# Solar Energy Drier for Algae with Water Recovery for Island Applications

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## Abstract:

The paper is presenting the results of the evaluation of a model to address the water-food-energy-ecosystem security nexus on islands from the perspective of structuring circular aquatic bioeconomy loops. The scientific research activities have been based on the achievements made in the ROMANA project on the establishment of a methodology for hierarchical EEA in some geographical control volumes. Specifically, there were taken into consideration two scales as the National economy of Romania and the regional economy of the Constanta County that is part of the Dobrogea Region. Using the results and the validation of the multi-scale approach from ROMANA project, in the present paper, there are presented the results of the possible extrapolation of the method for the case of a country with islands like it is the case of Spain.

## Keywords:

Solar Energy Drier, Algae Processing, Water Recovery, Island.

## 1. Introduction

In the current context of the population growth, degradation of the habitat, the evolution of the accumulation of Green House Gases (GHG) in the atmosphere and trends in the climate change, the situation of the islands and especially of the small islands, is one of the most vulnerable. There are several approaches to address the complexity of the factors that are affecting of mid and long term the socio-economic situation of the islands and the water-food-energy-ecosystem security nexus approach, as [1] demonstrates, is a holistic and well-structured one for their sustainable development.

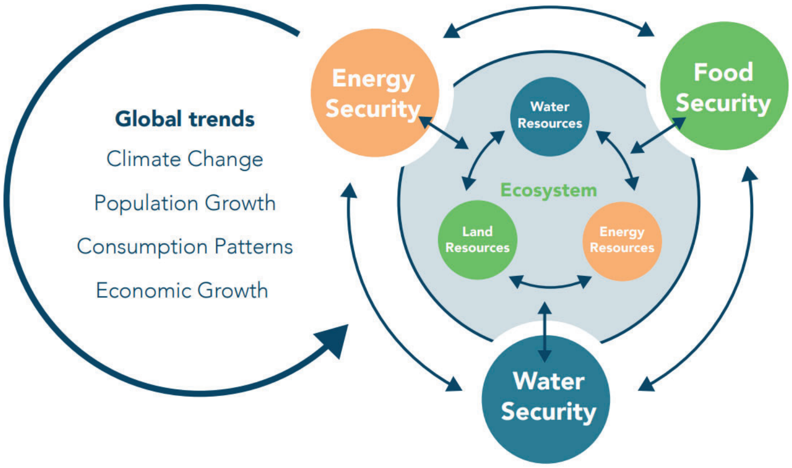

**Figure. 1.** The interdependences in the Water, Food, Energy and Ecosystem security Nexus [1].

As Austen et al [2] demonstrate, ecosystem valuation must be considered as part of this approach that has to help the achievement of objectives and targets of the environmental policies such as the Good Environmental Status (GES) of the island riparian sea or ocean waters.

As it is mentioned in [3], seaweed and microalgae are responsible of 50% of photosynthesis on Earth and using algae in the Circular Economy concept, the efficiency of solar-to-chemical energy conversion via algal photosynthesis is 4% – 10% compared to 0.5% - 2.2% in land-based farming crops.

In this context, algae harvesting on islands is considered a significant and beneficial activity, particularly if the islands are in areas with abundant algal growth. Algae are photosynthetic organisms that can be found in

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marine, freshwater, or terrestrial environments. They play a crucial role in various ecosystems and have numerous applications in industries such as food, pharmaceuticals, cosmetics, and biofuels.

Besides of appropriate selection of algae species and aspects of sustainability and environmental impact, a very important attention must be given to processing and utilization. Once harvested, algae can be processed for various applications. This may involve drying, extraction of specific compounds, or further refinement for specific industries. It's important to have appropriate processing facilities in place to maximize the value and utility of the harvested algae. The economic viability of algae harvesting depends on the costs associated with harvesting, processing, and transportation. Identifying potential markets and customers for the harvested algae products is essential to ensure profitability and sustainability in the long term.

Algae harvesting on islands can provide economic opportunities, promote sustainable practices, and contribute to the local economy. However, it's crucial to balance these activities with the preservation and protection of the island's ecosystems to ensure long-term environmental and economic benefits.

## 1.1. Humidity content and nutrient value of algae

Algae are considered an extremely heterogeneous group of organisms, very difficult to define. Without being able to consider algae as a single taxon, they could be defined as photosynthetic autotrophic organisms, with a very simply organized vegetative apparatus, called "thal", which can be microscopic, unicellular, or macroscopic, multicellular and which can be found in various habitats, from sufficiently moistened terrestrial ones, to aquatic ones. They are particularly important primary producers for living value chains, the only ones in the seas and oceans, also providing the oxygen necessary for the aquatic life. Macrophytes are also found in continental waters (fresh, salty, or brackish). The estimated net primary production of seaweeds in natural environment by vegetation type is reproduced in figure 2 after [3].

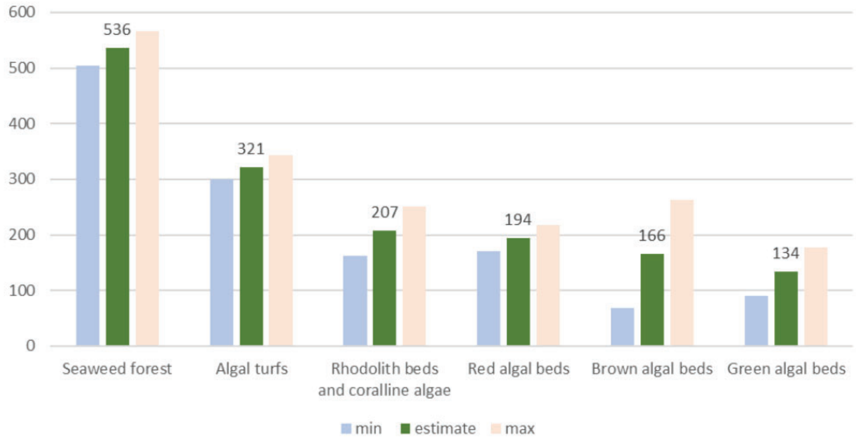

**Figure. 2.** The net primary production in natural environment by vegetation type, excluding floating algae (in gC/m$^2$/year) [3]

There are three large groups of algae as followings:

- The group of chlorophytes, characterized by the presence of A and B chlorophyll, represents a fundamental phylogenetic line within which the autotrophic terrestrial plants were differential.
- The group of rhodophytes, characterized by the presence of A and D chlorophyll, as well as of phycobilin and especially of phycoerythrin, which gives them the aspect of red colour.
- The group of chomophytes is distinguished by the presence of A and C chlorophyll, along with which there are different types of carotenoid pigments that determine their varied colour as: yellowish, brown – red and red.

As it is mentioned in [4], the total harvested output in the World was reported in 2019 as 34.7 million tonnes of farmed seaweed and 1.1 tonnes of wild-harvested seaweed.

The biochemical composition of seaweed varies depending on the species, geographical space, season, water temperature. Seaweed is valuable for its chemical and biochemical composition having a high content in minerals (magnesium, calcium, phosphorus, potassium, and iodine), micronutrients and carbohydrates. The quality of lipids and proteins is comparable to that of terrestrial plants due to the high content of essential amino acids and the relatively high level of unsaturated fatty acids.

According to Mamut and Ionescu [5], seaweed contains polysaccharides in the range of 30 to 50% of the dry matter content whose structure differs depending on the species. The fraction of soluble fibre is 51 –56% of the total fibres in green and red algae and 67-87% of brown algae. Macrophytes contain considerable amounts of polysaccharides: alginates in brown algae, carrageen, and agar in red algae. In smaller quantities there are xylenes (in red and green algae), ulvans (in green algae) and fucoidans (in brown algae).

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Macroalgae extract from the sea an extraordinary wealth of mineral elements. The mineral substance of some macrophytes can reach up to about 36% of the dry matter. Seaweed is a source of iodine and calcium. Only one gram of dried brown seaweed provides 500 to 8 000 µg of iodine, and green and red algae from 100 to 300 µg. Red and green algae, although they have a lower iodine content than brown ones, it is still superior to terrestrial plants. The calcium content in macrophytes accounts for approximately 4 to 7 % of the dry matter.

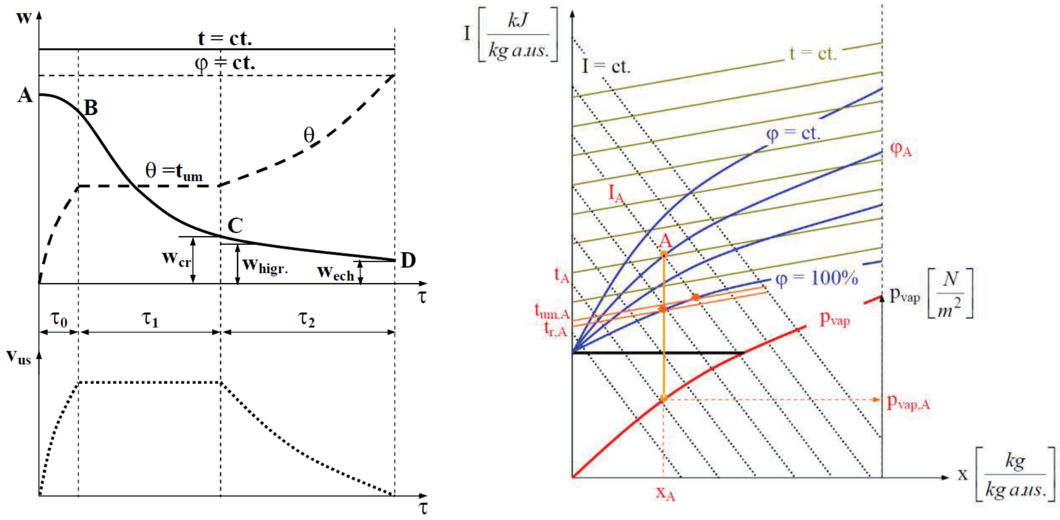
Macrophyte algae are a natural source of vitamins, polyphenols, and carotenoids with antioxidant properties. The extracts from brown algae are distinguished by the high content of fucoxanthin, β-carotene and violaxanthin. In red algae the main carotenoids are α- and β-carotene and their derivatives, zeaxanthin and lutein. The composition of carotenoids in green algae is similar to vegetal: anteraxanthin, zeaxanthin, neoxanthin, β-carotene, lutein and violaxanthin.

The harvested algal biomass is a raw material with high content of humidity and nutrients, which begins to degrade almost immediately after harvesting. For this reason, the algal biomass is requiring a solution for stabilization if it is not processed within a few hours of harvesting. The raw algal biomass can suffer of up to 20% dry matter losses within a week because of biochemical and microbial degradation.

Reducing the moisture content below 15% is a common conservation strategy for lignocellulosic biomass and is likely to be sufficient for the conservation of algal biomass. With few exceptions, drying experiments conducted in various studies were continued until the algae/terrestrial biomass mixtures reached humidity content below 10% at which point they were considered stable. In [6], there are also presented the results of drying temperatures of the algal biomass and the impact on the conservation of the most important components.

## 1.2. Algae solar drying

In general terms, biomass drying is a preservation technique that involves reducing the moisture content of biomass to prevent microbial growth, degradation, and spoilage during storage. By reducing moisture, the biomass can be stored for longer periods without compromising its quality or value.



A B

**Figure. 3.** The general process of drying of biomass by using thermal energy: A - Moisture reduction, feedstock temperature evolution and drying speed, B – Drying air humidity evolution during the drying process.

The removal of water from algae can be done with various techniques as: mechanical pressing or centrifugal processing, hot air drying, drum drying, solar drying, microwave drying, as well as freeze drying, spray draying or solvent extraction.

In Figure 3 there are presented the kinetics and main parameters of the hot air-drying process. An alternative of the hot air-drying process is the solar drying process.

Algae solar drying as the process of using solar energy to remove moisture from harvested algae, is an important step in various industries where algae are used, such as biofuel production, animal feed, and food supplements. Solar drying offers an environmentally friendly and cost-effective method for reducing the moisture content of algae.

The classical phases in solar drying of algae are as followings:

- Harvesting: Algae are typically harvested from ponds, tanks, or bioreactors when they have reached the desired growth stage.

- Pre-treatment: Before drying, the harvested algae may undergo pre-treatment processes such as filtration, centrifugation, or dewatering to remove excess water and impurities.
- Drying beds or trays: The algae biomass is spread out in thin layers on drying beds or trays. These surfaces should be designed to maximize exposure to sunlight.
- Solar exposure: The trays or drying beds are placed in an open area where they can receive direct sunlight. The solar energy heats the algae and evaporates the water content.
- Turning and flipping: To ensure uniform drying, the algae biomass needs to be periodically turned or flipped to expose all sides to sunlight. This promotes consistent drying and prevents the growth of moulds or bacteria.
- Protection: During the drying process, it is essential to protect the algae from rain, dust, and contaminants that can degrade the quality of the final product. This can be done by covering the drying beds or trays with a mesh or protective covering.
- Monitoring: The drying process should be regularly monitored to assess the moisture content of the algae and determine when it reaches the desired level of dryness. Moisture meters or visual inspections can be used for this purpose.
- Storage: Once the algae biomass has reached the desired moisture content, it is removed from the drying beds or trays and stored in suitable containers to prevent rehydration.

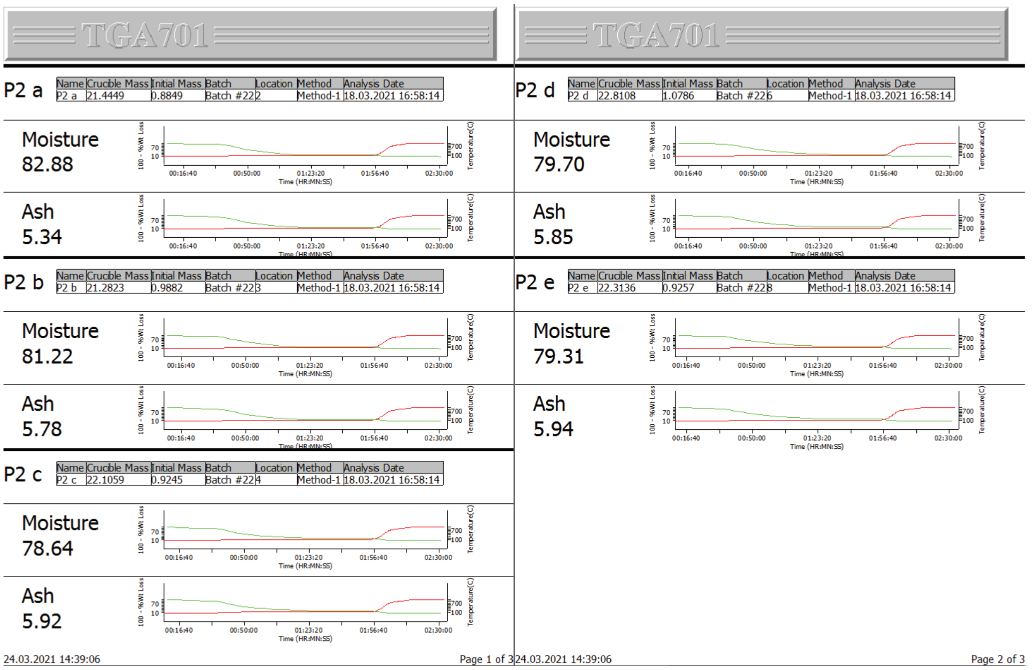
The drying time will depend on various factors such as the type of algae, thickness of the biomass layer, ambient temperature, humidity, and solar radiation. In the classical installations, the drying process can take several days to weeks, and it may be necessary to cover the drying beds during the night or in unfavourable weather conditions to protect the algae.

Solar drying offers a sustainable and energy-efficient method for algae drying, utilizing readily available solar energy and minimizing the use of fossil fuels or electricity. This method is particularly suitable for regions with abundant sunlight, where it can significantly reduce the energy costs associated with conventional drying methods.

# 2. Characterization of algae samples

## 2.1. Algae sampling and characterization

The evaluation of algae drying processes have been developed for the harvested algae from the Black Sea coast. On the basis of the samples collected from the Black Sea shore and from the continental waters, the physico-chemical properties regarding the moisture content were determined, using conventional drying methods: by using as reference the natural drying for 24h and by using an oven and determining the humidity content. Also, the humidity and ash content of the algae were determined using thermogravimetric analysis methods.



P2 a

| Name | Crucible Mass | Initial Mass | Batch | Location | Method | Analysis Date |
|---|---|---|---|---|---|---|
| P2 a | 21.4449 | 0.8849 | Batch #22 | 2 | Method-1 | 18.03.2021 16:58:14 |

Moisture
82.88

Ash
5.34

P2 b

| Name | Crucible Mass | Initial Mass | Batch | Location | Method | Analysis Date |
|---|---|---|---|---|---|---|
| P2 b | 21.2823 | 0.9882 | Batch #22 | 3 | Method-1 | 18.03.2021 16:58:14 |

Moisture
81.22

Ash
5.78

P2 c

| Name | Crucible Mass | Initial Mass | Batch | Location | Method | Analysis Date |
|---|---|---|---|---|---|---|
| P2 c | 22.1059 | 0.9245 | Batch #22 | 4 | Method-1 | 18.03.2021 16:58:14 |

Moisture
78.64

Ash
5.92

24.03.2021 14:39:06
Page 1 of 3

P2 d

| Name | Crucible Mass | Initial Mass | Batch | Location | Method | Analysis Date |
|---|---|---|---|---|---|---|
| P2 d | 22.8108 | 1.0786 | Batch #22 | 6 | Method-1 | 18.03.2021 16:58:14 |

Moisture
79.70

Ash
5.85

P2 e

| Name | Crucible Mass | Initial Mass | Batch | Location | Method | Analysis Date |
|---|---|---|---|---|---|---|
| P2 e | 22.3136 | 0.9257 | Batch #22 | 8 | Method-1 | 18.03.2021 16:58:14 |

Moisture
79.31

Ash
5.94

24.03.2021 14:39:06
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**Figure. 4.** Water and inorganic matter content of algae samples collected from sea water.

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For collected algal samples, the humidity and total solids content have been determined according to ASTM E1756-01 and T412 man-02.

The samples were weighed before being placed in the oven at a temperature of 60°C for 24h. After keeping them 24h in the owen, the samples were weighed, and the difference between the initial and the final mass of each sample is the loss of humidity.

For the samples of algae that were collected from the water and dried naturally for 24h, the average moisture content was 80,35 %. The average content of inorganic substances in water samples of algae was 5,76 %.

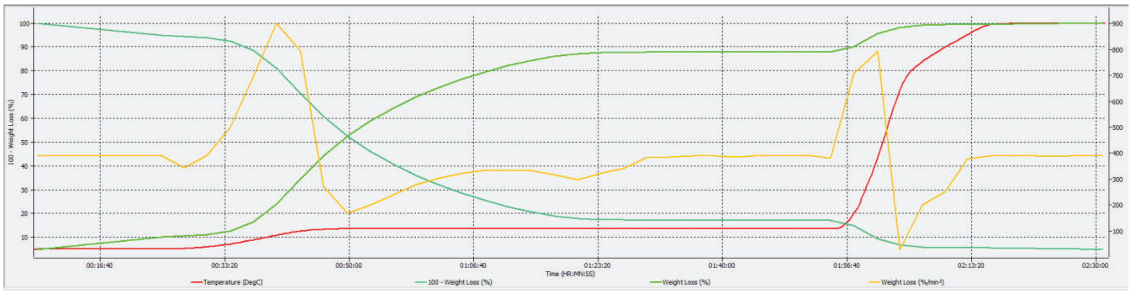

**Figure. 5.** Graph of the loss of weight in relation to the increase in temperature for algae taken from water.

According to the graph presented in Figure 5, the weight loss was recorded in relation to the increase in temperature. In the temperature range 30 – 45°C the weight loss of the sample was of 7,5%. In the temperature range 45 – 75°C the lost weight of the sample was 15%, and in the temperature range 75 – 90°C, the weight loss of sample was of 23.43%.

For seaweed samples taken from the beach and dried naturally, the average moisture content was 8,34 %. The average content of inorganic matter present in algae samples collected from the beach was 33,05 %.

## 2.2. Synthesis of the results

As a result of the performed experimental investigations, the dynamics of the weight loss was observed in relation to the increase in temperature.

In the temperature range 30 – 45°C the weight loss of the sample was of 0,98%. In the temperature range 45 – 75°C the weight loss was of 4.05%, and in the temperature range 75 – 90°C, the weight loss of was of 6.2%.

**Table 1.** Table with the synthesis of the algae sample analyses.

| Sample code | Oven Temperature (°C) | Drying period (h) | Initial weight (g) | Final weight (g) | Weight loss (g) | Percentage (%) |
|---|---|---|---|---|---|---|
| P1 a | 60 | 24 | 5,06 | 4,62 | 0,44 | 8,7 |
| P1 b | 60 | 24 | 4,96 | 4,51 | 0,45 | 9,1 |
| P1 c | 60 | 24 | 5 | 4,67 | 0,33 | 6,6 |
| P1 d | 60 | 24 | 5,07 | 4,65 | 0,42 | 8,29 |
| P1 e | 60 | 24 | 5,06 | 4,73 | 0,33 | 6,53 |
| P3 a | 60 | 24 | 5,16 | 2,46 | 2,7 | 52,33 |
| P3 b | 60 | 24 | 5,14 | 2,19 | 2,95 | 57,4 |
| P3 c | 60 | 24 | 4,95 | 2,73 | 2,22 | 44,85 |
| P3 d | 60 | 24 | 5,38 | 3,13 | 2,25 | 41,83 |
| P3 e | 60 | 24 | 5,04 | 3,03 | 2,01 | 39,89 |

Following the thermogravimetric analysis of samples collected from water, the following results were obtained:

- the average value of the moisture content of the samples was 5,51 % for the samples of algae collected from the water;
- the average value of the moisture content of the samples was 3,3 % for seaweed samples collected from shore;
- the average value of the total solids content of the samples was 36,43 % for samples of algae collected from the water;
- the average value of the total solids content of the samples was 43,79 % for seaweed samples collected from the shore.

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Based on the performed analyses, it was found a weight loss of samples depending on temperature range, as followings:

- in the temperature range 30 to 45 °C, the weight loss was 0.22%;
- in the temperature range 45 to 75 °C, the weight loss was 2.55%;
- in the temperature range 75 to 90 °C, the weight loss was 4.43%.

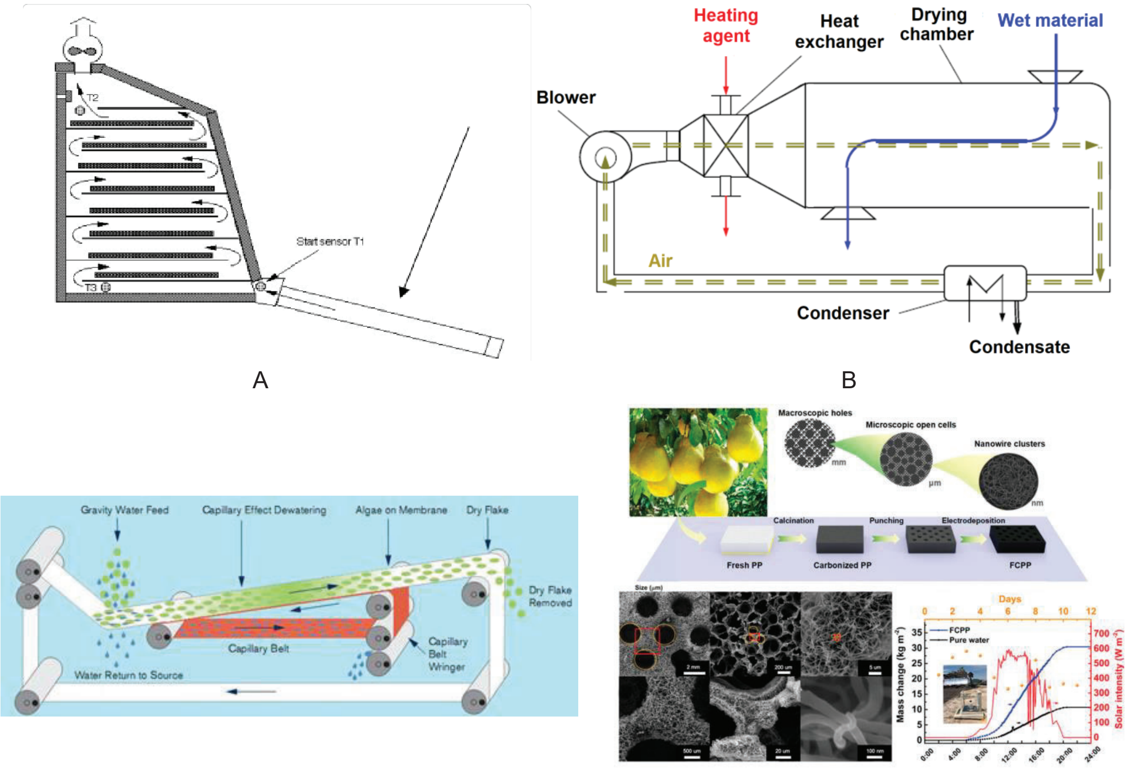
As it may be seen in the table above, depending on temperature range, the following results were obtained:

- in the temperature range 30 to 45 °C, the weight loss was 0.14%;
- in the temperature range 45 to 75 °C, the weight loss was 1.3%;
- in the temperature range 75 to 90 °C, the weight loss was 2.1%.

## 3. Drying equipment

### 3.1. Reference concepts

The reference concepts of driers that have been used for the development of the innovative solution are presented in Figure 6. It has been started from the reference concept of solar drier for algae as may be seen in figure 6 A (adapted after [7]). The solar radiation is heating air in the solar collector located in the bottom side and when the drying temperature is reached, the access valve allows the passage of hot air that is flowing over the fixed bed wet biomass absorbing the humidity and evacuating it by natural convection from the one-way evacuation exit located on the top side of the drier.



A

B

C

D

**Figure. 6.** The reference concepts of driers that has been used for the development of the innovative solution of solar algae drier: A – batch solar drier for small quantities of algae (adapted after [7]), B – continuous drying chamber with the recuperation of water condensate, C – drying booster based on a capillary belt (adapted after [8]), D - hierarchically structured nanostructured materials (adapted after [9]).

The solution has been adapted for a continuous drier concept as presented in figure 6 B. It consists of a drying chamber where there is a belt on which from the top side it is fed continuously the wet biomass. The hot air is circulated from the chamber absorbing the humidity of the wet biomass and after drying, the algae is evacuated from the bottom side of the chamber. The high humidity air is recirculated from the condenser and the excess water is recovered as condensate from the bottom side of the graph. The air is further recirculated and reheated before entering in the drying chamber.

To avoid the critical regime (point C in figure 3 A) in the drying process, the innovative concept has been developed by adding a capillary belt as presented in figure 6 C (adapted after [8]). The capillary belt is pressed to the conveyor belt transporting the wet biomass and by the very high hydrophobicity of the capillary material, absorbing the humidity from the bottom and giving a boost to the drying process.

The superhydrophobic material of the capillary belt has been developed as a hierarchically structured nanostructured material like the example presented in figure 6 D (adapted after [9].

### 3.2. Solar drier concept for continuous processing of wet algae

The concept of the drier has been developed based on a methodology of innovation that started from the definition of the requirements, collection of related information, development of new ideas to address the requirements, co-design of alternative solutions, modelling, testing validation and optimization of the solutions and finally, the selection of the final design by a Multi-Criteria Decision-Making process.

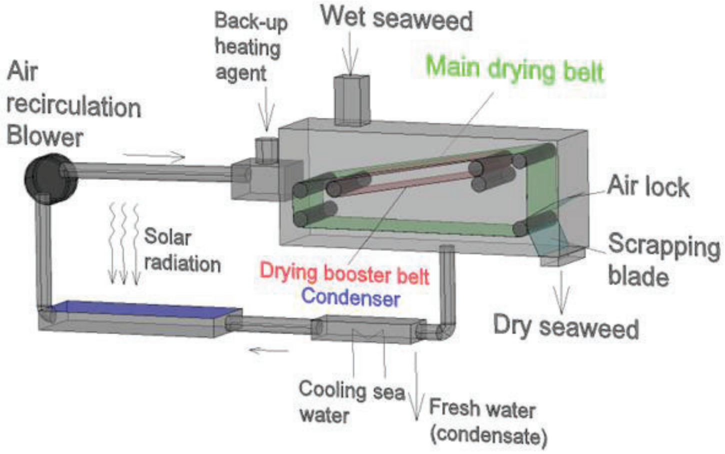


**Figure. 7.** Innovative concept of drier using solar energy and producing dried seaweed and fresh water.

The solution that has been developed, consists of a continuous belt drier using hot air. The thermal energy is obtained from a solar air collector. The air is circulated in a closed loop that includes a condenser for collecting fresh water resulting from the drying process of algae. As backup thermal energy source, for balancing the intermittence of the solar energy, it has been included a pellet boiler heater.

To avoid the critical drying regime and to improve the efficiency of the drying process, the installation includes a drying booster belt using a fabric that integrates super hydrophilic nanostructured powder for absorbing the humidity from the wet biomass by contact on the bottom side of the main drying conveyor belt.

Therefore, the innovative installation is processing the wet seaweed collected from the sea or the beach, to produce dry algae as a stable, high value concentrate of minerals, vitamins, and other important substances. At the same time, the installation is producing fresh water by the condensation of water vapours from the drying air. As condensing coolant is used the sea water.

The solar energy collectors have been developed by integrating an absorber of solar radiation with a paint integrating Multi Wall Carbon Nanotubes (MWCNT). For the improvement of the convective heat transfer from the absorber to the air stream, a special design architecture has been developed.

## 4. Hierarchically Multiscale Modelling

The proposed innovative approach is based on the Extended Exergy Accounting - EEA.

The EEA method [10], [11] and [12] is based on the idea that the three Externalities (Labour, Capital and Environmental Cost) can be assigned “equivalent primary exergy values”, under a set of assumptions derived from an exergy budget of the region in which the process is located. EEA is based on a series of assumptions that concern the control volume used for the analysis: since it is necessary to exactly quantify the mass- and energy streams flowing in- and out of a given economic system, the most proper „control volume” to use is at the Country or at the Regional level (like the EU or a sub-regions of Member Countries), where sufficiently disaggregated data are available from reliable sources. Thus, every EEA analysis ought to begin by considering the material, energy and economic balance of the entire Country. Once these global data have been extracted, manipulated and processed, EEA most convenient applications are at intermediate and low (highly disaggregated) levels, down to a single production line. The theory requires that two conversion functionals, the equivalent primary exergy of the unit of monetary circulation, $ee_K$ [J/€], and the equivalent primary exergy of the workhour, $ee_L$ [J/workhour], be calculated at the regional level, and they require the acquisition of two econometric parameters that contain global economic, social and exergetic data [11].

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The EEA method begins with the subdivision of the region in which the process is located, in 7 Sectors: Domestic (DO), Extraction (EX), Conversion (CO), Industrial (IN), Transportation (TR), Tertiary (TE) and Agricultural (AG). Each Sector exchanges material and immaterial fluxes with other sectors, with the environment and/or with another conventional -fictitious- system called "Abroad" that accounts for the import/export fluxes. Similarly, every single (material or immaterial) process S taking place in the region exchanges physical fluxes with some of the sectors: all of these fluxes can be converted to extended exergy (i.e., their primary exergetic equivalent) by means of the two above functionals. In particular, $EE_L$ is assumed to be originated only in DO, and $EE_K$ in TE. Imported commodities are handled through TE.

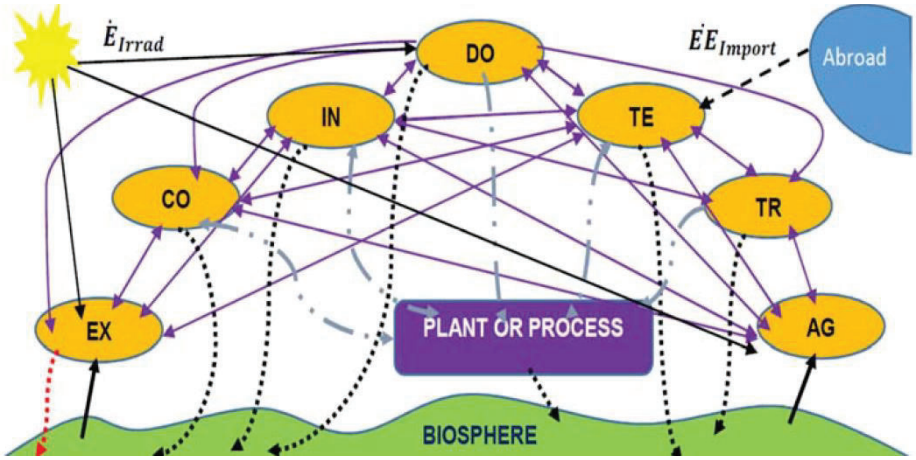


**Figure. 8.** Structuring the activities in a certain control volume in 7 Sectors: Domestic (DO), Extraction (EX), Conversion (CO), Industrial (IN), Transportation (TR), Tertiary (TE) and Agricultural (AG) (adapted from [12])

Once the above quantities are known, a balance for the $EE_j$ is performed, resulting in a specific extended exergy cost, $ee_c$ [$J_{primary\ exergy}$/unit] that reflects the total amount of primary resources consumed for the production of 1 unit of product X: a genuine exergy cost.

Notice that the EEA method is perfect tool for the assessment of medium- and long range scenarios: since it clearly identifies the contributions from renewable and non-renewable sources, it provides useful quantitative indications about the progress of a process, a technological line, an industrial sector, a Region or a Country along the so-called "transitional path to sustainability".

The calculation of the $ee_c$ requires that highly disaggregated data are available for the Region under analysis. It also requires that updated technical information is available for all feasible technical treatment processes of each pollutant. Additionally, labour and monetary statistics at regional level are necessary to calculate two econometric coefficients, called α and β [7,8] needed for the calculation of $ee_K$ and $ee_L$. Procedures to calculate these econometric coefficients for a multiscale approach have been validated in the Project ROMANA that is in final phase of implementation at Ovidius University of Constanţa. EEA-based procedures were developed for the integrated evaluation of energy efficiency at Country Level – Romania, county level – Constanţa, and process level for the District Heating System in the Constanţa Municipality.

## 4.1. Drier scale modelling

For the evaluation of the main energy and commodity flows, at the scale of the drying installation as it is presented in fig. 7, the following values have been calculated:

- required heat for drying,
- absorbed solar radiation energy,
- the resulting flows of water and dry matter the process.

At the drier scale, the conservation equations are as followings:

- specific heat in the convection heat transfer between air and wet biomass

$$q = \alpha\left(t_m - t_f\right) \tag{1}$$

- mass balance equation

$$\dot{m}_1 = \dot{m}_2 + \dot{W} \tag{2}$$

- humidity balance in the drying installation

$$\dot{m}_1 \frac{w_1}{100} + Lx_0 = \dot{m}_2 \frac{w_2}{100} + Lx_2 \tag{3}$$

- thermal balance in the drying process

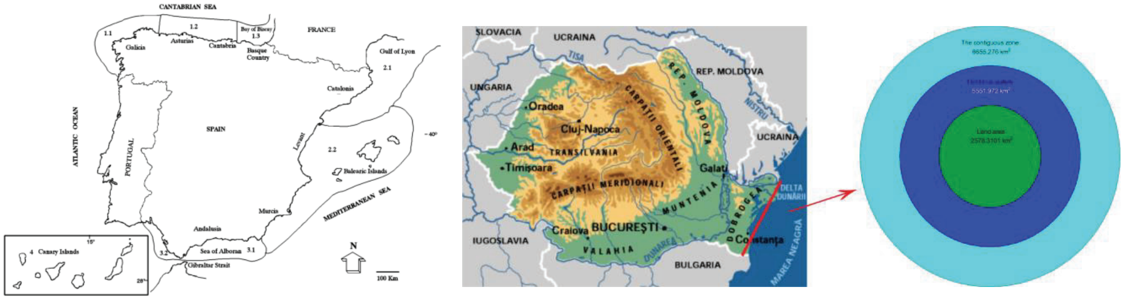
$$q = l(I_2 - I_0) = 1.006(t_1 - t_0) + 1.863x_1(t_1 - t_0) \tag{4}$$

The modelling equations (1) – (4), were written by taking into consideration theoretical conditions, without considering losses from the walls, chemical reactions, and the transportation losses.

The calculated streams of energy and commodities have been integrated in the EEA calculation toolbox.

## 4.2. Island scale modelling

The scientific research activities that have been developed under ROMANA project, have been concentrated on the establishment of a methodology for hierarchical EEA in some geographical control volumes. Specifically, there were taken into consideration two scales as the National economy of Romania and the regional economy of the Constanta County that is part of the Dobrogea Region. Using the results and the validation of the multi-scale approach from ROMANA project, in the present paper, there are presented the results of the possible extrapolation of the method for the case of a country with islands like it is the case of Spain.



A B

**Figure. 8.** Equivalent Island model for the yields of algae from the sea waters. A – Regions of Spain that are active in the aquatic bioeconomy [13]. B – Conventional model for structuring a coastal region as an island.

It has to be mentioned that the Dobrogea region has a specific characteristic consisting on the geographical boundaries established by the Lower Danube in the West, Danube Delta in the North and the Black Sea in the East. For this reason, it has been considered the shoreline to the Black Sea and a possible structuring of it as a conventional island shoreline as presented in the fig. 8 B. This offered the possibility to define an equivalent land surface for estimating the specific input of solar energy that could be used for calculating EEA in relation with aquatic bioeconomy inputs. At the same time, offering the possibility to define a reference surface for the associated coastal waters including the equivalent surface of territorial waters and contiguous zone according to the current international laws.

Using the above-mentioned assumption, an equivalent conventional island has been generated and used to apply the EEA method for the evaluation of the relation between the solar energy potential, the aquatic bioeconomy inputs and the outputs in terms of dried seaweed and fresh water, by using the data collected for the Dobrogea region.

# 5. Experimental results

The estimation of the annual yields of seaweed has been carried out for the conditions in the South-East region of Romania, where the collection season starts in June and ends in October.

A B

**Figure. 9.** Collection of the seaweed yields: A – Collection from water; B – Collection from the beach

There is a specialized company that is organized for collecting algae both from the sea shallow waters and from the beaches. The total shoreline is of 180 km and the average annual yield is of 40.000 tonnes.

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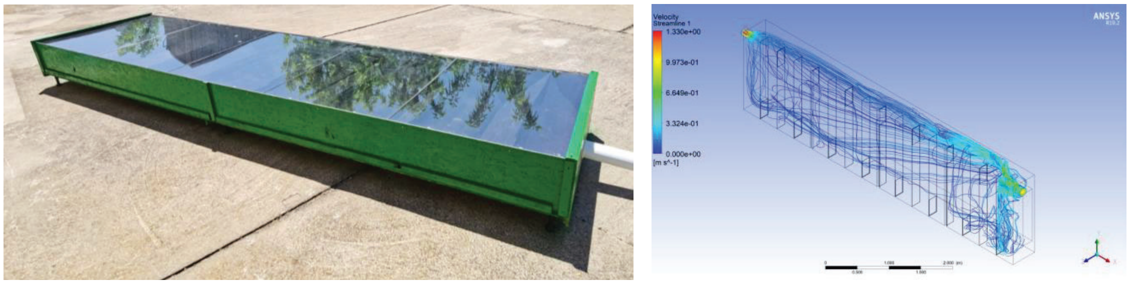
By comparing the SE region of Romania with other regions, it has to be underlined the importance of the contribution of the Danube River exit to the Black Sea. The high concentration of nutrients transported by the Danube has a major role in supporting the production of algae yields.

The validation of the model of the solar air collector has been done by using a 1:1 physical model that is presented in the Figure 10 A. The solar collector integrates an absorber that was developed using a special paint with MWCNT. The absorption rate of solar radiation that was measured on the experimental prototype was 98.8%.



A

B

**Figure. 10.** Solar air collector validation: A – Experimental validation prototype; B – ANSYS Fluent thermofluidic analysis and optimization model.

An ANSYS Fluent model has been developed for the study of the thermofluidic processes in order to improve the convective heat transfer properties and to define an optimal flow architecture for highest convection heat transfer coefficient.

Considering the annual yield of wet algae collected from water in the range of 40.000 tonnes with an average humidity of 80%, using the model described in paragraph 4.1, it has been calculated the total required heat for the drying process, in the amount of 28.000 MWh/year.

The calculated heat resulted for the estimated final humidity of the dry algae of 10%. The total quantity of dry algae is estimated at 12.000 tonnes.

The by-product obtained from the drying process is fresh water in an amount of 28.000 tonnes/year.

The price for dry algae was estimated at 200 Euro/tonne and the price for fresh water is 2 Euro/tonne.

The total income for the installation has been estimated at 2.4 million Euro for the dry algae and 56.000 Euro for water.

The operational costs included the following items:

- labour costs in an amount of 72.000 Euro
- energy costs (including cost of transport) in an amount of 168.000 Euro
- overheads in an amount of 24.000 Euro

Total operational costs have been estimated at 264.000 Euro.

The investment costs include the following items:

- Solar air collectors – 2.400.000 Euro
- Dryer – 400.000 Euro
- Ancillary equipment and construction works – 280.000 Euro

Total investment cost – 3.080.000 Euro.

Considering a depreciation period of 15 years, with a fix rate of depreciation, it has been obtained a yearly depreciation of 205,333.3 Euro.

From the economic point of view, the investment payback period is of 7.6 years.

But the benefits of exploitation of the seaweed yields are much more complex and include the avoidance of the GHGs that are resulting from the natural decomposition of the biomass. In this respect, it has been developed an EEA model for the evaluation of the energy efficiency in the hierarchical model that has been presented in paragraph 4.

Two configurations were compared: the first one uses a $CH_4$-fuelled drier, and the second one is the solar drying configuration described above.

The exergy flows of the two processes were analysed first, and the Solar configuration showed a slightly better efficiency: 0.68 vs. 0.66. But the EEA analysis, that includes in the "product cost" the primary exergy flow equivalent to the externalities (Labour and Capital in this case), provided a different picture. Table 2 shows the extended exergy cost $ee_c$ for the two co-products, dry biomass and desalinated water: considering that the exergy cost of Reverse Osmosis desalination is about 0.01 kWh/kg, the process is not a convenient desalinator. But the primary exergy cost $ee_c$ for the dried biomass is about one third of that of natural gas (3 vs. 15.88 kWh/kg), which makes the biomass very convenient both as a secondary biofuel or as a raw material input for the chemical industry.

**Table 2.** Extended Exergy Cost $ee_c$ [kWh/kg] of the two co-products.

| | Dried biomass | Desalinated water |
|---|---|---|
| Natural gas-fired drier | 5.61 | 1.12 |
| Solar drier | 5.81 | 1.16 |

The calculated quantity of GHG equivalent of $CO_2$ that is saved in the case the solar drier, is of 4453 tonnes/y. Considering a price per $CO_2$ certificate of 100 Euro/t the total value of the certificates is 445,300 Euros.

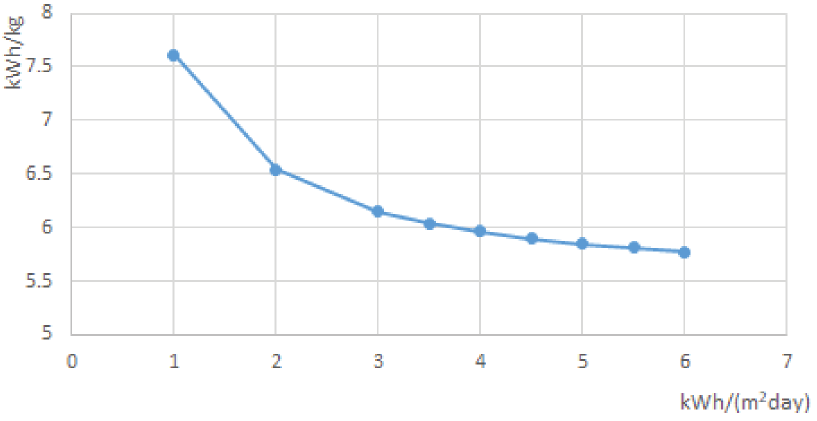


**Figure. 11.** The impact of solar irradiation of the extended exergy cost of the biomass

In fig. 11, it is presented the influence of the solar irradiation on the extended exergy cost of the dried biomass. It may be seen that the increase of the irradiation is reducing the extended exergy cost based on the reduction of the investment on solar panels.

A similar analysis must be done on the aspects referring to the primary exergy of the dry algae. Depending on the quality of the algae the price is varying between 200 and 1200 Euro/t. In the EEA model that has been used for the present study, the price was used as 200 Euro/tonne.

## 6. Conclusions

The water-food-energy-ecosystem security nexus approach is a holistic and well-structured model addressing the complexity of the factors that are affecting on mid and long term the socio-economic situation of the islands and for their sustainable development.

The scientific research activities have been presented in the paper were obtained based on the achievements made in the ROMANA project on the establishment of a methodology for hierarchical EEA in some geographical control volumes. Specifically, there were taken into consideration two scales as the National economy of Romania and the regional economy of the Constanta County that is part of the Dobrogea Region. Using the results and the validation of the multi-scale approach from ROMANA project, in the present paper, there are presented the results of the possible extrapolation of the method for the case of a country with islands like it is the case of Spain.

The innovative solution that is presented in the paper is efficient and taking into account only the commercial values for OPEX and CAPEX, the investment payback period is of 7.6 years

But the benefits of exploitation of the seaweed yields are much more complex and include the avoidance of the GHGs that are resulting from the natural decomposition of the biomass. In this respect, at present, there is under development the EEA model for the evaluation of the energy efficiency in the hierarchical model that has been presented in paragraph 4.

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## Nomenclature

$q$ heat, J/kg

https://doi.org/10.52202/069564-0170

| | |
|---|---|
| $t$ | temperature, °C |
| $\dot{m}$ | mass flow rate, kg/s |
| $\dot{W}$ | mass flow rate, kg/s |
| $w$ | specific humidity, $\mathrm{kg/kg_{wet\ biomass}}$ |
| $L$ | air flow rate, kg/s |
| $l$ | specific air flow rate, $\mathrm{kg/kg_{humidity}}$ |
| $x$ | air humidity content, $\mathrm{kg/kg_{dry\ air}}$ |
| $I$ | enthalpy, $\mathrm{kJ/kg_{dry\ air}}$ |

**Greek symbols**

| | |
|---|---|
| $\alpha$ | heat transfer coefficient, $\mathrm{W/(m^2\ K)}$ |

**Subscripts and superscripts**

| | |
|---|---|
| $m$ | mean value |
| $f$ | fluid |
| $0$ | air inlet section |
| $1$ | biomass inlet section |
| $2$ | dry biomass exit section |

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