

SOLAR SALTWORKS – CONSTRUCTED ECOSYSTEMS

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ABSTRACT

Man produces sea salt by solar evaporation since the dawn of human civilization. Initially, humans must have found salt where it can be still found, that is, in concave rocks or in lagoons of coastal areas, where seawater gets trapped and as it evaporates in the sun, deposits salt.

The evolution of solar sea salt production process that followed must have gone through some distinct stages, before getting its current configuration. These specific stages have been indentified and analyzed. It is demonstrated that the evolution and the optimization of the solar sea salt production process, eventually led to the creation of a unique and of particular importance ecosystem; the current Solar Saltworks.

The environmental uniqueness of current Solar Sea Saltworks is based on the fact that they consist of a series of **steady state** ponds, covering the whole range of regular to hyper saline environments, where organisms of all three domains of life, Eukaryotes, Bacteria and Archaea are present. It is widely recognized that if Solar Salterns are destroyed we will lose a significant source of microbial biodiversity [27]. Furthermore, Solar Saltworks establish high significant shelters for wildlife [8,23], where hundreds of protected bird species depend on them to feed and/or nest.

Current Solar Sea Saltworks are compared with Coastal Saline Wetlands in terms of their physical and biological processes, highlighting their advantages.

It is noteworthy that globally, in contrast with the aforementioned, the environmental appraisal of current Solar Saltworks is unjustifiably inconsistent thus many investments and/or optimization works encounter problems without distinct reasons. This study aims to substantiate and highlight the reasons upon which the Solar Saltworks globally, must be identified as constructed wetlands, similar to natural saline wetlands and should be included in the list of protected ecosystems where hunting is prohibited and human intervention helps the wild life.

KEYWORDS: solar saltworks, wetlands, ecosystems, sea salt, solar salt, production process, biological process, Salinas.

INTRODUCTION

Salt, the common name for the compound of sodium (Na^+) and chloride (Cl^-), is the first substance after water that has attracted humans' attention in their evolution from wilderness to civilisation.

Salt along with water, cereals (bread) and meat of domestic animals, constituted the main commodities of human society in its infancy [1]. Originally, salt was used to meet the human nutritional needs. However, when its significant food preserving

property was discovered, salt became one of the most important commodities for centuries, comparable to the importance of oil in our times.

Humans must have initially found salt, where it can be still found, that is in coastal rock concavities or lagoons, where seawater gets trapped and deposits salt by solar evaporation. At a certain time, humans' needs must exceeded nature's production rates. Therefore, it can be reasonably deduced that, after a long period of observation and knowledge building, humans eventually **copied nature** and began producing salt, in quantities meeting their increasing social needs.

Producing salt in single basins such as coastal rock concavities or lagoons, by solar evaporation of seawater, constitutes the first method ever used by man to produce solar sea salt. We define this method as the **first step (STAGE I)** of the Solar Sea Salt production process evolution. The optimization of this process in terms of quantity and quality of the produced salt, eventually led to the creation of an integrated coastal saline ecosystem!

SOLAR SEA SALT PRODUCTION PROCESS EVOLUTION

Production of salt from seawater involves the selective recovery of pure NaCl, free of other soluble or non-soluble salts and other substances. To this end, condensation of seawater through solar evaporation results in the fractional crystallization of all contained salts; a process based on their varying solubility in seawater.

We identify three main steps (Figure 1), which man should have made in his effort to optimize the solar sea salt production process. Solar evaporation of seawater in single basins such as coastal rock concavities or lagoons is the previously defined first step of that process (Figure 1, **STAGE I**). This method has certain disadvantages since it is a batch process with limited production rates and additionally all salts contained in seawater precipitate in the same spot.

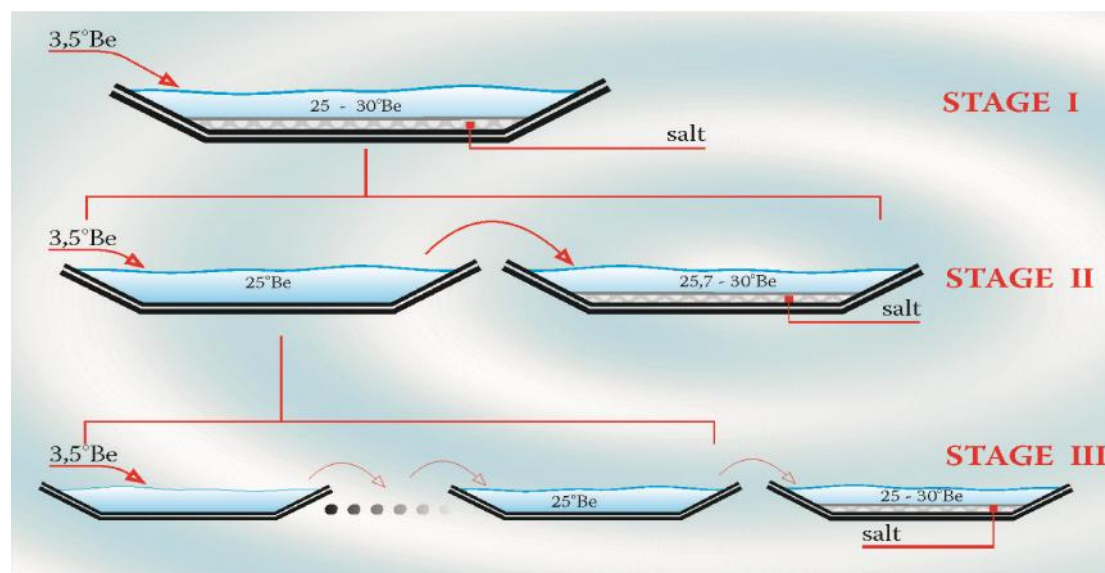


Figure 4. Solar Saltworks' Production Process Evolution

To overcome these limitations, man should have split the single basin into two successive and interconnected evaporation ponds (Figure 1, **STAGE II**). In this production scheme, the first pond is used to produce saturated (with respect to NaCl) brine that feeds the second pond, where now relatively pure NaCl precipitates. The

first pond is usually called “feeding pond” and the second “crystalliser”. Thus, it was made possible to:

- Unbound the salt production rate and achieve continuous salt crystallisation.
- Produce relatively pure NaCl since all unwanted seawater salts, with lower solubility than NaCl (i.e. CaCO_3 and CaSO_4), will now crystallise in the first pond.

The third and most decisive step was taken by the further division of the feeding pond into several ponds that are usually connected in series (Figure 1, **STAGE III**). According to this production scheme, the seawater enters the first pond and as it flows through the pond system its density gradually increases by solar evaporation. Key objective of the method is to maintain steady state conditions in every pond i.e. constant brine density and depth, allowing only small daily variations as each pond feeds the next that follows.

The brine density in the last pond in the series must have reached saturation value with respect to NaCl, since it is the pond that feeds the crystallizers. Thus, the Stage III production scheme:

- Enables optimal control of brine density and volume over the system of Evaporation and Crystallization Ponds
- Decreases the average brine density over the Evaporation Ponds system

Thus, according to Stage III scheme, prerequisite for salt production is the design of a **nonproductive** system of interconnecting Evaporation Ponds. That system while is used exclusively to feed properly the Crystallization Ponds with saturated brine, it covers almost 90% of the production area. That is a necessity since condensation of seawater up to saturation density ($\sim 25.7^\circ\text{Be}$), requires evaporation of almost 90% of its water content.

That is a key design constraint which actually **transforms the Stage III production scheme, in other words the Current Solar Saltworks into an integrated ecosystem!**

Furthermore, moving from Stage I to Stage III we introduce an inherent change, very decisive for the final process. In the single pond case (stage I) the salinity gradient changes with respect to time, whereas in the multiple pond case (stage III) it changes with respect to the area, where in fact every pond and crystallizer functions in steady state conditions. In other words, ***we started with a batch and transient process (stage I) and we ended up with a continuous and steady state process (stage III), where all phases of the initial process are alive*** since every pond of stage III is a live phase (a picture) of stage I. It can be easily deduced that the **multiple pond process establish a more integrated and manageable ecosystem than the single pond.**

These three stages constitute the basic steps towards improving the quality of solar sea salt making technology. Unfortunately, there are no data or information available confirming the time when the aforementioned production methods were first used, although it is certain that it has not been a uniform process throughout the world. It is impressive that that all stages in the evolution of salt making technology we have described are still alive today. The Saltworks on the island of Kythera, for instance in Greece, still produce salt in concave rocks by the sea.

CURRENT SOLAR SALTWORKS

Physical Process

Current Solar Saltworks recover salt (NaCl) from seawater using the previously described Stage III production scheme. Their annual capacity varies from some hundred to some million tonnes of salt, depending on the area used. The only differences that have occurred, since the method was first applied, concern its continuous optimisation as well as the means by which brine is transferred and salt is collected, resulting from subsequent technological progress.



According to the STAGE III production scheme, the available area for salt production is divided into a number of connected in series mainly, ponds which are distinguished in two main groups. The first group usually called **Evaporation Ponds (EPs)**, is used to condense seawater up to saturated (wr to NaCl) density and the second group usually called **Crystallization Ponds (CPs)** or **Crystallizers** or **Pans** is used to optimally produce Solar Sea Salt.

The seawater is fed into the first EP by pumping and/or tidal action and as it flows into the system of successive EPs, under controlled conditions, its density gradually increases through solar evaporation. Finally the last Evaporation Pond, usually called **Feeding Pond (FP)**, feeds with saturated brine the CPs where solar evaporation causes salt crystallization. The driving force for brine evaporation is the incident solar radiation and its rate depends on the prevailing microclimate of the region, particularly wind action, air temperature and air moisture.

Hence, a salinity (brine density) vector is created throughout the Saltworks production area (EPs & CPs), with a simultaneous brine volume reduction, which eventually leads to NaCl crystallization/production. The salinity range in Solar Saltworks Ponds covers the whole spectrum of brine densities, starting from that of seawater (3.5–4.0°Be) and rising up to 28.0–29.0°Be. This constitutes the **physicochemical (or physical) process** of Solar Saltworks.

Thus, the **non-productive** system of interconnecting **EPs** has the following main task and characteristics:

- They are a system of shallow ponds that are used exclusively for the continuous feeding of CPs with the appropriate amount of saturated brine
- They are bounded with dikes built out of clay to ensure very low brine permeability whereas their clay floor remains entirely natural, without any tampering or restructure
- They operate in steady state conditions and covering the whole spectrum of brine densities
- They take ~90% of the Saltworks production area
- They are totally free of pesticides or other chemical compounds used in farming

All the above are the structural elements of an **integrated saline coastal ecosystem (wetland); the Current Solar Saltworks**.

Finally the **CPs** take up only the remaining 10% of the production area. They are designed ponds, whose clay floor is levelled and condensed, aiming to facilitate and optimise the operation of salt harvesting equipment.

Biological Process

Surprisingly enough, despite rising salinity, life in all ponds of Saltworks does not stop. The known marine organisms (fish etc.) gradually disappear as they move from the initial ponds to the hostile environment of the others that follow. However, other organisms develop in their place and since there are no competitors, they proliferate as they are able to survive in areas with different salinities (that is, in different ponds) [9,14,18,26]. Microbes are not only able to withstand salt stress but they also serve several functions in the saline and hypersaline environment of ponds. [10,27,30]

Thus, in parallel with the physical process, an extremely important microbial community develops in the EPs and CPs of all Solar Saltworks, composed in planktonic and benthic communities and covering all three domains of life, Eukaryotes, Bacteria and Archaea! This chain of organisms constitutes the **biological process** of Solar Saltworks.

In the flow from low to intermediate and high salinity ponds the composition of planktonic and benthic communities gradually changes from low levels of diverse groups of species (kinds) in low salinity to high concentrations of few important kinds in high salinity [18-22]. Each pond community consists of producer organisms, i.e. algae, cyanobacteria, and certain bacteria, that manufacture organic substances via photosynthesis powering the entire biological system and consumer organisms i.e. Artemia, brine flies, bacteria, ciliates, crustaceans, mollusks, nematodes which use organic substances to power their physical activities, growth and reproduction. The presence of Artemia is of key importance for salt production since it controls the microbial synthesis in crystallizers, which in turn affects the salt crystallization process.

The 'unusual' microorganisms of Archaea domain that grow in extreme environments are dominant in the crystallizers. Characteristic example is the Halobacterium species that colours light pink the brines in crystallizers. The hypersaline systems such as salt lakes and solar saltworks are reservoirs of significant bacterial communities whose potential has barely been examined. [27] There are several questions that have not been answered yet regarding the bacteria in hypersaline environments. Who is there, how stable and diverse is that community, what role(s) are the bacteria playing in the environment, how many organisms are present and do any of these bacteria have a useful function for man? [26,27]

We can assert that we don't know how many microbes, ecologically and evolutionary important, exist in Salinas but we do know that if Solar Saltworks are destroyed we will lose a significant source of microbial biodiversity. [27]

Optimal salt production

As the two processes, the physical and the biological, develop and interact with each other, they are both responsible for the brine microbial composition in CPs; in other words they are both responsible for the quality and the quantity of the Solar Saltworks product since microbes affect the formation process of salt crystals. However the mechanism through which microbes cause the formation of salt crystals with good or bad quality is not known. Generally a comprehensive explanation of the biological physical and chemical mechanisms that determine the salt crystal formation process has not been developed yet. [40] Nevertheless it is known from practice that if the microalgae Dunaliella Salina dominates in CPs then the salt crystal quality deteriorates. In contrast, when the predominant organism is the

Archaean, *Halobacterium*, the produced salt is of high quality with large, solid and transparent crystals.

It is therefore obvious that management of the physical process alone is not sufficient for optimal salt production. Production of solar salt with optimal quality and quantity, involves proper control of both, the physical and the biological processes. [21] However, this cannot be realized without the proper design of Solar Saltworks. Thus the prerequisites for optimal solar salt production are the following:

- Optimal design of the production area and the equipment for salt harvesting & washing
- Optimal control of the physical process
- Optimal control of the biological process and finally
- The intake seawater must be free of pollutants

The **optimal design** of Solar Saltworks is the basis for its performance. Its main objective is to determine the number and size of the required Evaporation Ponds and Crystallizers in order to maintain steady state conditions in the entire system of EPs and CPs. That enables the development of a healthy biological chain of microorganisms and the production of optimum quality salt, in maximum quantity. Indispensable tool for Solar Saltworks optimal design is the development of the suitable **mathematical model** (mass and energy balance) that simulates the evaporation rate of brine in shallow lakes. [5,6,7]

A healthy biological process develops in admirable harmony with the physical process:

- Creates and maintains the appropriate conditions in the Evaporation Ponds and the Crystallizers, that maximises the amount and optimises the quality of produced salt which is characterised by clear, compact and mainly thick granules [10,19,21]
- Benthic communities functioning to control leakage and trap nutrients remain firmly attached to floors, and maintain desired thicknesses and species composition and concentration in each pond. Thus minimising brine losses, particularly at low concentrations. [27,20]
- Also the microorganisms of benthic communities compete for nutrients, aid control of gypsum accumulation (Geisler, 1981) and help prevent dominance of undesirable mucilage producers
- The archaean **Halobacterium**, colours light pink the brine in CPs. That maximizes the brine evaporation rate and the amount of produced salt by eliminating the reflection of solar radiation caused by the white salt bed [11].

Alterations of the healthy biological process in the Saltworks Ponds usually derive from poor Saltworks design and/or negligent operation. Excessive amount of pollutants carried by the intake seawater could also lead to the same outcome [10]. Disturbed biological process results in:

- reduction of the available area of EPs (downgrade solar saltworks) by producing excessive amount of organics
- higher brine viscosity values in the CPs that deteriorates the quality and quantity of produced salt
- in extreme cases, the production of non-manageable and therefore non-marketable product

The aforementioned analysis leads us to a **paradox**, according to current industry; current Saltworks constitute healthier and more stable ecosystems compared to traditional ones whose design is generally non optimal and their operation poor.

Solar Sea Salt is the only product whose manufacturing is fully compatible with global environment! If this was the case with all industries, we would have no environmental problems on earth!

Solar Saltworks avifauna

The ecological importance of Solar Saltworks is also connected to their ornithological interest as shelters to avifauna. Basic organisms of the biological process described above, constitute excellent food for a large number of birds living in the Saltworks for this matter. Certain species of birds, especially the Avocet, the Black-necked Grebe, the Kentish Plover etc., depend directly on the productivity of the Saltworks, since their diet is exclusively based on *Artemia salina*. *Artemia* is also part of the diet of the beautiful flamingos and it is the main reason for the orange colour of their feathers.

More than 100 species of birds (average) have been observed in each of the Company's Solar Saltworks (188 in Kitros Saltworks, 1990). Many of them have been identified as endangered species, or are protected by Greek, European Union or international conventions.

Following the redesign and modernization of Kalloni Saltworks (Lesvos Island), there was a remarkable increase in bird species and population that has led in the development of a strong wave of ecotourism (bird watching) in the area, especially during the months of March, April and May every year. Furthermore flamingos start building nests for three consecutive years, where they lay eggs, but eventually the effort proved unsuccessful. That was the second breeding attempt of flamingos in Greece following that of Kitros Saltworks (Northern Greece) a few years earlier.

COASTAL WETLANDS

Coastal wetlands are more or less shallow lakes where the seawater undergoes higher evaporation rates than open seas. They are single pond transient processes that can be categorized into the following two main cases:

- Wetlands where the seawater under some special hydro-geological conditions is trapped and though solar evaporation finally produces salt and
- Wetlands where the sea water enters and renews more or less freely.

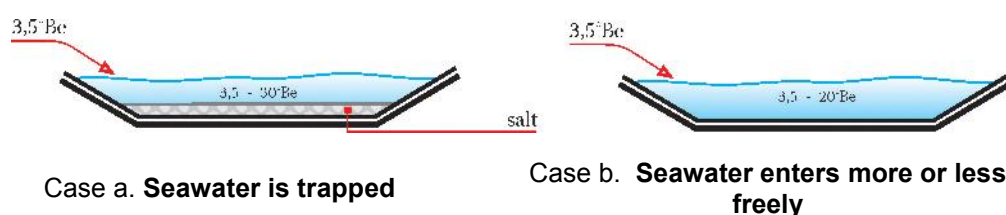


Figure 3. Coastal Wetlands operating scheme

In Case a wetlands the seawater condenses gradually till salt is crystallised on their floor whereas in Case b wetlands the brine density is getting higher than seawater but never reaches saturation value (wr to NaCl).

It is evident therefore that in accordance with the scheme of Solar Saltworks production process evolution (Figure 1), coastal wetlands are categorized as Stage I processes (the single pond case) and since Solar Saltworks are Stage III processes, apply all findings reached earlier regarding the differences between the two stages. That is, **wetlands are single pond, transient processes whereas Solar Saltworks are multi-pond steady state processes. Every phase in time of natural wetlands**

is alive in Solar Saltworks since every Evaporation Pond is a picture (live phase) of wetlands!

That is the **key difference** between the current Solar Saltworks as constructed ecosystems and natural wetlands. It can be easily deduced that Solar Saltworks is the epitome of all kind of saline coastal and inland wetlands.

Table 3. Comparison of Solar Saltworks & Natural Wetlands

SOLAR SALTWORKS vs Natural WETLANDS	
Multi pond, steady state processes.	Single pond, transient processes.
Salinity covers the whole spectrum from that of seawater up to 28°Be.	Salinity may or may not reach brine saturation density.
Constructed dikes offer more nesting area and more shallow waters for small birds.	There are no dikes.
Salt is produced in a small (10%) fraction of the production area.	Salt is produced in the whole lake area.
They are totally free of pesticides.	Inflow rainwater may carry pesticides.

Case a, wetlands usually undergo a dry period during which they don't function as wetlands and people can walk in and collect the produced salt. Similarly seasonal Solar Saltworks undergo a non-productive (rainy) period. However, even in the seized period, Solar Saltworks can never dry out if care has been taken to feed every EP with the proper amount of brine and retain the ecosystem in function.

Table 1, summarizes the differences between Solar Saltworks and wetlands and identifies the ecological importance of the former as well as their environmental uniqueness as constructed ecosystems.

In contrast with the aforementioned, the environmental appraisal of current Solar Saltworks is unjustifiably inconsistent since many investments and/or optimization works encounter problems without distinct reasons [28,25].

Purpose of this work is to:

- Contribute to the global recognition of Sea Solar Saltworks as integrated, constructed ecosystems.
- Facilitate globally new investments in Solar Saltworks

Solar Saltworks should be included in the list of protected ecosystems where hunting is prohibited and human intervention helps the wild life. Especially in our times where globally, wetland area is continually decreasing due to drainage, cultivation and urbanization, new investments in Solar Saltworks will help to reverse that trend contributing positively to the planet climate change.

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