.

3.2.6. Algae production

The estimates for algae production, and the correspondent energy consumption, implementing the SMORP are reported in Annex A. Specifically, the mean value of the monthly daylight has been used to calculate the solar radiation in the Baltic climate

conditions. The conditions suitable for SMORP location in a greenhouse are considered. The actual average pond temperature has been selected as equal to the optimal growing conditions temperature when the heating system is activated and equal to the ambient air temperature when the ambient temperature is higher than the desired temperature.

Biomass potential production is the quantity of biomass the SMORP pilot can theoretically produce if no culture crashes occur during the production. The proposed model considers that the plant is not producing algae during holidays and festivities. The amount of biomass produced also considers the lost biomass by crashes as the difference between theoretical and actual production. This parameter defines the wasted water during crashes, which considers the refill of water for cleaning to avoid contamination that could compromise the restart of the culture (i.e. two times the overall values).

Water evaporation value is selected from the heat parameters and implemented in the total water calculation expressed as the quantity of water that evaporates from the pond surface over a period, i.e. m^3 $month^{-1}$, (see Annex A). At this stage biomass losses due to centrifuge or recirculation to the ponds are not considered.

A specific consumption per m^3 of water treated has been used to calculate the electricity consumption in centrifugation. This value is then multiplied by the volume of treated water by scaling down a larger pond system [65].

All the previously mentioned assumptions provide a reasonable indication of the expected values for the SMORP pilot, thus helpful for constructing the LCA study.

3.3. LCA framework

The methodology selected for this study originates in the broader and innovative concept of Life Cycle Thinking, which integrates various aspects related to environmental, economic, and social development. One of the most significant advantages of an LCA study is the possibility of comparing different products or processes consistently and systematically. This approach is thus applicable at different technological levels, from pilot to industrial.

LCA refers to the ISO 14040:2006 and ISO 14044:2006, respectively including the general principles and frameworks, application, and limitation of the LCA methodology, and the specific requirements and guidelines for conducting an LCA study. According to them the four main phases of an LCA study are Goal and Scope definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Life Cycle Interpretation. This study applies the ISO 14040 and 14044 Standards to perform an LCA on SMORP integrated in the biogas CHP plant.

3.3.1. Goal and scope definition

The main goal of this study is to evaluate the potential environmental impact of microalgae biomass production in the SMORP pilot and to identify possible areas for future improvement.

Specifically, the study included a comparison with two other additional scenarios: a scenario implementing a pre-commercial scale SMORP and a scaled-up version to a commercial size corresponding to a cultivated area of 1 ha.

During cultivation and at different harvesting stages, the algae concentration in the growing medium changes; for this reason, it was assumed a reference concentration of 5 % for the wet weight (WW) in the cultivation phase inside the pond to 20 % WW after the centrifugation, which is suitable for the anaerobic digestion (AD). Therefore, the functional unit (FU) selected is 1 kg dry weight (DW) biomass corresponding to 5 kg WW 20 %.

The two other comparative scenarios consider a SMORP concept with 5 stacked ponds for a total area of 50 m^2 (i.e. pre-commercial scenario), while the commercial scaled-up scenario

with 1 ha of cultivated surface considers 200 pre-commercial scale SMORP modules. All three scenarios consider the integration within a biogas production plant.

A cradle-to-gate type LCA is conducted including all main processes and materials necessary to harvest 1 kg biomass DW to further feed a biogas plant. The system boundaries are presented in Fig. 4.

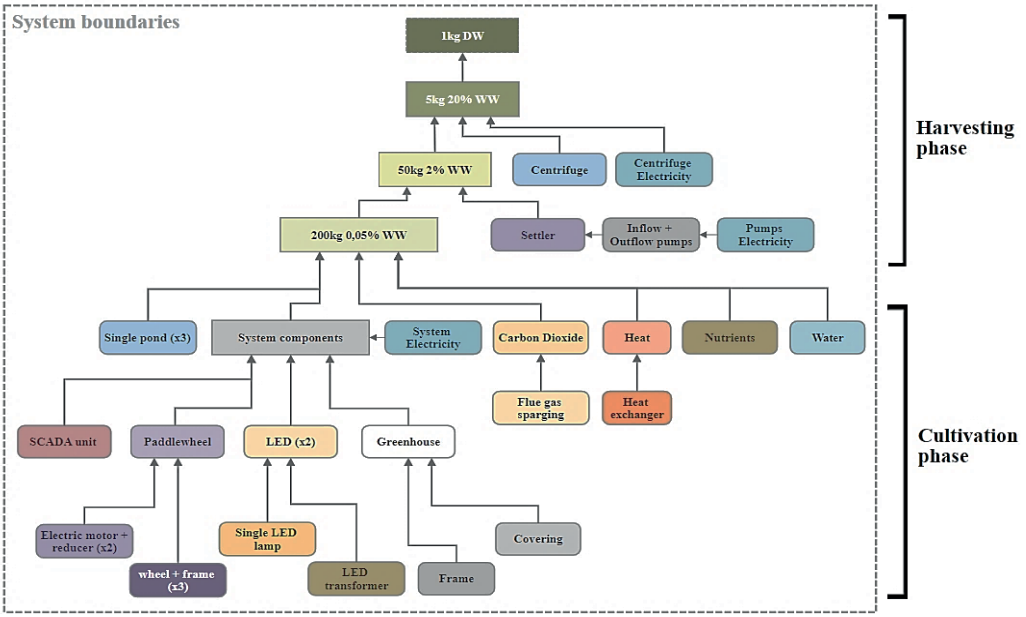


Fig. 4. System boundaries.

The processes within the system boundary can be summarized in algae cultivation, algae harvesting, and partial dewatering to reach 1 kg algae with 20 % WW. Transport and materials to build system components are included, while materials and energy associated with the infrastructure construction are excluded. Moreover, the final disposal or the possible waste scenario at the end of the life span is excluded.

3.3.2. Life cycle inventory

The LCI mainly consists of all the energy and materials involved in producing 1 kg DW biomass within the defined system boundaries. An average life span of 20 years was considered for all the components. Maintenance, as parts replacement in case of failure, was not considered.

The LCI is based on the data analysis in section 3.2 collected from the literature and using kinetic empirical models for microalgae growth. Parameters to define the pond characteristics are reported in Annex C. Processes referring to transport, electrical components, hydraulic components, and material used for the pond are based on Ecoinvent 3.5 database©. The summary of input data for SMORP pilot materials is reported in Annex D. For each production process, it is assumed that 10 % of material is production waste, and therefore the amount of raw material needed has been increased by this value. Scaling-up of the pilot system could be assumed in several ways. Studies report an overall impact reduction due to the scaling-up ranging from 23 % to 90 % [66] based on different assumptions and conditions.

The following technical assumptions are made for SMORP pre-commercial scenario:

1. Five ponds with a length of 10 m and width of 1 m (i.e. total area 50 m^2);
2. Flue gas injector: 180.0 m length of pipes necessary for covering two turns of the pond perimeter;
3. Rotating paddle wheels: 3 units of the same types of electric motors and reducers as in the SMORP pilot with a weight of 7 kg;
4. The same type of lighting system and transformers as in the SMORP pilot scenario to provide the quantity of PAR necessary for microalgae growth;
5. Greenhouse area of 98 m^2;
6. Heat exchanger: 330 m (i.e. 129 kg) length of copper pipes covering 3 turns of the pond perimeter for the 5 ponds module;
7. Settler tank: 12 m^2 of tin-plated chromium steel sheet, 200 kg.

The commercial size of 1 ha considering 200 units of the pre-commercial SMORP module includes the following assumptions:

1. Use of steel tubes to reduce the capital costs and environmental impact of the plant, according to [67];
2. 1 ha of cultivated microalgae surface corresponding to 6000 m^2 of land occupation, considering a 40 % land saving and 2 m of space between each SMORP module;
3. Total surface needed for the greenhouse is equal to 12 000 m^2.

The assumptions made for the scaled-up version did not consider the inoculum cultivation necessary to restart the culture after crashes.

3.3.3. Selected assessment method

The IMPACT 2002+ method is selected for environmental impact assessment [68]. This method presents results both at midpoint categories (i.e. with 15-based impact categories) and endpoint methods with damage categories, namely human health, ecosystem quality, climate change, and resources.

The IMPACT 2002+ method was selected because it is an endpoint environmental impact type with climate change as the final standing-alone endpoint impact category. Results at endpoint categories are reported as an ecological score – i.e. Pt, where 1 Pt represents the average impact in a specific category caused by a person during one year in Europe [69].

3.3.4. Sensitivity analysis

A sensitivity analysis has been performed to evaluate the influence of the results from the most relevant assumptions. The sensitivity analysis included: the effect of the scaling-up, the biomass productivity, temperatures of the growing conditions, and the type of material used.

The sensitivity was made by a sensitivity ratio evaluating the percentage of the output variation in mPt to the variation of the data input. If this ratio is less than 1, the change in the input has little effect on the output and vice versa. If it is more than 1, the output is strongly affected by the change in the data input. If the second case occurs, the model is sensitive to a specific data input that needs more investigation or associates the results with a higher input data uncertainty.

4. RESULTS AND DISCUSSION

4.1. Results of data analysis

Using the parameters and assumption described in section 3.2, the biomass output yield of SMORP pilot is 53.6 kg DW per year, which corresponds to about 49 tons per hectare per year. The overview of the SMORP pilot, with the related consumptions and annual production, has been presented in section 3.3.3 (i.e. LCI). All energy consumption and biomass production data are summarized in the Annex E.

According to the literature, the biomass output yield value is about twice the actual yields recorded in other pilot ponds [70], [71]. The reason could be that all growth parameters are set to guarantee the best possible conditions for microalgae growth, a complex condition to be achieved in real ponds.

For the scenario of SMORP pilot, a total of 11 000 thermal kWh should be provided from the CHP plant. In the considered system this is controlled by a hot water circulation pump activated by the SCADA unit. The more significant contribution to energy consumption is due to the heat lost in evaporation and heat dispersion through the walls of the pond.

4.2. Comparative Life Cycle Impact Assessment

The comparative Life Cycle Impact Assessment (LCIA) is performed on 3 scenarios: the SMORP pilot, the SMORP pre-commercial scale, and the SMORP scaled-up commercial concept using the IMPACT 2002+ v2.14 method. The model was developed with the support of Simapro software ©.

The results of the LCIA, for the selected FU, show an overall impact score 13.7 mPt for the SMORP pilot, 13.1 mPt for the SMORP pre-commercial scale, and 10.9 mPt for the SMORP scaled-up.

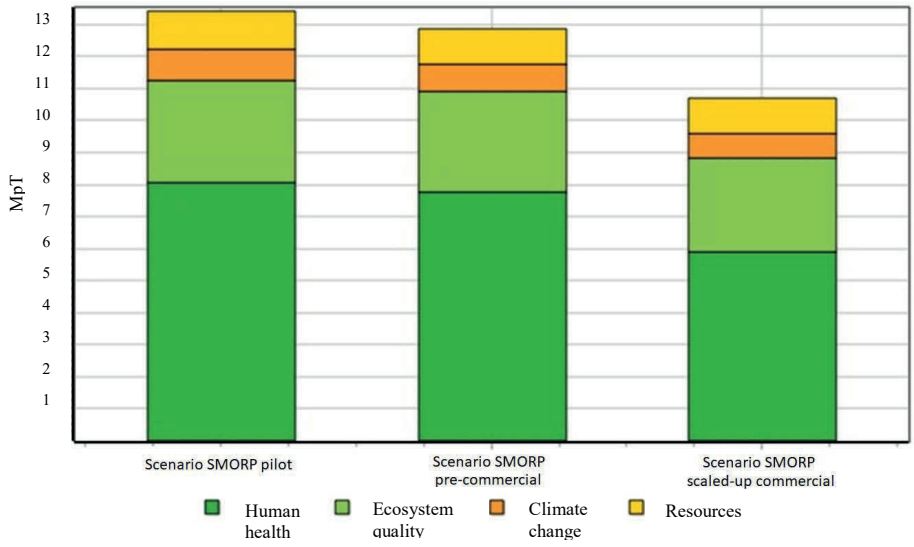


Fig. 5. Comparative LCIA results, single score comparison referred to 1 FU.

The results for midpoint categories (see Annex F) shows that four out of fifteen midpoint categories account for almost 90 % of the total impact:

1. Respiratory inorganics (about 50 % of the total) are related more than 99 % to the ammonia (NH_3), released from the degradation of amino acids during acidogenesis in the anaerobic digestion process;
2. Terrestrial ecotoxicity (about 15 % of the total) is related mainly to aluminium, zinc, and copper necessary for the pond components;
3. Global warming (about 9 % of the total) derives from the carbon dioxide originating from fossil fuels, of which half is due to the production of organic glass made in Poly methyl methacrylate (PMMA), which is used for the structure of the ponds;
4. Non-renewable energy (about 9 % of the total) is related to different non-renewable substances such as coal, oil, and natural gas, which are used to produce the energy needed for processing materials, mostly (around 50 %) in the production and processing of PMMA sheets.

The aggregation of sub-categories into main categories Human health, Ecosystem quality, Climate change, and Resources shows the endpoint results (see Fig. 5). The results show that the overall impact, referred to as the production of a functional unit of 1 kg DW biomass, is reduced by increasing the plant size. The results for endpoint categories per impact category are reported in the Annex F.

Human health category accounts for most of the impact in all of the compared scenarios, from 8.07 mPt in the SMORP pilot to 5.9 mPt in the SMORP scaled-up commercial and is about 60 % of total impact, mostly because of the strong impact of Respiratory inorganics midpoint category. Categories such as Ecosystem quality, Climate change and Resources vary little between different scenarios.

4.3. Interpretation of results

The results from the LCA study complement other studies found in the literature [73], [74]. The results of an LCA study conducted in Belgium, [74] report a 26 kg CO_2 equivalent kg^{-1} microalgae-bacteria flocs substrate (i.e. Mab-floc) for the pilot scale and 8 kg CO_2 kg^{-1} for the scaled-up version. The major difference of the studies is that study investigating SMORP relates to the specific conditions of the Baltic region, which is located in northern Europe and has weather conditions hindering microalgae cultivation during winter. The construction of a greenhouse, heating system, and lighting system for algae cultivation in SMORP inevitably affects the final environmental impact of the system. In the case of the algae cultivation in SMORP, the greatest impact share 84.6 % derives from the cultivation phase, and the harvesting phase affects the remaining 15.4 %, while results conducted on different ponds in temperate climates report a greater contribution of the harvesting phase compared to the cultivation phase. Such difference is acceptable considering that the systems built in the areas where the climate is milder often do not require heating or additional lighting system.

In the case of SMORP, heating has a substantial impact, contributing 45.8 % on the total environmental score, followed by electricity (35.4 %), and materials (17.9 %). The high energy contribution for heating raises doubt on whether the energy required to keep the system in optimal conditions during colder months in winter is compensated by increased production, therefore a sensitivity analysis is conducted to understand how feasible microalgae cultivation in SMORP can be in the specific climatic conditions.

The effect of the scale-up is less evident in the impact evaluation performed using different methods compared to different studies in the literature. The main reason is that a linear scale-up of several specific SMORP modules is applied in this study. In a real situation, the scale-up would consider remodeling of all the components, for example by using larger hydraulic pumps that can serve a greater number of ponds, a common lighting system, and other devices that would increase overall efficiency.

4.4. Sensitivity Analysis

The first parameter undergoing sensitivity analysis is biomass productivity. This parameter directly affects the amount of energy and materials within the system and thus the final environmental impact. The variations tested were limited to the productivity range indicated in the literature review, i.e. from a lower value of 10 g $(m^2\ d)^{-1}$ to a higher one of 30 g $(m^2\ d)^{-1}$, keeping the 20 g $(m^2\ d)^{-1}$ chosen in this study as the central reference. The environmental impact values vary from 26.2 mPt when productivity is equal to 10 g $(m^2\ d)^{-1}$, to 8.73 mPt in the case of productivity of 30 g $(m^2\ d)^{-1}$. Results of sensitivity analysis in Fig. 12 show that for both lower and higher values in relation to reference data the biomass productivity ratio to environmental impact score is always greater than baseline, which is equal to a ratio of 1.

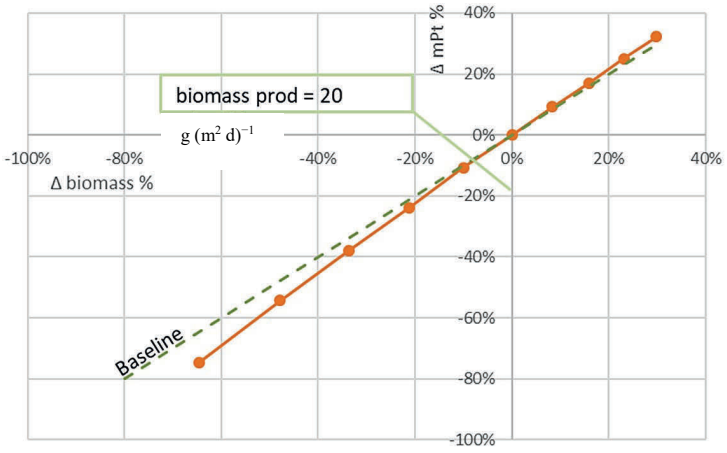


Fig. 12. Biomass productivity impact on environmental score.

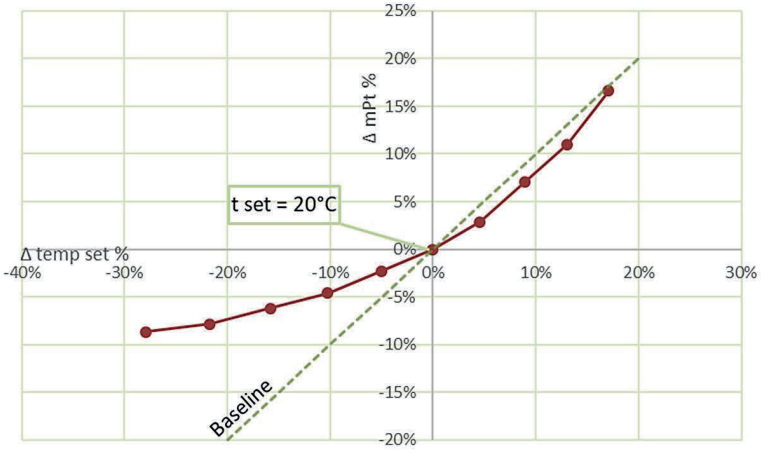


Fig. 13. Greenhouse temperature relation to environmental impact score.

Temperature sensitivity analysis is performed on the air temperature of the greenhouse where the microalgae cultivation plant is located. The sensitivity analysis considers a greenhouse reference temperature of 20 °C for temperature values in the range of 15 °C, corresponding to conditions with a non-optimal factor of 0.67 for microalgae cultivation during winter, and up to 25 °C for a non-optimal factor of 1 during summer. The sensitivity analysis is based on calculations presented in Annex E. Results of temperature sensitivity analysis in Fig. 13 show that a temperature decrease in the greenhouse would result in a smaller decrease of environmental impact score than signified by a baseline ratio of these two parameters, which equals 1. On the other hand, increasing the temperature by a few degrees shows a smaller environmental impact score increase (e.g. the area of the red line below the baseline). This occurs because a greater production of algal biomass compensates for the increase in temperature due to a more favorable non-optimal temperature factor. Nevertheless, for the temperature of 25 °C this condition is not verified because of a tipping point in algae productivity.

Preliminary analysis which does not consider optical, mechanical, and economic factors is performed for the materials of the pond. The baseline scenario for material is PMMA with an environmental score value of 13.1 mPt. The alternatives materials considered and the respective scores for environmental impacts are following:

1. High-densityity polyethylene (PEHD) with a specific weight of 1350 kg $(m^3)^{-1}$ and an overall impact score 11.9 mPt;
2. Polypropylene (PP) with a specific weight of 900 kg $(m^3)^{-1}$ an overall impact score 11.4 mPt;
3. Polycarbonate (PC) with a specific weight of 1200 kg $(m^3)^{-1}$ an overall impact score 12.6 mPt;
4. Glass fiber with a specific weight of 1790 kg $(m^3)^{-1}$ an overall impact score 13.9 mPt.

The results of material sensitivity analysis show that the total environmental impact score can change considerably up to 15 % by only changing the construction material of the ponds.

Monthly sensitivity analysis n temperature aims to identify how heating provided to SMORP concept affects the total environmental score. This sensitivity analysis is performed by supposed to stop the production of algae cultivation in different months of the year. The sensitivity analysis showed a decrease in environmental impact score when stopping the algal production in 6 months with the lowest ambient temperature. However, the study found that stopping the production for more than 6 months would increase the total score of environmental impact with respect to the FU due to the allocation of all the SMORP materials for a smaller quantity of produced algal biomass. Furthermore, the analysis showed that stopping algae cultivation in the two coldest months of the year January and December shows the highest benefit. In this case, the annual production of microalgae decreases by 24 % from 248 kg $year^{-1}$ to 188 kg $year^{-1}$, while the required heat decreases by 64 % from 50269 kWh $year^{-1}$ to 18103 kWh $year^{-1}$, and the environmental impact goes down by 16 % from 13.1 mPt to 10.3 mPt.

5. CONCLUSIONS

This LCA study compares three different scales (i.e. pilot, pre-commercial and scaled-up commercial) for a novel microalgae cultivation named as SMORP integrated into a biogas CHP plant. SMORP technology stands for Stacked Modular Open Raceway Pond where microalgae are grown. This is as a side-stream waste recirculation process coupled with a biogas plant able to reuse the centrate from the biogas plant and the CO_2 fraction from the exhaust gases from the CHP unit.

The SMORP pilot scale scenario results show an environmental impact of 13.7 mPt for 1 kg DM microalgae (selected as the functional unit) with a production capacity of 53 kg DW biomass per year. At the same time, the impact on the commercial scale decreased by approximately 16 % till 10.3 mPt.

Sensitivity analysis showed that the productivity of the SMORP concept is the most sensitive parameter. This study's hypothetical value for the production yield is medium-high compared to other open systems. Still, it can be even higher because of the great surface-to-volume ratio of the pond and the use of transparent acrylic material. However, in the study, it was not considered that increased algal biomass production in the raceway pond could increase maintenance costs due to periodic cleaning necessary to prevent the clogging phenomenon.

The results of LCIA showed that the material chosen for the ponds greatly affects the system's environmental impact, especially in the categories of global warming and non-renewable energy. The study did not consider other similar materials that can be used as a substitute to lower environmental impact. The relationship between selected materials, the amount of light radiation that goes through it, the optimal thickness, the biomass production, and the environmental impact are important aspects that must be considered more in-depth in future research. This study underlines the important role of LCA as a tool for the process design and optimization of future commercial-scale plants.

The findings of this study show that environmental performance depends on local conditions. A substantial amount of heat can be necessary to maintain an appropriate temperature in the pond for algae cultivation, hence the meteorological conditions have a strong influence on cultivation costs. This aspect should be considered in selecting an appropriate system configuration and a suitable area to build the system. In the areas of Baltic Countries, the possibility of accessing waste heat produced by industrial plants becomes an essential condition for the feasibility of microalgae culture cultivation, thus this affirms the necessity for microalgae pond integration with a biogas plant.

The second aspect concerning heating is the optimization of the temperature to be supplied to the microalgae cultivation pond during the year. As demonstrated in this work, an optimal temperature profile would allow to reduce the amount of heat by 64 % or even more, while slightly reducing biomass production. Based on this approach a guideline for microalgae cultivation pond integration with a biogas plant in areas with different climatic conditions can be developed.

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ANNEXES

Available at: https://zenodo.org/record/7584612

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