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NEREU Project: Construction of a Plasma Reactor for Reform of Greenhouse Gases for Treatment of Wastewater of the Marine Farms

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Additional information is available at the end of the chapter

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Abstract

The predatory exploitation techniques used for the supply of protein resources have been systematically causing the decrease in seafood. The solution was sought in the form of marine farms, for the purpose of production of fish and seafood. Brazil created an incentive production of seafood in order to increase seafood production. In 1998, the state governments joined the project, encouraging the creation of marine farms without an assessment of the impact on the environment. In 2005, after several records of seafood production in Santa Catarina started an epidemic of white spot shrimp, decimating several fishing farms. In Bahia came the disease lethargic crab, which simply decimated almost 90% of crabs those states. In 2010, the State Government of Bahia invested in research to combat this degradation of mangroves; the project had to in essence deal with the brown mare and help save the fishing industry of the state. It was based on these principles that Nereu project emerged, which provides for the rational and intelligent use of contaminated and hypersaline water of the marine farms from the production area of fish and seafood, in order to neutralize all pathogens and produce pure water with energy cogeneration.

Keywords: colloidal carbon, desalination, hydrogen, methane, stirling engines

1. Introduction

The constant negative action of man over nature, promoting deforestation, releasing waste without treatment and chemicals in the water, grounding of the mangroves that are nurseries for many species, and overfishing causing the decrease of fish stocks and leading the fisherman to stop fishing and look for other activities. The crisis in the fisheries sector caused by the

uncontrolled exploitation of the coastal zone with the consequent reduction of marine stocks makes aquaculture an important food production alternative, significantly contributing to food security and poverty alleviation on the planet [1, 2].

The aquaculture is a deliberate attempt by humans to modify and manipulate the trophic relationships controlled by nature. Thus, it can be seen that all production activities are influencing the environment and in aquaculture, such impacts can be classified into three groups: those from the environment (exogenous), those resulting from aquaculture owned (endogenous), and those caused by the aquaculture on the environment. Moreover, it is noteworthy that the environmental impacts caused by aquaculture will always be more negative than positive [2, 3].

Thus, fish farming and shellfish generate waste in the form of particles and inorganic and organic soluble material. The nature and quantity of effluent vary with the type of cultivation, crop species, and intensification level. In general, feces, excreta, and pseudo-feces are the main sources of inorganic and organic nutrients [4].

The bacteria, fungi, and protozoa participate in the degradation process of organic matter, and release of toxic gases such as sulphur become unavoidable. The ideal of sustainable aquaculture, which is consistent with the economic, social, ecological, spatial, and cultural contexts [4, 5], is at an early stage in Brazil, where mistakes are being evaluated and studied so that new management techniques may be suitable for targeting a smaller effect on the ecosystem balance.

This concern about the environmental impact was not taken into account by the Federal Government of Brazil, which despite the warnings given by CONAMA [6] decided, through the Ministries of Agriculture, Environment and Development of Industry and Trade in 1997, to create an incentive to the fishing and production of seafood through the creation of marine farms. In 1998, the state governments began to join the project, and the states of *Bahia*, *Santa Catarina*, *Ceara*, and *Espirito Santo* invested heavily in the project for installation of farms mainly shrimp, oysters, and scallops. Through tax incentives, public funding, and federal funding, there was an incentive to create these marine farms, but there was no evaluation on the impact of aquaculture in the environment [4–9].

Between 2000 and 2005, the record increase in the seafood production was achieved. A total of 75% of this production aimed at export [4, 6–9]. However, in 2005, it began a productive decline, beginning with Santa Catarina, southern Brazil, which started an epidemic of white spot syndrome in the shrimp. It is a disease that affects shrimps and is one of the four identified in Brazil contained in the OIE list of aquatic animals. The WSSV—“White Spot Syndrome Virus”—is a persistent infection, with high mortality in shrimp cultivation. This disease began to spread along the Brazilian coast, currently reaching the state of *Ceara*, with production loss of nearly 80% of shrimps. Almost concurrent appearance of this disease arose in the mangroves of *Espirito Santo* and *Bahia*, the disease lethargic crab (DCL). It was found that the causative agent of DCL is the pathogenic fungus *Exophiala cf psycrofila* that simply decimated almost 90% of crabs in these states [3, 4, 9].

In 2015, the disease proliferates reaching other states, decimating the mangrove areas and ending with the crab. After several analyses of the environmental agencies, it was found that

the marine farms established in these states generate waste, which cause the problem, generating conditions for the proliferation of pathogens in the environment, often resistant to the immune system of animals due to the indiscriminate use of antibiotics in effluent ponds and crops laboratories. The DNAs of the *Exophiala cf psychrophila* and *Nimaviridae* were found in the existing mangrove in the region of *Jaguaribe*, fishing town in the state of *Bahia*. This organic material was present in a phenomenon known as brown tide and was caused by the discharge of waste from marine farms who had settled in this region [4, 6–9].

It is problematic and with the need to clean the environment of this waste, the principles of Nereu project were built, which provides for the rational and intelligent use of contaminated water and hypersaline of the marine farms, in order to neutralize all pathogens and produce pure water with energy cogeneration.

2. Farm of shrimp: the problem

Despite the changes in development models that have taken place throughout history, natural resources have always been exploited without any concern for the sustainability of the system, often exhausting these resources to the extreme. The current model of development has generated global environmental impacts, putting the biosphere at risk. Development models that revert to the situation or at least minimize impacts on the biosphere are urgently needed.

According to some data, world mariculture expanded rapidly from 16.7 million tons in 2004 to 22.8 million tons in 2014, an increase of 35.8%, whereas the fishing sector declined in this period from 83.8 to 69.9 million tons. In 2004, mariculture accounted for 16.6% of the world's fish production, which increased to 30.1% in 2014. In contrast to the increasing decline in fisheries, seafood production is seen as an alternative to maintain the world demand for aquatic products. If current development is maintained over the next 15 years, 32% of the world's total production of marine fish will come from mariculture [1, 4–7, 9].

In Brazil, mariculture has been progressively expanding, mainly since the 1990s due to government programs, which is represented by bivalve mollusks in the South and Southeast regions and by shrimps in the North and Northeast regions [4].

Brazil produced 91,405 t of mariculture products in 2014, of which 71,000 t are shrimp and 20,405 t represented by mollusks. The total value of mariculture production is US\$876.8 million, of which US\$256.8 million is represented by mollusks [3, 4, 8–10].

Thus, mariculture is a deliberate attempt by humans to modify and manipulate nature-controlled food relationships. It can be observed that all productive activities are impacting the environment and that in aquaculture, these impacts can be classified into three sets: those from the environment (exogenous); those resulting from aquaculture (endogenous), and those caused by aquaculture on the environment [8–10].

In addition, it is emphasized that the environmental impacts caused by aquaculture will almost always be more negative than positive.

These impacts arise mainly from the use of resources, such as space, water, raw materials, and food, reduction of biodiversity, as well as from the production of organic and inorganic waste (e.g., excreta production, introduction of microorganisms, pathogens and parasites in the environment, accumulation of residues of cultivated organisms, and release of antibiotics in the effluent of nurseries and crop laboratories) [3–5, 10].

Therefore, it can be observed that the negative impacts can be of two types: direct, for example, by the introduction of exotic genetic material into the environment and indirect, due to loss of habitat and ecological niche.

Any alteration of the physical, chemical, and biological properties of the environment caused by any form of matter or energy resulting from human activities that directly or indirectly affect the health, safety, and well-being of the population shall be considered an environmental impact, which include social and economic activities; biota, aesthetic, and sanitary conditions of the environment and the quality of environmental resources. These changes need to be quantified, since they present relative variations, which can be positive or negative, big, or small [8, 10]. The different aquaculture modalities can generate diverse environmental impacts, depending mainly on the cultivation system (closed, semi-open, and open systems), aquaculture (freshwater or marine), of the species used and especially the density and quantity of production. Due to the many variables that may influence the generation or identification of such impacts, and because it is a relatively recent activity in Brazil, few conclusive studies have been published on the possible environmental impacts caused by aquaculture, especially by mariculture. Nevertheless, in any form of production, the impact on the environment occurs through three processes: the consumption of natural resources, the process of transformation, and the generation of final products (waste) [3].

The main environmental impacts caused by aquaculture (including fish farming and shrimp farming) are conflicts with the use of water bodies, sedimentation and obstruction of water flows, over nutrition and eutrophication, discharge of pond effluents, and pollution by chemical residues used in the different stages of cultivation [2, 5].

Thus, fish, crustacean and mollusk crops generate waste in the form of particles and organic and inorganic soluble material. The nature and quantity of the effluent vary with the type of farm, cultivated species, and level of intensification. In general, feces, excreta, and pseudo-feces are the major sources of inorganic and organic nutrients [5].

The water column is the container for the dissolved material, while the greater proportion of solid waste precipitates into the sediment below the growing area or in the immediate vicinity of the farm. This almost immediate deposition of daily organic matter in the sediment leads to an onset of eutrophication with the decrease of the oxygen rate dissolved in the medium. The level of water contamination of the shrimp farms in the Jaguaripe/Bahia—Brazil can be demonstrated by **Figure 1**, which contains the photo of containers of water samples, which were collected by federal agents of the Ministry of the Environment.

Bacteria, fungi, and protozoa participate in the process of degradation of organic matter, and the release of toxic gases such as sulphur become unavoidable. In this sense, the alteration



Figure 1. Sample containers of contaminated water discharged to ocean [8].

of the marine community caused by the accumulation of organic matter in the sediment has already been studied by several researchers. The ideal of sustainable aquaculture, which is consistent with the economic, social, ecological, spatial, and cultural contexts, is at a final stage in Brazil, where errors are being evaluated and studied so that new management techniques can have a lower effect on the ecosystem balance [3, 8, 10].

This concern about the environmental impact was not taken into account by the Federal Government of Brazil, which, despite the warnings given by CONAMA, decided, through the Ministries of Agriculture, Environment and Development of Industry and Commerce, to create in 1997 a project to encourage fishing and seafood production, through the creation of marine farms, in order to increase the production of seafood, mainly crustaceans and mollusks. In 1998, the state governments began to join the project, and the states of *Bahia*, *Santa Catarina*, *Ceara*, and *Espirito Santo* invested heavily in the project for the installation of farms mainly shrimp, oysters, and scallops. Through fiscal incentives, public funding, and federal funds, there was an incentive to create marine farms in these states, but there was no prior and direct evaluation of the impact of the implementation of aquaculture in these states and in the environment [4, 6–10].

Between 2000 and 2005, records of seafood production were achieved. A total of 75% of this production was for export [4, 10]. But in 2005, a productive decline began, beginning in Santa Catarina, southern Brazil, where an epidemic of shrimp of the white spot started. It is a disease that affects shrimps and is one of the four identified in Brazil that are listed in the OIE in aquatic animals. It is of viral etiology. WSSV—“White Spot Syndrome Virus” is a persistent infection throughout the animal’s life and has a high mortality in shrimp cultures.

Animals that recover from the infection are persistent carriers of the virus. There are no known biological vectors. This virus has a type of flagellum and its genetic material is DNA (being genetically more stable) and is part of the *Nimaviridae* family, decimating several fishing grounds. This disease began to extend along the Brazilian coast, currently reaching the state of *Ceara*, with productive loss of almost 80% of the prawns [4, 5, 9].

Almost concomitant with the appearance of this disease, in the mangroves of *Espirito Santo* and *Bahia*, appear the disease of the lethargic crab (DCL), it was found that the agent that causes DCL is the pathogenic fungus *Exophiala cf psychrofila*, which simply decimated almost 90% of the crabs in these states [3].

By 2015, this disease spread to other states, decimating the mangrove areas and drastically reducing the population of crabs. After several analyses of environmental agencies, it was verified that marine farms, implanted in these states, generate residues that provoke the problem, generating conditions for the proliferation of pathogens in the environment, often resistant to the immune system of the animals, due to the indiscriminate use of antibiotics from nurseries and crop laboratories.

The DNAs of *Exophiala cf psychrofila* and *Nimaviridae* were found in the mangrove in the region of *Jaguaripe*, a fishing town in the State of *Bahia*—Brazil. This organic material was present in a phenomenon known as brown tide and was caused by the discharge of tailings from the fishing farms that had settled in this region (see **Figure 2**).

Thus, from the studies of the discharge effluents from tanks of shrimp farms in the *Jaguaripe*—*Bahia*/Brazil region, promoted by the Ministries of Fisheries and Environment, a map of the destruction and contamination of the region known as the coast of the *Dende* was created that raised the points of impact and associated the degradation of the aquatic environment to the effluents discarded by these farms, which influenced native marine life, causing the degradation and destruction of native species [8].



Figure 2. Shrimp farm: region of *Jaguaripe*—*Bahia*, Brazil [8].

3. Nereu project

The oceans and seas are vital to sustain life and to provide for the various human activities and are the primordial elements for the entire global economy.

In this context, it is verified that the activity of fishing and gathering of seafood stands out due to its importance in the production of food and world economy. But in order to reach the levels of production and productivity demanded today, fishing has destroyed most of the oceans' fishing grounds due to the phenomenon of overfishing.

The oceans have strategic relevance for maintaining the dignity of human life and for the economy, which converges to the challenge of integrated management of seafood production and management. Environmental resources, especially ocean resources, are currently in a vulnerable position of degradation and scarcity. Several authors argue that the main factors of the maritime crisis are the environmental pollution and the unbridled increase of the world population, without the policies on territorial planning and environment to adequately meet the new demands.

The degradation of ocean water quality is a reflection of the current pattern of consumption and lack of care with the oceans. In addition, the Industrial Revolution, in which the concern to increase fish production, without considering the externalities, resulted in the degradation and waste of marine resources. In this crisis scenario, countless losses can be raised, such as loss of ecological balance, loss of biological diversity, climatic imbalance, and profound changes in the water cycle, which affect society and the environment leading to reduced or depleted resources. Thus, today, the world population has established a situation of imbalance between the spatial pattern of availability in the oceans and the spatial pattern of demand for consumption centres' [11–13].

With the emergence of aquaculture, the first attempt was made to reduce the pressure on fishing banks, but the lack of an environmental policy to treat wastewater has increased the degradation of the oceans. To address this degradation caused by the seafood farms that affected several Brazilian states, the Ministry of the Environment analyzed the environmental issue in order to build an environmental awareness. In this sense, with the introduction of new sustainable development concepts, a new cycle began, based on the elaboration and implementation of environmental policies, in the search for negotiation and understanding between preservation of the environment and production processes.

Advances can be verified with the Green Protocol (Federal Law: institutional device of introduction of the environmental variable as a relevant criterion in economic policy decisions and project financing) and other devices of environmental dimension inserted in the decisions of public policies. Specific measures for the rational management of irrigated areas and collection for the use of water are already established by law.

From these premises, the Nereu project was conceived by associating two Chiron and Prometheus projects, which combine three basic conditions for the production of water and energy, with food production based on a clean production system. A conception was used

that interrelated CH₄ reform through a systematic pyrolysis in a cold plasma reactor to obtain H₂ whose thermal cycle was used for water desalination and energy generation combining with the production of totally sterilized rock salt (see **Figure 3**).

With this conception, the Nereu¹ project has the following structure:

- Chiron² project: the purpose of this project is to carry out pyrolysis of CH₄ through a cold plasma reactor for the separation of colloidal carbon and hydrogen, which will feed the Prometheus reactors and produce O₂ using a modular and interchangeable structure [12, 13].
- Prometheus³ project: it provides for the rational and intelligent use of reuse water from aquaculture systems, whether having a high content of dissolved solutes, with the purpose of sterilizing, purifying, and neutralizing pathogens present in process waste water, through a reactor of hydrogen. This process desalinates water by generating the superheated steam which is sent to a set of the stirling system, without affecting the environment and having by-products of the process the generation of clean energy, gem salt, and demineralized and deionized water (water pure; see **Figure 4**) [12, 13].

In view of these premises, the Nereu project seeks to meet the main characteristics of the Apollo Research Group projects, that is, to have a simple automation in their constructive characteristics, guaranteeing their interchangeability and maintenance, as well as their low automation costs. In addition, the Nereu Project units were conceived and developed in modular systems, proto-units, to be placed in reduced and limited physical spaces; from its constructive concept, the Nereu project can expand its productive capacity according to the needs.

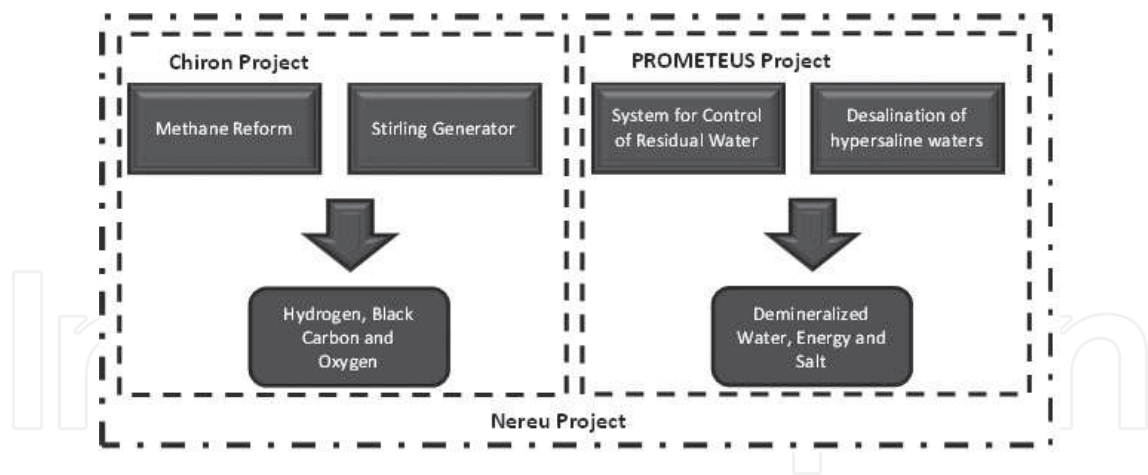


Figure 3. Diagram of the Nereu project.

¹The Nereus project is a tribute to Nereus (Greek: swim), in Greek mythology, is a primitive sea god, depicted as an elderly character - the old man of the sea. He is known for his virtues and his wisdom. Pindar celebrates his fairness, hence his epithets "true," "benevolent," "without lying or oblivion".

²The Chiron project is a tribute to Chiron (Greek: hand), in Greek mythology, was a centaur, considered superior by his own peers. Chiron was intelligent, civilized and kind, and celebrated for his knowledge and skill in medicine; he was professor of Heracles and other demigods.

³The Prometheus project is a tribute to Prometheus (in Greek: foresight), in Greek mythology is a titan; he was a defender of humanity, known for his astute intelligence, responsible for stealing the fire of Hestia and giving the Mortals.

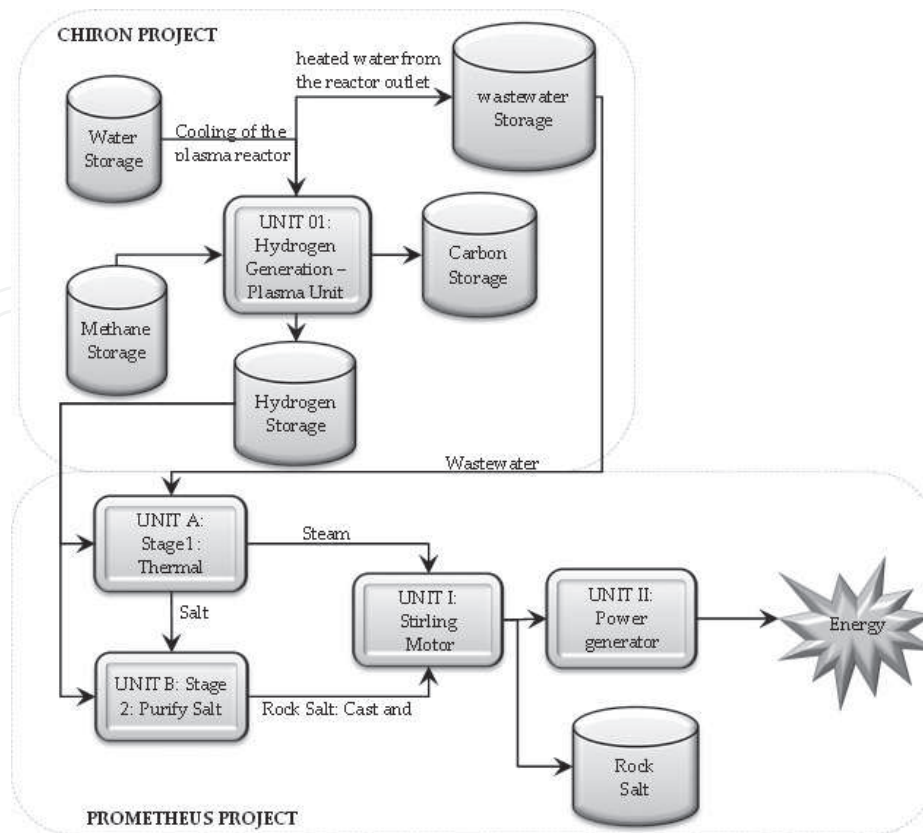


Figure 4. Process flowchart [12, 13].

3.1. Chiron project

The desalination process is a complex process because the salts are strongly bound to the water molecules, which makes conventional water treatment processes inefficient. Therefore, it is necessary to make use of other processes capable of breaking the forces of attraction between molecules [12, 14, 15].

3.1.1. Plasma generation reactor for H_2 —Unit 01

In the specific case of pyrolysis of CH_4 by thermal plasma, the products formed include hydrogen, which can be used as fuel, and colloidal carbon, with many uses in the cement and rubber industry.

Conventional hydrogen and black carbon production processes are based on the incomplete combustion of hydrocarbons, subject to low yields and emission of high levels of pollutants. Due to incomplete combustion in the presence of oxygen, the process is inevitably accompanied by the emission of CO , CO_2 , SO_2 , NO_x , and volatile hydrocarbons. In addition, the maximum reaction temperature achievable is from 1500 to 2000 K [11–15].

The reactor of the Chiron project was designed to produce colloidal carbon and hydrogen, through thermal plasma, although using electric energy and an inert gas in the process have

several advantages in its application that are compensatory, as for example: increased efficiency, reduction of the reaction time, low cost of the equipment, favoring variety of productive size, and making possible its industrial application. The use of a noble gas as a plasma gas avoids the formation of CO_2 in the process and is only necessary to initiate plasma formation and was initially replaced by H_2 , and then by CH_4 , another important factor is that the plasma process enabled the use of different sources of raw material, besides CH_4 gas, butane and propane, but for this project, we chose to use the gases from landfill gas. Thus, the production of hydrogen as an energy source and that of colloidal carbon as an industrial input becomes attractive and compensates the energy and operational expenditure of the system [11–13, 15, 16].

3.1.1.1. *The plasma system*

The Chiron project has a thermal plasma system, which is composed of a plasma arc torch, and a reactor or pyrolysis chamber designed to retain most of the heat flux from the plasma jet. The inert gas argon (Ar) was used as a plasma gas and was introduced in the torch by a controlled flow [12, 13, 15, 16].

The electric arc between the cathode and anode was initiated by a high-voltage discharge and a variable current. The formation of the plasma arc occurs between the cathode and the anode (cooled by water). The gas to be degraded, CH_4 , was introduced into the pyrolysis chamber with controlled flow [12–14, 16].

The torch consisted of a cone-shaped cathode and an anode rivet, channel-shaped. The electric arc established between the electrodes (cathode and anode) was initiated by a high-voltage discharge. The gas is heated, ionized, and emerged from the torch as a plasma jet. CH_4 injected into the reactor was heated and passed then into the liner, by contacting the plasma and suffering degradation [11, 12, 16].

3.1.1.2. *The process*

The values of degradation of CH_4 and the efficiency of H_2 production depend directly on the CH_4 flow; these results do not depend on the argon flow. Important to note that the amount of CH_4 converted is related to the total flow of CH_4 , relating to what has been transformed into solid and gaseous products. For example, when the flow of CH_4 was adjusted to $0.001 \text{ m}^3/\text{min}$, 59.4% of the gas was transformed into solids and the remainder 40.6% by gaseous products (see **Figure 5**) [12–16].

The proportional reduction in the conversion relates to the constant electric power applied to the torch; since the available power is controlled, the CH_4 conversion is also limited and any additional amount of CH_4 remains in the system as a nondegraded fraction. To correct this problem, argon flow was increased in the plasma torch, which caused the increase in plasma jet temperature and consequent increase in system power [11, 12].

The decomposition of CH_4 to produce hydrogen and colloidal carbon is quite promising, if aggregated with other activities that use their products. As the CH_4 conversion function is endothermic, the thermal plasma is very efficient because in these conditions of high temperatures

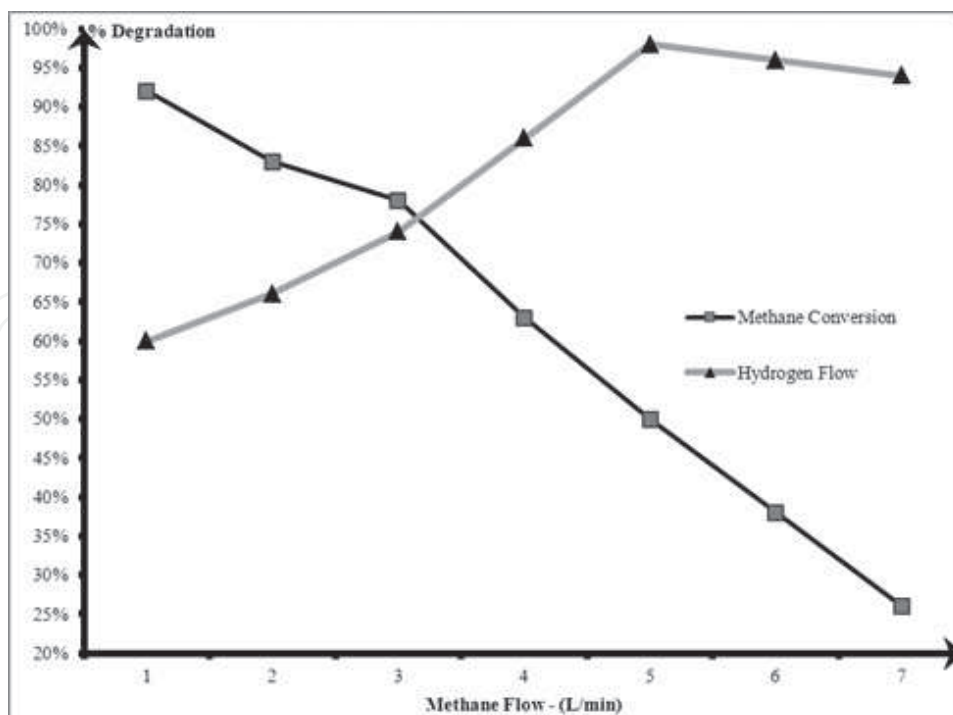


Figure 5. Percentage of degradation of CH_4 (■) and efficiency of H_2 (▲).

and high degree of ionization, chemical reactions are accelerated by the power supply, and moreover, there is no CO_2 emissions or other contaminant gases, once the system is deoxygenated [12, 13, 16].

In the Unit 01 plasma pyrolysis reactor, CH_4 is broken down mainly by the heat from the arc plasma. However, the existence of a collision process between the existing elements in the plasma catalytically assists the decomposition reaction of CH_4 . Different types of crashes happen in a plasma state of this nature; dissociation of CH_4 and other molecules (CH_3 , CH_2 , and CH) may also occur as a result of impacts between the molecules, atoms, ions, electrons, and protons [11–15].

A CH_4 molecule can be dissociated into one or more parts to collide with another particle. Various collision processes may occur inside the plasma reactor, including the recombination of occurring particles forming a molecule [16].

The usage of Unit 01 – reactor pyrolysis – has several advantages such as high energy density existing in the plasma which allows the construction of a compact reactor. Due to the plasma characteristics, a continuous flow is possible, enabling the formation of carbonaceous materials of different qualities and providing no pollution to obtain two commercial products (H_2 and C), both of high purity [12, 13].

A revolutionary constructive architecture for the treatment of methane, the reactor provides a greater CH_4 residence time in the reaction zone and also a longer residence time inside the reactor, enabling minimizing the ionization of CH_4 molecules. This feature is important for a high efficiency in the conversion of CH_4 into H_2 and C. In addition to presenting a favorable flow of the mixture of CH_4 and hydrogen flow, important for the heat exchange between the

flows and good distribution of current lines coupled with good mixing between the flows, it is important to provide a homogenous treatment of particles of carbon [13, 15].

Thus, in the pyrolysis gas plasma, the energy required for reaction is supplied to the elements in the reaction chamber of the reactor by a high-energy electrical discharge. The electrical discharge at atmospheric pressure generates thermal plasma with high temperatures that can completely dissociate CH_4 molecules. The molecular decomposition in the absence of oxygen generates hydrogen and carbon, which do not bother catalysts, for there is the formation of CO and CO_2 [12, 13].

The pyrolysis of CH_4 does not produce CO or CO_2 ; the carbon in CH_4 molecule does not react with the oxygen because it does not exist in the process. What happens in the process is the breaking of the molecules; resulting in isolated black carbon. The process allows a simple purification of hydrogen, since the solid carbon may be extracted by physical separation of the flow [12].

3.1.2. Oxygen unit

Oxygen is the most known and widespread of the gases, being the most abundant element in the earth's crust, about 46.6% by weight. To meet the oxygen needs of the Prometheus project, a little production plant of O_2 was created in this unit, taking advantage of the project's power generation. Thus, the O_2 production system followed a PSA ("Pressure Swing Adsorption") process, which is a classical mechanical O_2 production system [16].

Pressure swing adsorption—PSA allows the viability of obtaining oxygen at various on-site scales and its low operating cost was the main drivers of this process.

In this system, there is an oxygen production plant, which is installed next to the consumer (on site). This technology allows the separation and concentration of oxygen (approximately 95% O_2) by subjecting the ambient air to a zeolite molecular sieve under low pressure (3–6 bar) for a period sufficient to adsorb carbon monoxide, steam, CO_2 , and almost all of the nitrogen present in the air [13].

The process uses two metal vats containing molecular sieve (zeolite) in antiparallel, through six valves, which retains nitrogen from the air at high pressure, which will be released at low pressure, and allows the oxygen to cross the adsorbent bed as final product.

Also, there must exist in the process a filtration and drying step of the compressed air that is admitted in the sieves, protecting the zeolite from contamination so as not to compromise the efficiency of the sieve.

Thus, this is an alternative of lower cost and better energy efficiency, if compared to the cryogenic process, but produces a gas with a lower oxygen percentage, that is, a minimum purity of 92% (see **Figure 6**)

3.1.3. Power generators—using stirling engine

This type of engine operates with a thermodynamic cycle composed of four phases and executed in two-stroke piston: isothermal (= constant temperature) compression, isochronous

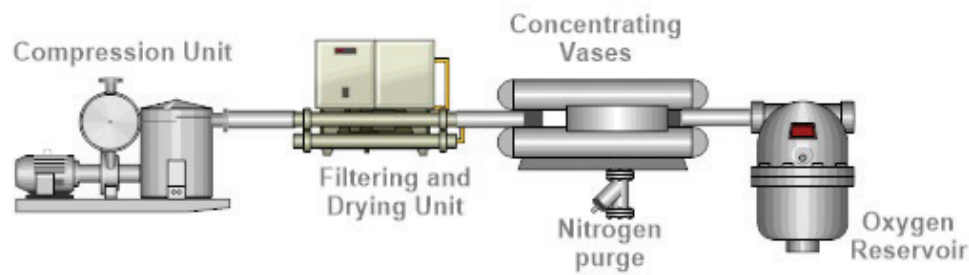


Figure 6. Oxygen unit [13].

heating (= constant volume), isothermal expansion, and isochronous cooling. This is the idealized cycle (valid for perfect gases), which diverges from the actual cycle measured by instruments. Nevertheless, it is very close to the so-called Carnot Cycle, which establishes the maximum theoretical limit of thermal machines performance.

The Stirling engine surprises for its simplicity, because they are of external combustion and are used in the process to generate energy, since they can work with more than one source of heat and thus are projected, receiving heat of the cooling water of the pyrolysis reactor, of the salt leaving the bottom of the salinization unit at a temperature of approximately 1000 K of the steam leaving the desalination unit and even of heating of solar origin (see **Figure 7**).

Because they are very simple machines with easy maintenance, easy operation, quiet operation, and low vibration, these peculiarities made possible their use in a distributed way throughout the entire production chain, reducing the cost of energy and the need for large generation units. The use of the stirling engine for power generation is the best way to reduce costs and increase energy production. Thus, the option to use the stirling engine as driver for power generation units is due to its low cost of manufacturing, the ease of working with small

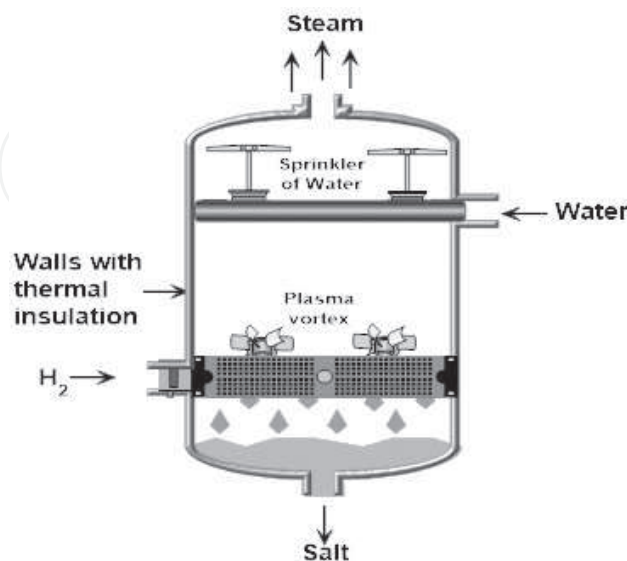


Figure 7. Prometheus unit [12, 13].

generating units, and the distribution of several generating units throughout the production unit. Thus, Stirling engines are used along the production line, using the generated steam and heat of the gem salt, which is extracted by the lower nozzle of the Prometheus unit.

3.2. Prometheus project

The need to obtain drinking water, increasing demand and neglect of much use by the population are the few factors because of which water scarcity begin to emerge in places where hitherto was not a problem. Water, unlike other natural resources, cannot be replaced, must be preserved, and distributed properly to avoid its loss.

Desalination is a technique that has been used for thousands of years in places where we cannot get enough fresh water. It is considered the future alternative to meet the needs of living beings, since 97.2% of the planet's water is salty or brackish. It is currently underutilized due to the high cost of the process, since it requires a lot of energy and sophisticated materials [12, 13].

Since the sixteenth century the desalination of sea water was used in vessels. Land desalination began in the 18th century and began to play an important role in the late 1940s and the early 1950s, especially in countries where potable water is scarce as in the Arab Gulf, USA, Caribbean and some areas of North America.

The composition of the salinized water varies according to the source, although the concentration of salts varies from place to place, the ratio between the most abundant constituents is practically constant. Among these constituents are sodium chloride, bicarbonates, calcium sulphate, and magnesium sulphate [12, 13].

Another alternative to obtain water is to reuse it, by replacing a source of drinking water with another of inferior quality where such substitution is possible, supplying the less restrictive demands made, releasing water of better quality for the noblest uses, such as domestic supplies.

The reuse of water in the urban sector can be accomplished by appropriate treatment of sewage and its reuse for potable purposes (indirect reuse) or non-potable (irrigation, fire reserve, dust control, decorative aquatic systems, etc.). In the industrial sector, the reuse of water is a frequent practice, since it reduces production costs. They are often used in cooling towers, boilers, civil construction, and maintenance of industrial facilities and within industrial processes. The recharge of aquifers is another form of water reuse [12, 13].

The Prometheus project uses a systematic rationalization in the use of water and energy, basing its process on a continuous control of what is generated and what is consumed. Thus, the project provides for the rational and intelligent use of wastewater from industrial processes, whether it has low oxygenation content and a high presence of dissolved salts, in order to desalinate and neutralize dissolved solutes in the water.

In Counterpart, there is to the production of electricity by the use of H_2 and associated thermogeneration cycles, at low cost and with high profitability, constructed in a modular and interchangeable way, without affecting the organizational structure and the environment, and having by-products of the process generation of clean energy, gem salt and demineralized and deionized water [12, 13].

Thus, the reactor receives the salinized water mixed with all the solutes of the production of mariculture, which would become a contaminant very dangerous for the environment, mainly to the mangroves; although the concentration varies according to the source, the productive stage and the type of production and the relationship between the most abundant constituents is practically constant. Among these constituents are chlorides, sulphates, iodides, bacteria, fungi, protozoans among others.

The reactor configuration used in plant is the type of rotor under pressure with an arrangement in which the saline solution is introduced into the chamber through a spray system; the spraying occurs on a vortex hydrogen plasma vaporizing it. One container captures the salts deposited in the bottom in the form of rock salt. The superheated steam is sent to Unit 03 in order to generate energy (see **Figure 7**) [12, 13].

4. The results analysis

The production of energy, water, and food in sufficient quantity and at competitive prices is important for economic development. At present, there is great concern about the environmental aspects of production in these segments, with emphasis on the use of renewable sources that do not degrade the environment and guarantee the productive continuity for future generations.

Therefore, it is no secret that fishery supplies are being affected by predatory fishing and discharges of chemical and organic waste. The disorderly growth of the world's population, coupled with the intensified demands of protein needs, has been draining the oceans. But, the solution found by mankind through aquaculture apparently solved the question of productive continuity and protein reserves. What is the problem with this activity? The vast majority of the water available for swimming pools is not suitable for return to the oceans and also is not suitable for the demands of aquaculture. These tailings are dumped in the oceans and can create areas of marine desertification in dump areas, which would lead to famine in many communities.

Over the years, the conviction that infrastructure in the world should be based on a mix of productive sources and self-sustainable systems, composing production triad—sustainability—environment. In the same way, it offers great opportunities for expansion of new business initiatives and integrated production projects; they are relatively new and suffer the discrimination of the need for productive specialization to guarantee the maximum profit of the capital employed.

As the production of energy, food, and water treatment are important elements for the economic development of societies and the maintenance of the quality of life and health of families; in recent years, emphasis has been placed on the relationship between production and the environmental issue, considering possible reductions in the availability of nonrenewable natural resources.

Thus, in order to evaluate these investments, there are indicators of analysis capable of assisting in the perception of the behavior between risk and return, the Nereu Project would have a

distinct characteristic for all desalination projects. To carry out this technical-economic evaluation, it is necessary to make a hybrid analysis, taking into account four basic characteristics of this project, which are as follows:

- **Technique:** development of new technologies; reducing the emission of greenhouse gases into the atmosphere; producing water and energy for regions lacking these resources.
- **Economic:** the low cost of implementation, the low maintenance cost, and diversification of income and production.
- **Environmental:** carbon sequestration, eliminating greenhouse gases, and producing water and energy without generating contaminant residues.

It is worth noting that the Nereu project aimed to reduce the risks of contamination in the oceans caused by aquaculture tailings, supported by a demand from CONAMA, which provided for the eradication of pathogenic releases to coastal areas.

The project, in an experimental phase, was built in a proto-unit system in the region of the *Dende Coast*, in the city of *Jaguaripe–Bahia*, Brazil, operating for 8 months, in laboratory scale, with the support of *Funil Farm*, which invested in materials and assembly, with the purpose of neutralizing the pathogenic elements of the pool 03AD, with volume of 3.5 m³, purge tank used to deposit filtration wastes from other pools. Thus, the Nereu project operated to make the cleaning residual water from the existing filtration system.

4.1. Techniques resulting

The Nereu project used its two reactors and seven generators with stirling engine to treat waste water from *Funil Farm*, generating energy and producing food. To perform this procedure, the Chiron Project was miniaturized to work with limited flow rates to meet the needs of the Prometheus project. Thus, the project was conceived as a pilot plant with the following technical characteristics: total flow: 100 l/h; CH₄ flow rate: 400 l/h; and average concentration of salts: 35 g/l.

It was verified that the Nereu project consumes a total of 25.4 kWh of energy to meet the energetic demands of desalination and decontamination of the waste water, and the reactor consumption, in maximum efficiency, for CH₄ pyrolysis, is 7.2 kWh, with advantages over other techniques, as the process does not release CO₂.

The percentage of degradation of CH₄ reaches the maximum value of 98.8% for an applied power of 7.2 kWh. In order to cope with the energy needs of the system, seven stirling engines of the Alpha type have been adapted which have been developed for other purposes and reused for the project. Thus, it was possible to adapt them for power generation, producing a total of 40 kWh of energy, which has its stepped drive, being connected as the energy needs are presented. The Nereu project consumed 54.4% of the energy produced, and 45.6% was made available to the electricity grid of the farm.

The C produced by the degradation of CH₄ in thermal plasma has hydrophobic characteristics, is amorphous and of high purity, presenting added value and can be commercialized, for companies producing carbon fiber and carbon nanotubes.

In spite of the Nereu project, a miniaturized version of the Chiron project and the equipment of the Prometheus project were coupled to its structure, and the average project yield was 79.6%.

The average yield in the project stems from the main constraint adopted in the operationalization and implementation of the Nereu project. In other words, due to budget constraints, it was only possible to use recycled materials, scrap, and/or products recovered from old irons.

Thus, the great problem generated by the filtration of the shrimp production ponds and dumped in the pool 03AD, without having a real destination for this residue, was solved with the Nereu project, which desalinized and sterilized this residue, producing pure water and gem salt, totally free of any pathogenic element. At this point, the Nereu project stands out in relation to the other desalination processes, because while the other systems consume energy, the Nereu project produces its own energy to maintain the system and to be commercialized in the energy market.

4.2. Economic resulting

When analyzing the feasibility of desalination projects, one should not only consider the question of return on investment, but also the impact on the entire productive and social context, especially for locations lacking these resources. It is therefore of utmost importance not to dwell on a simplistic reading of numbers and results. The Nereu project was a predetermined research funded by an investor with limited resources, with a limited value of US\$35,000.00 to prove that it was technically and economically viable.

With the architecture of the project working with the thermal cycle of the H_2 , the nonexistence of the generation of residues, nor greenhouse gas emanations, in the operation of the system was verified. Thus, the combination of the processes added to a system of financial control would enable the recovery of the investment in a period of 10 months. This was made possible by the generation of several marketable by-products that have added value.

Throughout the Nereu project's operating time, it was possible to operate at low production costs and it was observed that, based on the standards of taxes and input costs in Brazil, the project has a low maintenance cost, despite being fully developed with scrap. In this way, the average cost of the plant is low per hour of operation. The cost of each product, including taxes and operating costs, can be deployed as follows: pure water: US\$0.12 per 1 l/h; electric power: US\$0.037 kWh; Carbon: US\$1.46 per 1 kg/h; hydrogen: US\$1.46 per 1 kg/h; and rock salts: US\$ 0.028 per 1 kg/h.

With the diversity of by-products generated, the Nereu project had a multiplicity of revenues that allowed the recovery of investments within 6 months, and an investment profit of around 10.6%, despite being a basic small plant, built from scraps. These results reflect the reality of the Brazilian market, incidental taxes and charges, labor costs, and employed automation. These values will change according to the economic, fiscal, and equipment conditions present in each country.

4.3. Environmental results

The development of projects based on environmental preservation attitudes is part of the goal plan of any research project prepared by GPAP. The goal proposed in any project of the research group is in the search for the development of actions with emphasis on sustainable development projects, the insertion of needy communities, in generation of new projects, always focused on the protection of the environment.

Contained in the thinking of sustainability is the possibility of change in the relationship between the individual and the environment. From the normative point of view, it is the necessary adoption of attitudes more coherent with the demands of environmental conservation. Thus, the development of an education strategy that allows better relations with the environment is undoubtedly one of the most strategic and effective actions to achieve the objectives proposed by the notion of sustainability.

With these bases, the Nereu project was built with a sustainable development procedure, so as not to generate any residue and to use only what one cannot take advantage of. Using natural resources such as hypersaline waters, greenhouse gases and scrap, sequestering C and generating pure water. The main characterization of sustainable development is the assurance of environmental concern. As, the plasma reactor did not generate CO_2 , decomposed CH_4 , with C sequestration, which can be sold or used in the production of shrimp.

The salt produced by the Nereu project was sent for testing at the university. It was verified that there were no pathogens present in the product. This had a very relevant chemical balance of chlorides, iodides, sulphides, and carbonates in the mixture, similar to the rock salt that is produced in mines in Europe and Asia. As the salt produced was processed from wastewater treatments, despite being completely free of pathogens and contaminants, under Brazilian laws, the rock salt could only be sold for animal feed.

Thus, serious environmental problems from desalination plants, such as high energy consumption, greenhouse gases, and waste generation were solved in the Nereu Project, which processed and neutralized greenhouse gases, generated its own energy for desalination, and treated the waste from the desalination process.

5. Final considerations

The Nereu project combined two different guideline projects, combining a plasma reactor for H_2 generation, a steam desalination unit and a turbo-generator of electrical energy in a totally clean system. This was created to work with desalination residues. In this way, a system of treatment of contaminated hypersaline waters of any origin has been developed. To achieve these goals, the Nereu project has adopted a sustainable development rule and, consequently, the nonproduction of waste that damages the environment.

The Nereu project, when it unified the two projects, created a totally high sustainable and closed process, ensuring that the most critical points in Prometheus, which is continuity of energy supply and combustion for thermal energy generation, were fully met by Chiron.

It should be noted that the project's application potential is directly associated with its uniqueness, simplicity, portability, modularity, and constructive speed, so the Nereu project is fully applicable to work in consortium with other desalination systems, producing energy to sustain them and treat the waste from the filtration without the environment being attacked, as it works as an alternative to take advantage of the wastewater potential without the need for large engineering projects and civil works for its implementation. In addition, the generation of energy is justified by the thermal availability of the process, compared to the conventional production of separate thermal and electromechanical energy, which, from this point of view, has led to the search for the most appropriate technology in order to provide the highest possible energy efficiency, therefore the option to use stirling engines to power the generators, due to its low cost of production and ease of maintenance.

In the process, it was possible to determine that the most relevant costs in the project come from four basic factors: energy, pure water, natural gas, and oxygen, which have a much greater influence than other costs. In this way, the Nereu project prioritized to minimize costs in three of the four items, which were energy, oxygen and water, directly impacting the final cost of the project.

As the Nereu project produces pure water, this productive cost is minimized by using the water that is provided by the Chiron subproject. With this advantage in mind, stirling engines are used for energy production, since they can be introduced at any stage of the production system in order to generate energy with any existing thermal potential, minimizing costs, and dependence on external energy to the project, stirling engines have low production and maintenance costs.

Nomenclature

ANA	National Water Agency
BR	Brazil
HDI	Human Development Index
MMA	Ministry of the Environment
Ar	Argon
CO	Carbon monoxide
CH ₄	Methane
H ₂	Hydrogen
NG	Natural gas
O ₂	Oxygen
CONAMA	National Council for the Environment
MPA	Ministry of Fisheries and Aquaculture
IBGE	Brazilian Institute of Geography and Statistics

GPAp	Apollo Research Group
C	Carbon black
CO ₂	Carbon dioxide
CH ₃ , CH ₂ , CH	Methane decomposition chains
HC's	Hydrocarbons
NO _x	Nitrous oxide
SO ₂	Sulfur dioxide

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