Marine biomass as potential energy source. The state of art

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***Abstract*—The use of biomass to produce biofuels represents an interesting opportunity for the progressive replacement of fossil fuels, without drastic changes for the final users. Some common fuels for terrestrial transports are already a blend of fossil fuels and biofuels. However, the contribution from renewable sources is still marginal. The adoption of biomass is a delicate aspect since some ethical issues should be properly managed. An interesting solution is currently offered by the cultivation of biomass in the seas. The goal of this paper is to assess the current state of art of this sector, depicting the possibilities, critical aspects, and opportunities.**

***Keywords*—blue energy; biomass; ocean energy**

I. Introduction

The modern society is still strongly dependent on fossil fuels, especially for the transport of goods and people. Recent statistics on Europe suggest that the transport sector is responsible for 28.4% of final energy consumption in 2020 [1].

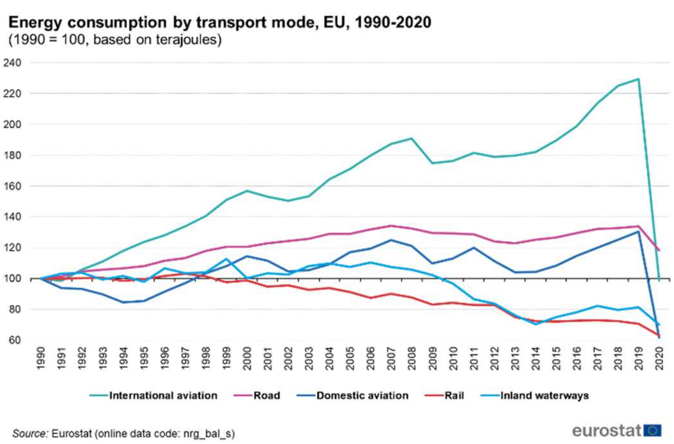

Fig. 1. Primary energy consumption by sector in Europe in the last three decades

The previous graph shows an increasing trend for the aviation transport in the last three decades, as well as for the road transport [2], [3]. A significant drop occurred in 2020, due to the Covid-19 restriction that affected the mobility of citizens [4], [5]. However, it is expected that the trend will follow the previous years because of the removal of travel restrictions.

The rail transport can be easily supplied through the electrical grid, in which a relevant contribution is given by renewable energy sources [6]. Instead, the other means of transportation continue to use traditional engines supplied with fossil fuels.

According to the European Green Deal, one of the more fighting targets is the "gas emissions reduction target by 2030 compared to 1990 of at least 55% including emissions and removals" [7], [8]. Recent news suggests the desire to abandon the combustion engines in the near future, maybe from 2035 in Europe [9], [10].

A possibility to overcome the problem of fuel consumption in terrestrial transportation is given by the e-mobility, through hydrogen coupled with fuel cells [11], [12], or highly efficient chemical batteries [13], [14]. In both cases, the vehicle is equipped with electrical motors. To avoid the CO_2 emission, the use of renewable energy sources is mandatory to produce hydrogen or to recharge the batteries of vehicles [6], [15], [16].

It is important to remind that in both strategies, radical changes are required:

- The massive use of hydrogen requires the creation of a distribution network, like the current fuel stations, where the hydrogen tanks of vehicles can be refilled. This network is practically inexistent, though the fuel stations could be converted to the new energy carrier [17], [18].
- Hydrogen storage requires more precautions than the storage of fossil fuels [19].
- The electrification of transportation sector requires a large investment plan to strengthen the electricity grid

and increase generation capacity, especially from renewable energy sources [20], [21].

In this context, an alternative approach is given by the production of biofuels [22], [23]. The starting point is represented by the cultivation of biomass, that is derived from organic material such as trees, plants, and agricultural and urban waste. The main advantages are:

- The cultivation of biomass is potentially neutral to the emission of CO_2.
- The utilization of waste from the food industry.
- The creation of jobs.
- The utilization of unused lands.

Biomass for energy must be produced, processed, and used in a sustainable and efficient way to optimize greenhouse gas savings and maintain ecosystem services [24], [25].

With this aim, the production of biomass on mainland should be properly managed and planned to avoid potential impacts, like:

- Excessive water consumption
- Competition with foodstuff cultivation
- Land consumption
- Reduction of biodiversity and forests
- Excessive use of fertilizers

A new frontier is represented by the utilization of biomass cultivated in the oceans.

II. Biomass from the Sea

During the Second World War, the cultivation of algae gained the attention of research in Germany, in particular the micro species. Due to the continuous increase of the energy demand in recent decades, interest in the cultivation of algae has largely intensified, thus trying to find a valid alternative to the use of fossil fuels.

Microalgae can be used to produce lipids from which biofuels can be extracted with zero greenhouse gas emissions and compatible with current infrastructures [26]. As reported in the following table, algae have a high producibility, up to one or two order more than other terrestrial cultivation of crops.

TABLE I. Comparison of Oil Production from Biomass

Crop	Oil production (lt./ha-y)
Soybean	450
Camelina	580
Sunflower	955
Jatropha	1890
Oil palm	5940
Algae	9350-60800

Microalgae are part of the family of primitive thalofide plants, devoid of roots, stems and leaves. They have a simple structure, not containing further apparatuses beyond the cell, which allows them to be able to adapt in different ecosystems and correctly carry out the photosynthetic process. Microalgal biodiversity includes millions of species, divided into kingdoms (prokaryotes and eukaryotes), classes and divisions.

Eukaryotic algae, unlike prokaryotic algae, contain cellular organs and photosynthesis also takes place in the chloroplasts during the light and dark phases. During the day, solar energy is converted into ATP and NADPH, used during the night to fix CO_2 through the catalyzing action of the RuBisCo enzyme, which has the task of starting the production of sugars by attacking a CO_2 molecule. There are also heterotrophic algal species which, if the respective nutrients are supplied from the outside, can grow during the night. Below, the more popular microalgae are described.

A. *Chlorella*

This is a unicellular green alga of spherical shape, diameter of about 8 microns, containing chlorophyll and chloroplasts and capable of carrying out photosynthesis. The lipids contained belong to the class of triglycerides, therefore suitable for biochemical conversion [27].

Fig. 2. Chlorella

B. *Dunaliella*

This is a cellular halophilic microalga that grows in highly saline environments, where few other organisms would be able to live. It has a cylindrical or ovoid cell and is equipped with two flagella of the same length which allow it to move through sudden movements. Dunaliella can contain lipids up to 23% and although the content is not very high, the cultivation of this species is well established for the commercial production of carotenoids [28].

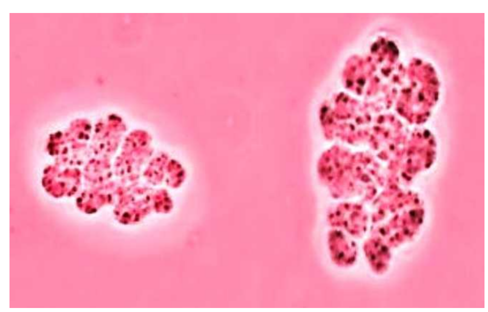

Fig. 3. Dunaliella

C. *Botryococcus Braunii*

This is a pyramid-shaped green planktonic microalga that is quite important in the field of biotechnology. This species is known for its ability to produce large quantities of hydrocarbons, mainly oils in the form of triterpenes. It is characterized by low growth rates, which are increased by the administration of CO_2, which makes the following species suitable for integration with energy production plants for carbon dioxide capture [29].

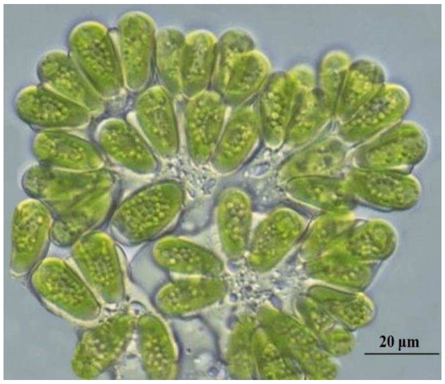

Fig. 4. Botryococcus Braunii

III. Cultivation of Microalgae

The main cultivation techniques for the growth of microalgae are essentially two (in open and closed environments), i.e., in ponds or photobioreactors.

It is still not easy to establish which is the best system to use; however, experience has shown several problematic photobioreactor systems, affirming the prevalence for commercial purposes of production for open systems only [30]. In the following table a comparison of the two systems is reported.

TABLE II. Comparison of Open and Closed Cultivation Systems

Characteristic	Open	Closed
Ratio S/V	High	Low
Different algae	Limited	Flexible
Concentration	Low	High
Collection's efficiency	Limited	High
Cultivation period	Limited	Extended
Contamination	Possible	Difficult
Water loss	Evaporation	Limited
Light utilization	Low	Optimizable
Gas transfer	Limited	Controllable
Temperature control	Through evaporation	To implement
Main costs	Mixing and O_2 control	Temperature control
Scalability	Simple	Expensive
Investment	Limited	High

A. *Canalization ponds*

The most common flue systems employed for commercial purposes are open pond reactors. The following systems are often designed as sewer ponds, equipped with paddle wheels and baffles to enhance mixing. The optimal pond depth is somewhere between keeping the pond shallow enough to get enough light for photosynthesis, but deep enough to improve mixing and remain unaffected by evaporation. Open ponds must necessarily be connected to a collection system, which conveys algae cells for biomass concentration, cell lysis and oil extraction.

In addition to the main economic problem, open ponds present further significant technical challenges. One of the main difficulties is the presence of competition and predation, as it is very difficult to maintain a monoculture of one type of algae in an open environment. In fact, the most successful algae varieties grown in open ponds are mainly located in extreme environments, for example, rich in salinity and alkalinity, which certainly inhibit competition. However, the main problem with open ponds is inadequate control of the design parameters essential for ideal algal growth.

A possible configuration is the raceway ponds, depicted in Fig. 5. In this open system, microalgae culture is recirculated along a path like a racetrack loop. The depth ranges between 15 to 50 cm, using only the solar radiation for the culture's growth [31]. A paddlewheel is used to mix properly the culture avoiding the sedimentation.

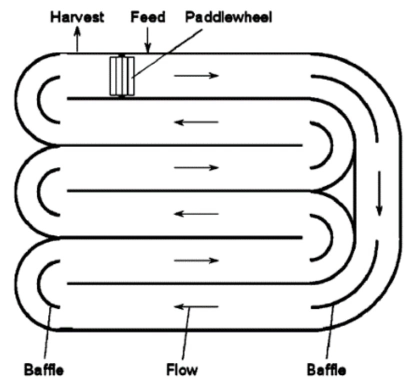

Fig. 5. Layout of a raceway pond

Another common layout is the circular pond system: the ponds have typically a diameter between 40 and 50 cm, and a depth between 20 to 30 cm. A central pivot rotating agitator is used to maintain the culture well mixed.

Finally, an inclined surface system is also proposed (see Fig. 6 [31]). In this case a microalgae suspension flows over a sloped planes. The depth of the culture is very limited (less than 1 cm), allowing an high exposure to the solar radiation.

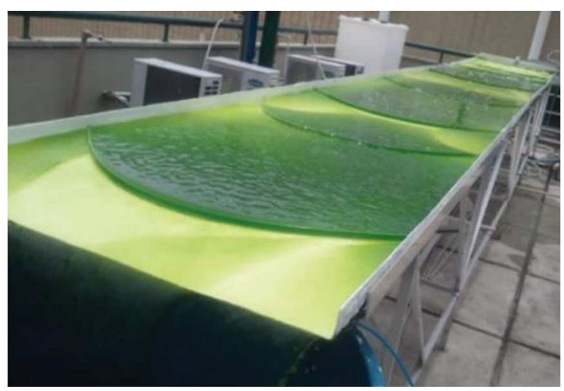

Fig. 6. Example of inclined surface systems

B. *Photobioreactors*

Several authors have expressed and recommended the need for closed systems to achieve and obtain important progress in the production of algae on a large scale [27], [32]. Inside the closed photobioreactors it is possible to better control the growth factors of the various species discussed above. There are now three types of photobioreactors for large-scale cultivation, including: tubular, column, flat-panel reactors.

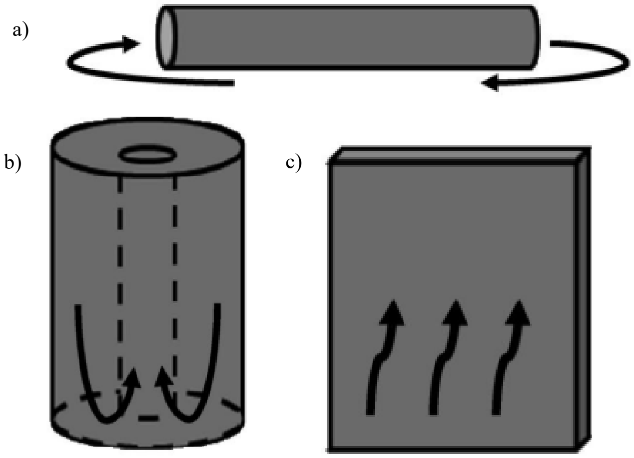

Fig. 7. Conceptual layouts of reactors: a) tubular, b) column, c) flat panel

Following a comparison between the following reactors it is known that the photosynthetic efficiency is higher in tubular reactors than in flat panel reactors, since their curved surface causes the dilution of light with consequent reduction of the efficiency itself. A further drawback for flat panel reactors, absent in tubular ones instead, consists in the fact that cellular damage can occur caused by the high stress deriving from aeration. However, flat panel reactors have advantages over other closed reactors, as for example, the oxygen path is much shorter than for tubular reactors. A shorter oxygen path therefore results in reactors with less accumulation of dissolved oxygen than horizontal reactors. In addition, flat panel reactors also consume less energy than other plant types to achieve similar or higher mass transfer capacity.

IV. Pilot Plants

A. *BSX-ASL annular column hybrid photobioreactor*

Fig. 8. A prototype of BSX-ASL photobioreactor

The BSX-ASL ring-shaped hybrid photobioreactor exploits the sunlight and artificial light generated by a high-efficiency LED cover, which makes the system suitable for both indoor and outdoor installations. The basic unit consists of a module, composed of 32 photobioreactors. Thanks to the integrated ASL system, algal species can be produced in otherwise unfavorable climatic zones. To guarantee a suitable distribution of the light, a light diffusion system has been patented by Biosyntex which allows the possibility of avoiding light intensity gradients along the profile of the reactor.

B. *BSX-SLP concentrating solar photobioreactor*

The BSX-SLP concentrating solar photobioreactor exploits solar radiation, channeling it through optical fibers and diffuser tubes inside the photobioreactors. This system makes it possible to exploit natural radiation through a "light dilution" mechanism. It is ideal to install the BSX-SLP system in sites with a large presence of the direct radiation component.

The peculiarity of the photobioreactor is that of transferring the solar radiation, concentrated by tracking panels, to provide a high quantity of direct illumination to plants or microalgal cultures [24].

Fig. 9. A prototype of BSX-SLP photobioreactor

V. Integration with other plants

Nowadays it is essential to invest in the use of marine biomass, since given the immense versatility of algal species, it is important to study process solutions that can fully exploit the potential of this biomass. The exploitation of marine biomass can represent an innovative method to contrast and mitigate the harmful effects of climate change mainly due to the increase in the greenhouse effect, related to the continuous CO_2 emissions.

The integration of microalgae cultivation fields with pre-existing plants can bring great benefits to both sectors, reducing their impact on the environment and costs. The secret of the following solution is the fundamental ability of algae to transform waste from industrial plants into nutrients for the growth of biomass.

There are different solutions and motivations that see the algae involved in integrating with plants already in operation, for example:

- The ability of microalgae to absorb large quantities of CO_2 deriving from combustion processes, thus constituting an innovative method for eliminating emissions from plants fueled by fossil fuels.
- Microalgae can also remove NOx, (very harmful to humans). The level of removal can be pushed up to 96% by increasing the area and contact time between gas and liquid.

A. Mini offshore algae farms against CO_2

The use of CO_2 in photosynthesis makes algae a possible way to reduce emissions into the atmosphere from energy production plants with a consequent decrease in the greenhouse effect. Interest in algae as a carbon dioxide removal tool has increased in recent years, as several studies have found that the world may need to break down huge amounts of greenhouse gases and that there are various types of macro-algae that they manage to naturally store almost 200 million tons of carbon in a year.

Running Tide, an aquaculture company based in Portland, Maine, plans to send huge quantities of floating kelp farms into the Atlantic Ocean in the next few years. The result that the company hopes to achieve is that the rapidly growing algae, after reaching a certain volume, will sink to the ocean, storing thousands of tons of carbon dioxide which can balance the emissions of industries and thus contribute to the huge amount of CO_2 that will need to be removed to keep global temperatures under control over the next few years.

The company said its floating microfarms could be seeded with algae sporophytes and "mechanically rigged" to sink below 1,000 feet after about eight months. Much of the attention has focused on kelp, a large brown seaweed that grows mainly along the coasts by attaching itself to the rocky seabed and assimilating the nutrients of the fresh, shallow waters. Through photosynthesis it manages to absorb large quantities of carbon dissolved in the sea which in turn absorbs further carbon dioxide from the air in the following period, restoring the balance between the oceans and the atmosphere.

Despite the enormous help that the project developed by Running Tide could grant to the planet, there are several controversies and dangers for the ecosystem with which one could collide. The company described a floating apparatus that could be seeded with macroalgae spores and "boosted with a nutrient load" that could also release iron oxide into the water. This idea has attracted a lot of criticism, as it could represent a real form of fertilization of the oceans.

Several algae experts have pointed out in interviews that Running Tide's interventions could deteriorate highly complex and delicate ecosystems. Furthermore, algae could outrun phytoplankton communities that already remove high amounts of carbon harming global systems that regulate climate and provide crucial sources of income and food. A further problem concerns the question of the growth of the kelp seaweed which, after reaching a large size, begins to lose its blades and fronds.

Once washed up on beaches, algae residues are engulfed by bacteria and invertebrates, or otherwise decompose before reaching the ocean depths, releasing much of the carbon they contain back into the atmosphere [33].

B. Integration of microalgae cultivation in marine plants

In recent years, various studies have proposed the integration of aquaculture systems, coupling microalgae production plants, both with fish farming and with off-shore wind farms, thus also optimizing the efficiency of the exploitation of natural spaces. A schematic is shown in the figure below.

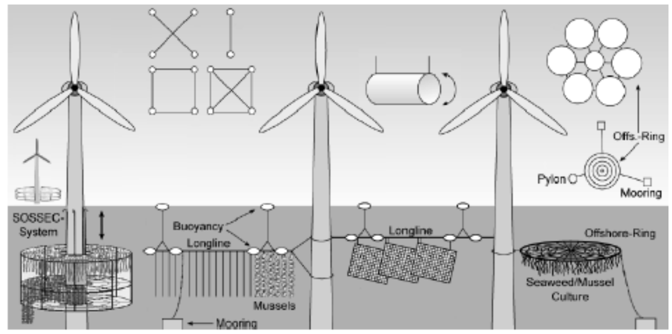

Fig. 10. Integration of biomass cultivation farm with an offshore wind farm

Using this system, the environment is self-fertilized, as there is a reduction in the required nutrient load, thanks to the natural recycling of farming waste. In this way, the benefit is obviously bi-directional, considering that the growth of marine biomass acts as a biofilter, thus restoring the quality of the water for which farming is intended. In addition to the important advantages just discussed, this solution has greater complexities associated with the processing of two totally different products, the variable efficiency of nutrient removal by the algae, the logistical problems due to the sharing spaces and equipment.

Some studies have shown that during the growth phases, algae absorb nitrogen and phosphate from the water, thus subtracting it from other living beings, creating a real competition between the inhabitants of the sea. The researchers then performed a calculation to determine the impact of seaweed cultivation on phytoplankton.

In fact, the well-being of the entire ecosystem derives from the impact that algae have on the phytoplankton, which is not easy to quantify in absolute terms, since various agents play a fundamental role on it: pollution, human activities, the increase sea temperatures and so on. Further studies will therefore be needed to find out to what extent it is beneficial to grow algae in wind farms without harming the natural environment [34].

VI. Conclusion

The cultivation of algae and microalgae can be managed in a sustainable way, not subtracting resources from agriculture but allowing the abatement of polluting atmospheric gases and the recycling of water.

In recent decades, algae have received considerable interest from institutions, industry and policy makers resulting in a wide range of experimental projects to test its potential in the fuel sector. Eni, for example, has launched an experimental plant in Ragusa for the production of bio-oils from green algae. The goal is therefore to synthesize sustainable fuels by exploiting natural resources and collaborating in the reduction of greenhouse gases. The production of algal biofuels primarily depends on the selected algal species and their characteristics.

The production of biodiesel deriving from marine biomass is not yet competitive with traditional fuels. On average, the production of 1 kg of microalgae costs about \$2.95 using photobioreactors or \$3.80 using raceway tanks, assuming that CO_2 is free. Fortunately, research has been making progress in recent decades, thanks to economies of scale, with an annual capacity of 10,000 t, the production cost is expected to drop to 0.47 \$/kg and 0.60 \$/kg.

Microalgae could represent an interesting source of substances required by cosmetic and pharmaceutical industries. The cultivation on mainland is almost consolidated by the using of photobioreactors. The next frontier is represented by the cultivation directly in the oceans, with a potential integration with offshore wind farms. Thanks to the technological development and the increase in the cost of fossil fuels, it is probable that this technology will find a widespread use in the future. However, such systems will need to be carefully managed to avoid creating unwanted effects in the environment.

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