Emergy Analysis of the Salt Production Process at the Sečovlje Saltpans, Slovenia

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ABSTRACT

We evaluated a salt production process driven by solar energy by means of the emergy analysis method.

The salt production process in the Sečovlje saltpans represents one of the last examples of a vanishing traditional method in Europe. Sečovlje saltpans were operating until approximately 1960 on an area of about 700 ha. The investigated area belongs to the Sečovlje Museum of Salt Making, which is part of a natural preserve.

Seawater flows through a series of shallow basins and becomes more and more concentrated due to solar driven evaporation. Salt is manually collected and carried away approximately every other day during favorable weather conditions. It is white and clear due to the special algal mat on the bottom of the crystallization basins. As a consequence, no further purification is needed. These process characteristics enable the salt to have a more pleasing, less bitter taste compared to industrially produced salt or to salt that is harvested only once a year. Energy for the evaporation comes from sun radiation and wind, whereas labor, gravity and wind serve for brine decantation and pumping.

A two-week period of salt-producing process was monitored, accounting for all inputs and outputs of energy, matter and labor. Influences of environmental conditions on the evaporation rate were also investigated. Calculations of emergy transformation ratios (solar transformities and specific emergies) were done and sustainability indicators were calculated. A brief comparison to industrial processes, which use fossil fuels for water evaporation, was also performed.

INTRODUCTION

Exponential rise of knowledge causes deep changes in technology as well as extensive changes in landscape. Values and worths are changing, old methodologies and knowledge are gradually dismissed and forgotten. Resource use changes as well, affecting the overall sustainability of a process, a sector, or a landscape. We investigate here the resource use for salt production by means of both a fully natural technology driven by solar energy and industrial technologies based on fossil fuels.

Salt or halite (NaCl) is an abundant resource on the planet and it is currently produced by means of thermal desalination or by rocksalt mining. Past ways of producing salt were quite different. We analyze the solar-driven evaporation process for salt production as it was done in our country for centuries, before modern alternative techniques based on fossil fuels were introduced. Emergy analysis is used for this investigation. Since the process relies significantly on labor and primary environmental sources like sun, wind and seawater, which are generally neglected in conventional energy and matter assessments, the emergy analysis method seems to be most suitable for the investigated case study, in
order to highlight the most relevant aspects of solar-driven compared to fossil-fuel-powered production.

**CASE STUDY: SEČOVLJE SALTPANS**

**Description of the Area**

Slovenia is a country characterized by very high biodiversity, among the highest in Europe. One of its most important and interesting regions from an ecological point of view is the Sečovlje saltpans area, located in the southwestern part of the state, near the Croatian border. It is protected as a cultural, ethnological and regional park according to the Ramsar Convention.

The Sečovlje saltpans were first mentioned in the middle of 13th century. They were established on a flat salty marsh. The marly and clayey grounding assures impermeability even for highly concentrated brine (Pahor and Poberaj, 1963).

Due to the importance of salt, the saltpans had a significant role in the social, economic and cultural life of the coast. At the beginning of the 19th century there were over 4000 independent salt producing units and 440 houses. The saltpans’ operation ended in the 60’s, when transport of the salt from Africa proved to be cheaper (Žagar, 1991).

The northern part, named Lera, is still operating in a traditional, only slightly modified way. Modifications include much larger basins, and use of motor pumps instead of wind-pumps. Other areas are mostly abandoned and they are an important waterfowl reservoir. The only exception is a small, approximately 15-year-old museum in the southern part of the region (Žagar, 1991). Its personnel try to maintain the memory of the old, wholly traditional process of salt production. They allowed our research to take place during the peak season 2003.

In the northern part of the Adriatic Sea rainfall is more abundant than would be ideal for the solar salt production (on average 1050 mm per year, 97 mm per month during summer). During the past centuries a method was developed, in order to allow sufficient production despite this climate. Daily collection of salt, reservoirs for storage of highly concentrated brine during rain, shallow brine and regular adjustment of its depth and salinity were the most important adaptations. The average production of salt was 4,5-6 kg/m² per year (Žagar, 1991).

**Salt Production Process**

According to Pahor and Poberaj (1963), Žagar (1991), personal interaction with salt-workers and personal experience in the field we obtained an overview of the saltpans operation. A complex system of inflowing and outflowing channels, dams, and manually regulated wooden gates brings seawater to all parts of saltpans. Most saltpans are slightly under the seawater level and saltwater can flow into the basins due to gravity when needed. The first four subsequent basins constitute the evaporation stage of the process. To enable optimal evaporation the basins are shallow and even. Each basin receives more concentrated brine from the previous one and its volume is suitably smaller. During favorable weather water is retained for approximately one day in each of them.

When the brine reaches the desired salinity it is allowed to flow to the next stage, for the crystallization steps. In pre-crystallization basins the salinity of brine increases almost to the saturation point, then it is allowed to flow to the last series of basins, for the actual crystallization process. The crystallization basins are carefully prepared and managed. A special algal mat on the bottom assures a firm barrier to the soil. It enables the salt to be clean, so that no further cleaning is necessary. This layer is up to 10 mm thick and it is made out of cyanobacteria and gypsum. It is bred during winter, together with other maintenance operations.

Some steps require brine to be lifted to higher levels. A typical, wind-powered wooden pump with linen sails is sufficient for this work. When the weather is appropriate for rapid evaporation, there
is a constant and strong wind blowing from the sea throughout the day. This allows the pump to work sufficiently and reliably. In fact, the wind-pump met all the needs during the time we monitored the process. However, when workers need to speed the process up, a motor pump is also used.

To summarize, our unit of saltpan is composed of two parallel sequences of basins (Figure 1). In each of them there are 33 basins: four subsequent basins form the evaporation stage, followed by one deeper basin for storage. Then, the wind-pump raises the brine from the storage basin to a level about 0.4 m higher. This allows brine to flow into the crystallization stage, composed of a series of 14 pre-crystallization basins, and finally to the series of 14 crystallization basins. Dimensions are given in Appendix B.

In the past highly concentrated brine was stored in special small basins during the rain. Now the brine is poured into the outflowing channel after heavier showers because the mixture of rainwater and concentrated brine could harm the algal mat.

As the concentration of the halite exceeds saturation, the halite begins to crystallize. As soon as the layer of the salt is thick enough it is collected with special scrapers and stored in heaps. Then it is put into heel barrels and carried to the storehouse. After that some “fresh” brine is added from the pre-crystallization basins and the procedure starts again. In this way the basins are never dry. At desired salinity we can get quite pure crystals of NaCl. This gives the salt its peculiarly pleasant taste. If we left the brine to achieve higher concentrations, bitter salts would crystallize as well and they would affect the taste of the salt. These bitter salts (MgCl₂, MgSO₄, etc.) have higher solubility and lower proneness to crystallize than NaCl. After repetition of some cycles of salt collection, a large amount of halite (NaCl) is removed from the brine and bitter salts become more concentrated. The latter also slow the evaporation. As soon as they begin to crystallize the salt becomes bitter and cannot be used for food any more. Such “heavy” brine is appreciated in health resorts due to its medicinal properties; or it can be used as a source of chemicals for the industry. During our research we let it flow into the outflow channel and regarded it as waste brine.

A couple of times per season basins are emptied and cleaned. The remaining salt is removed and refused as waste salt in our case.

Dry salt is stored in a storehouse. Then it is packed into sacks, by means of suitable machinery.

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**Figure 1.** Schematic representation of the production unit on the Sečovlje salt pans. Arrows indicate directions of brine decantation. Numbers 1-4 are indicating four subsequent evaporation basins, P indicates pre-crystallization basin and C indicates crystallization basin. Semicircle represents the wind-pump.
METHODS

Conceptual Approach

After studying the process and making a flow chart, 12 days were spent making measurements and annotations regarding the salt production process. Annotations were performed between 15th and 26th July 2003 on the described producing unit. Energy flows were evaluated, represented in a systems diagram (Figures 2 and 3), arranged in a table (Table 1) and converted into solar emergy units. Transformities were found in the literature or calculated, when needed. Several sustainability indices were calculated (Table 2). Indices used are precisely described in Ulgiati and Brown (1998). Procedures are given in Notes at the end of the paper. Transformity factors themselves can serve as an index of output quality and production efficiency (Odum, 1996).

In our analysis we decided to exclude cultural, aesthetical, ethnological and ecological values and activities as well as knowledge, experiences and learning, since these data would be hard to determine reliably. Problems regarding the emergy in culture and information are discussed in an article by Higgins (2003).

We analyzed the current process and compared it to the process totally without mechanization (resembling the original process except for the need for labor and services) and to a further modernized process using a motor pump and eliminating the wind pump (resembling the process on the nearby Lera salt pans). In the current process we considered the use of a wind pump. For special cases there is a motor pump, which requires low fuel use. At the same time mechanization is needed for packaging as well as for labor in transportation.

Data Sources and Emergy Evaluation

Salinity, depth and temperature in all evaporation basins, in four selected pre-crystallization and four selected crystallization basins were measured every two hours during the day. Following the same schedule air humidity and air temperatures at four heights above the soil were measured.

We obtained half-hour meteorological data necessary for calculating evaporation with the Penmann-Monteith equation (FAO, 1998) as well as data on precipitation from local meteorological station, located three kilometers from the site. To account for the effect of salinity, this value was corrected with the equation noted in Kolundrović (1954).

Total emergy was obtained by summing all individual contributions of emergy flows. The total flow of emergy was divided into four separate streams: renewable sources (R), nonrenewable local sources (N), imported goods and tools (M) and emergy for labor and services (S).

To avoid double counting (Odum, 1996), only the highest of the renewable flows driven by solar radiation was considered. In our case the chemical emergy of rain over land had the highest value.

The amount of evaporated water was calculated using data about salt production and waste salt and known seawater salinity. The rest of the calculation was the same as is usually performed in emergy calculations with the exception that the effect of concentrated brine was considered (see notes to calculations in Appendix A). In the calculation of energy for evaporation (contribution to rain) we calculated chemical potential of rainwater compared to the brine of average salinity.

The contribution of wind was calculated from data about its contribution to evaporation and the mechanical work of the wind pump. The first was estimated by lowering wind speed in the Penman equation to zero. Consequently, evaporation decreased by 8%. In the same way 71.5% was found to be caused by sun radiation. With these data and known (measured) energy of sun radiation we estimated the contribution of wind to evaporation. Then, using the solar transformity of wind (Odum, 1996) we converted it to emergy flow. The remaining 20% probably belongs to the other data needed for...
Penman equation calculation (relative humidity and air temperature), which are connected to solar and wind energy flows. They have not yet been evaluated using emergy transformation factors.

A question arose regarding the emergy content of seawater as our main material source. Seawater is the reference level for the calculation of the chemical available energy of rainwater; therefore its emergy should be zero. According to the same rationale, we assign a transformity equal to zero to the salt dissolved in seawater: in fact, the transformity of sedimentary minerals in the Earth crust reflects the work performed by the environmental driving forces in order to concentrate them from their dissolved matter state. The latter state should therefore be considered the reference state. It would be worth investigating the unavoidable loss of biota in the seawater (phytoplankton, zooplankton): the amount of environmental work diverted from its natural pathway towards the process of salt production, similarly to the loss of organic matter in topsoil used up due to erosion in intensive agricultural practices. Due to the low phytoplankton density of the Adriatic Sea, we estimate that this amount would be negligible compared to other environmental inputs and therefore it is not included in the present evaluation.

Rock salt can be undoubtedly considered a nonrenewable source, like other minerals. On the other hand, there is a question whether seawater (and seasalt) is renewable. It is available in huge amounts and is exploited in much lower rates than it renews itself, receiving salts from the ocean bottom and from rivers. In our opinion it meets the criteria for sustainability noted in Ulgiati and Brown (1998).

The amount of produced salt was measured as a number of carried wheelbarrows and the average weight of salt per wheelbarrow. Similarly we measured the number and average weight of waste salt in the wheelbarrows taken away during cleaning. Waste brine concentrate was poured out two times: once because of bitter salts and once because of the rain. Its amount corresponded to double the average volume of brine in crystallization basins. Waste salts and brines were not used in our case. We considered that salt and waste salt have the same transformity (i.e., emergy splits) due to their similar chemical composition and similar possibilities for their use. On the other hand waste brine was considered a by-product.

In our case there were no local nonrenewable indigenous sources. It was estimated that there is no considerable erosion as the soil particles from the dams are mostly trapped in the water again. Like other superfluous material, they are fed back to the dams during winter maintenance. As a rule there is no need to add any material for dams and basins to the saltpan unit. Loss of soil during salt collecting is negligible thanks to the protection offered by the algal mat.

During the research a group of six volunteer students helped two part-time salt-workers, who usually maintain the saltpan. We calculated that there were eight people total working for 10 days, as two days were free for excursions. They were living in a house on the saltpan, without electricity or water supply. They prepared their own food. Water, food and other goods were brought from a village, which is about five km away. This way we were able to control water and food use, as well as labor transportation.

Students helped at salt collecting and packaging. Furthermore, they were renovating basins and dams. Such renovation is usually carried out during winter. The amount of work for renovation corresponded to the percentage of maintenance during the whole year.

According to results from neighboring Italy, labor is assumed to be approximately 90% nonrenewable and 10% renewable in the last decade (Ulgiati et al., 1994 in Bastianoni et al., 2001). More recent studies (Cialani et al., 2004) found a decrease in this percentage down to 5-6% renewable in the last two decades.

Emergy for services was estimated with regard to their price. This emergy supports production process.
**Energy for Evaporation in Different Salt Production Practices**

The salt production process is similar to the initial part of water desalination process. Thermal distillation processes are preferred for the desalination of seawater due to their cost-efficiency. Up to 10 kg of distillate can be produced per kilogram of steam (Heitman, 1990). In our range of temperatures water vapor above the seawater is approximately 1.84% less than that above freshwater (Bemporad, 1995).

The minimal theoretical energy required to produce 1 kg of freshwater (desalination) is about 7.5 kJ (Bemporad, 1995). According to data noted in Mannar (1982), 97% of the water has to be removed to achieve crystallization. In the case of thermal distillation the energy consumption for evaporation is almost unaffected with increasing salinity below the concentration of 25 Be\(^1\) and rapidly increases by about 50% above this level. Above the salinity of 25 Be \(6\%-7\%\) of water has to evaporate to achieve crystallization.

On the other hand Reverse Osmosis (RO) and electrodialysis processes show a pronounced increase in energy consumption with increasing salinity. Consequently they are less suitable for salt production. At a salinity of 20 ppm the energy required to desalinate water is 8 kWh/m\(^3\) of water for RO process (about 29 kJ/L) and 25 kWh/m\(^3\) (about 90 kJ/L) for electrodialysis. At the salinity of 35 ppm the energy for desalination increases to 13 kWh/m\(^3\) (47 kJ/L) for RO and about 45 kWh/m\(^3\) (162 kJ/L) for electrodialysis (Delyannis, 1979). Other authors report that minimal energetic requirements for RO and mechanical vapor compression methods are about 25 kJ/kg of produced freshwater (Bemporad, 1995).

**RESULTS AND DISCUSSION**

The systems diagram for the investigated process is given in Figure 2, whereas a further aggregated flow scheme is given in Figure 3.

The main raw inputs of energy and matter and their emergy equivalent are listed in Table 1, while emergy based indicators and performance ratios are reported in Table 2.

Chemical emergy of rain above land is the highest among the renewable emergy flows (R) (90% of R and 42% of total emergy flows, Tot) (Table 1). As we are at the sea level (or, precisely, about 0.6 m below it), the geopotential emergy of rain is assumed to be zero.

Emergy of wind has proved to be much lower than the emergy of rain (11.5% of R and 5.4% of Tot) and consequently it was not included in the calculation of R and Tot.

Rain has just the opposite effect on our system than usual. It does not only comprise an unprofitable source of emergy flow to the system, but it increases the transformity factor of the salt, as additional water has to evaporate. The amount of rainfall must be considered in the calculation of the salt’s transformation factor. However, in our case it was very low.

Labor contributes the largest part of nonrenewable emergy flows (63%) and 45.5% of Tot (Table 2). The percentage of labor contribution is quite variable in different systems and can exceed 80% (Ryder and Jansen, 2002), or it can be lower than 15% (Leofroy and Rydberg, 2003). The percentage of nonrenewable emergy needed to support labor would need revision in our case as people were living without electricity and electrical devices, with minimal water consumption and transportation, and food was partly from a nearby organic farm. This percentage was found to be as low as 54% for labor serving horse traction in 1927 (Ryder and Jansen, 2002). However, if there were more people living on the salt pans it would be impossible to avoid some modernization and we would again approach 10% of R for labor or even lower. This was the reason to keep the given percentage. The comparison with the possibility that 20% of emergy supporting labor would be renewable, showed that R would increase up to nearly 52% of the total emergy used. EYR (Emergy

\[ x = 144.3 \times (1 - 1/d); \ x = \text{degrees Baumé (Be)}, \ d = \text{density (kg/L)} \]
Yield Ratio) would be higher by nearly 9.5%, ELR (Environmental Loading Ratio) would decrease by 16.6% and SI (Sustainability Index) would increase by more than 31%.

The second largest imported flow of emergy is the house, followed by the fuel for labor transportation and for salt packaging (about 1% of total emergy used). The use of fuel for motor pumps

**Figure 2.** Summary systems diagram showing emergy flows on the Sečovlje saltpans.

**Figure 3.** A three flow diagram showing aggregated emergy flows on the Sečovlje saltpans.
### Table 1. Aggregated system input/output analysis of the Sečovlje saltpans.

<table>
<thead>
<tr>
<th>Inputs/Outputs</th>
<th>Raw units</th>
<th>Transformity (seJ/unit)$^2$</th>
<th>Energy (seJ)</th>
<th>Ref. for transf.</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUTS (12 days)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Sunlight (J)</td>
<td>1.074E+13</td>
<td>1</td>
<td>1.074E+13</td>
<td>a R</td>
<td>R</td>
</tr>
<tr>
<td>2 Wind (J)</td>
<td>5.19E+11</td>
<td>1500</td>
<td>7.78E+14</td>
<td>a R</td>
<td>R</td>
</tr>
<tr>
<td>3 Rain - chemical energy of rain over land (J)</td>
<td>3.37E+11</td>
<td>18199</td>
<td>6.13E+15</td>
<td>a R</td>
<td>R</td>
</tr>
<tr>
<td>4 Rain - physical energy (J)</td>
<td>0</td>
<td>18199</td>
<td>0</td>
<td>a R</td>
<td>R</td>
</tr>
<tr>
<td>5 Geothermal heat (J)</td>
<td>1.99E+09</td>
<td>6.06E+03</td>
<td>1.21E+13</td>
<td>c R</td>
<td>R</td>
</tr>
<tr>
<td>6a Seawater (L)</td>
<td>9.82E+06</td>
<td>0</td>
<td>0</td>
<td>a</td>
<td></td>
</tr>
<tr>
<td>6b Salts dissolved in seawater (g)</td>
<td>3.55E+07</td>
<td>0</td>
<td>0</td>
<td>a</td>
<td></td>
</tr>
<tr>
<td>7 Water (washing) (J)</td>
<td>2.47E+07</td>
<td>1.82E+04</td>
<td>4.50E+11</td>
<td>a M</td>
<td>M</td>
</tr>
<tr>
<td>8 Other goods (J)</td>
<td>3.00E+07</td>
<td>3.49E+04</td>
<td>1.05E+12</td>
<td>b M</td>
<td>M</td>
</tr>
<tr>
<td>9a Fuel (transportation, packaging) (J)</td>
<td>2.26E+09</td>
<td>6.60E+04</td>
<td>1.49E+14</td>
<td>a M</td>
<td>M</td>
</tr>
<tr>
<td>9b Fuel (motor pump) (J)</td>
<td>1.23E+09</td>
<td>6.60E+04</td>
<td>8.12E+13</td>
<td>a M</td>
<td>M</td>
</tr>
<tr>
<td>10a Tools (g)</td>
<td>*</td>
<td>*</td>
<td>3.00E+12</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>10b Of this – wind-pump (g)</td>
<td>2630</td>
<td>4.04E+08</td>
<td>1.06E+12</td>
<td>c M</td>
<td>M</td>
</tr>
<tr>
<td>11 Machinery (g)</td>
<td>8.19E+03</td>
<td>6.70E+09</td>
<td>5.48E+13</td>
<td>b M</td>
<td>M</td>
</tr>
<tr>
<td>12 Stony house (g)</td>
<td>2.29E+08</td>
<td>6.62E+06</td>
<td>1.53E+15</td>
<td>this study *</td>
<td>M</td>
</tr>
<tr>
<td>13 Human labor (J)</td>
<td>8.37E+08</td>
<td>7.70E+06</td>
<td>6.45E+15</td>
<td>a S</td>
<td>S</td>
</tr>
<tr>
<td>14 Services (€)</td>
<td>48.45</td>
<td>1.64E+12</td>
<td>7.95E+15</td>
<td>d S</td>
<td>S</td>
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<tr>
<td>- Machinery (€)</td>
<td>1.45</td>
<td>1.64E+12</td>
<td>2.38E+12</td>
<td>d S</td>
<td>S</td>
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<tr>
<td>- Woody tools, gates (€)</td>
<td>3.38</td>
<td>1.64E+12</td>
<td>5.54E+12</td>
<td>d S</td>
<td></td>
</tr>
<tr>
<td>- Wind-pump (€)</td>
<td>1.35</td>
<td>1.64E+12</td>
<td>2.21E+12</td>
<td>d S</td>
<td>S</td>
</tr>
<tr>
<td><strong>YIELDS, OUTPUTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Salt (g)</td>
<td>2.00E+07</td>
<td>6.55E+08</td>
<td>1.31E+16</td>
<td>this study *</td>
<td></td>
</tr>
<tr>
<td>16 Waste salt (g)</td>
<td>2.00E+06</td>
<td>6.55E+08</td>
<td>1.31E+15</td>
<td>this study *</td>
<td></td>
</tr>
<tr>
<td>17 Salts in waste brine (g)</td>
<td>1.35E+07</td>
<td>1.07E+09</td>
<td>1.44E+16</td>
<td>this study *</td>
<td></td>
</tr>
</tbody>
</table>

*R: renewable resource, N: local nonrenewable resource, M: imported nonrenewable resources, S: labor and services*

<table>
<thead>
<tr>
<th>Note</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>a Odom, 1996.</td>
<td></td>
</tr>
<tr>
<td>b Brown and McClanhan, 1996.</td>
<td></td>
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<tr>
<td>* Calculations are given at the end of the paper.</td>
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</tbody>
</table>

$^2$Total energy contributions to the geobiosphere are about 15.83E+24 seJ/yr, based on a re-evaluation and subsequent recalculation of energy contributions done in the year 2000 (Odom et al., 2000). Prior to that date, the total energy contribution to the geobiosphere that was used in calculating unit emergy values was 9.44E+24 seJ/yr. The increase in global emergy reference base to 15.83E+24 seJ/yr changes all the unit emergy values, which directly and indirectly were derived from the value of global annual, empower. Thus, unit emergy values calculated prior to that year should be multiplied by 1.68 (the ratio of 15.83/9.44). However, we did not use the new reference base in this paper, for easier comparison with previous investigations on similar topics (Buenfil, 2002), performed on the basis of the 9.44E+24 seJ/yr baseline.

$^3$Result is for neighboring Italy for the year 2002.
Table 2. Summary of emergy flows and sustainability indices in Sečovlje saltpans.

<table>
<thead>
<tr>
<th></th>
<th>A TRADITIONAL</th>
<th>B NOWADAYS</th>
<th>C MODERNIZED</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R) SUM OF RENEWABLE INPUTS (seJ)</td>
<td>6.78E+15</td>
<td>6.79E+15</td>
<td>6.79E+15</td>
</tr>
<tr>
<td>(N) SUM OF NONRENEWABLE LOCAL SOURCES (seJ)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(M) FUELS AND GOODS (seJ)</td>
<td>1.52E+15</td>
<td>1.74E+15</td>
<td>1.80E+15</td>
</tr>
<tr>
<td>(S) LABOR (90% of 13 and 90% of 14 in Table 1) (seJ)</td>
<td>5.82E+15</td>
<td>5.88E+15</td>
<td>5.87E+15</td>
</tr>
<tr>
<td>(Tot) TOTAL EMERGY USED (seJ)</td>
<td>1.41E+16</td>
<td>1.44E+16</td>
<td>1.45E+16</td>
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</table>

TRANSFORMITY

<table>
<thead>
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<th>A TRADITIONAL</th>
<th>B NOWADAYS</th>
<th>C MODERNIZED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt and waste salt (seJ/g)</td>
<td>6.426E+08</td>
<td>6.55E+08</td>
<td>6.58E+08</td>
</tr>
<tr>
<td>Waste brine (seJ/g)</td>
<td>1.05E+09</td>
<td>1.07E+09</td>
<td>1.07E+09</td>
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SUSTAINABILITY INDICES

<table>
<thead>
<tr>
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<th>A TRADITIONAL</th>
<th>B NOWADAYS</th>
<th>C MODERNIZED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable proportion to total emergy used (R/Y)</td>
<td>0.48</td>
<td>0.47</td>
<td>0.47</td>
</tr>
<tr>
<td>Ratio of nonrenewable to renewable emergy ((N+M)/R)</td>
<td>0.22</td>
<td>0.26</td>
<td>0.27</td>
</tr>
<tr>
<td>EYR (Emergy Yield Ratio (Tot/(M+S)))</td>
<td>1.92</td>
<td>1.89</td>
<td>1.88</td>
</tr>
<tr>
<td>ELR (Environmental Loading Ratio ((N+M+S)/R))</td>
<td>1.08</td>
<td>1.12</td>
<td>1.13</td>
</tr>
<tr>
<td>Empower Density (Tot/area) (seJ/m²)</td>
<td>7.35E+11</td>
<td>7.50E+11</td>
<td>7.53E+11</td>
</tr>
<tr>
<td>SI (Sustainability Index (EYR/ELR))</td>
<td>1.78</td>
<td>1.69</td>
<td>1.67</td>
</tr>
</tbody>
</table>

Emergy of imported goods and fuels to total emergy (M/Tot) | 0.108 | 0.121 | 0.125 |
Emergy of imported nonrenewable to renewable emergy (M/R) | 0.224 | 0.256 | 0.265 |

A Traditional operation using wind-pump and without steel machinery and fuels.
B Traditional using wind-pump but with other steel machinery and fuels (nowadays).
C Operation using motor pump and other steel machinery and fuels (Lera).

would cause the emergy for fuels and goods (M) to increase by 5% at a consumption rate of 30 L in 12 days (10 L per day, 2 days free or with low evaporation or even precipitation).

The amount of salt produced was estimated to be about 73% of all salt (NaCl) entering the saltpan unit. Its transformity factors (Table 2) were 6.42E+08 seJ/g in the case of wholly traditional production, 6.55E+08 seJ/g in the case of production as it is nowadays in the investigated saltpan and 6.58E+08 seJ/g in the case of production as it is in Lera. The differences among our three varieties of process are small, indicating small differences in production energy efficiency. No considerable difference can be observed between the process in our saltpan and the process in the nearby Lera saltpans.

The ratio of R to Tot (Table 2) is about 0.47 in all three cases, which exceeds a typical value calculated for agricultural systems. In a way, a relatively high ratio should have been expected, since
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the saltpan is almost completely driven by solar energy (rain) and labor, such as non-intensive agricultural production.

The ratio of nonrenewable emergy to renewable flows ((N+M)/R) (Table 2) is 0.26, indicating that a low percentage of nonrenewable sources other than labor and services is used. The greatest part of this ratio results from emergy for labor and services. It slowly rises with modernization due to the higher need for nonrenewable imported sources.

The EYR is 1.89. This is higher than it was calculated for planned dams on the Mekong River (1.3-1.4) (Brown and McClanahan, 1996) as well as for agricultural systems (Ulgiati et al., 1994). Higgins (2003) has found EYR of 1.57 for the Oak Openings region, which is quite low compared to other environment-dominated systems. This indicates that our system exploits the local resource with good efficiency. EYR slowly decreases with modernization.

An ELR of 1.08 (lower than 3) indicates that this system causes a relatively low load on the environment (Brown and Ulgiati, 1997). Comparison of the three processes suggests that modernization of the process progressively increases environmental stress. The result is lower than was calculated for a farm in the Chianti area (Italy, Bastianoni et al., 2001) and the Italian agricultural average (Ulgiati et al., 1994). At the same time, the value was lower than calculated for the dam in Korea (2.96 with sediments included) (Kang and Park, 2002) and Thailand (3.1-3.2) (Brown and McClanahan, 1996).

As an additional outcome of the investigation, we can also calculate the average solar emergy needed for each mass unit of water evaporated in the process of evaporation from seawater to concentrated brine. To evaporate one gram of seawater, $1.324 \times 10^7 \text{seJ}$ of total emergy are needed. Of this, about $6.24 \times 10^6 \text{seJ}$ come from renewable sources driving the evaporation process.

Comparisons of emergy use for evaporating the whole amount of water that entered the investigated unit using three different methods provide interesting results. To evaporate 982,150 L of water using sun and wind, approximately $6.13 \times 10^{15} \text{seJ}$ were used. To perform this work using fossil fuels $1.9 \times 10^{16} \text{seJ}$ would be needed. RO would require $1.84 \times 10^{17} \text{seJ}$ for the same work since it commonly deals with much lower concentrations. However these results are only comparative and include only the emergy of fuels used.

Finally, an Index of Sustainability SI (Ulgiati and Brown, 1998) of 1.69 indicates that the process has a net contribution to a society and that the yield per unit of environmental stress is quite high. Increased modernization causes SI to decrease, indicating decreased sustainability. The major limitation for achieving higher sustainability is the labor, since it is characteristic of industrial societies. This result should not be disregarded: “ancient” techniques are sustainable if they are embedded in subsistence societies. Instead, if they are driven by emergy intensive inputs, they may not be sustainable and simply become high-cost memories of the past culture. More appropriate processes should be found, instead. Talking about a more sustainable society achieved by adapting assets and lifestyle to declining resources, Odum and Odum (2001) say: “Coming down doesn’t mean going back to ways of the past. In general, descent means new ways”.

CONCLUSIONS

The process of salt production on the Sečovlje saltpans has proved to have a high degree of sustainability. However the degree of sustainability strongly depends on the percentage of renewable energy serving labor and services, whereas yield is highly dependent on weather conditions. This process can be classified as causing low stress on the environment. Aside from labor as the highest emergy input, the process is based mostly on the emergy of the environmental forces driving evaporation. Consequently it can be regarded as a moderately to highly renewable process producing a nonrenewable product. The differences between the three systems studied were found to be quite low.

Increased modernization caused somewhat decreased sustainability and increased environmental load due to a higher use of nonrenewable resources. At the same time we could expect reduced contribution of labor, which is considered to be energetically costly, and increased reliance
predominantly on nonrenewable sources. Moreover, modernization enables additional functions such as packaging and labeling to be done on site. A careful and accurate emergy analysis can be very useful in selecting the best possibility.

Inclusion of ecological, cultural and aesthetical values, as well as the value of experience, would considerably increase the “donor-side value” of this process and its contribution to society. This may illustrate how important these values are and how their changes affected the landscape on the researched area through history.

Our case study was based on previously calculated transformities and ratios, available in emergy literature. A more detailed investigation of emergy flows driving Slovenian economy is needed and is actually in progress in our research group. The emergy value of labor in our research can show how important it is to accurately estimate the amount of labor needed as well as the proportion of renewable versus nonrenewable emergy driving each individual process. Transformity values are highly dependent on the inclusion or exclusion of individual flows. Consequently databases with specific values for each transformity will be needed in the future. They should include data on how each transformity was calculated, what was included and what was omitted. Dynamic simulation programs would enable calculations and adjustments in transformity factors to suit each individual case. Furthermore, this would enable a rapid comparison of variations in processes, as well as consideration of possible impacts and their consequences to the environment. At the same time this would be a useful tool for cradle-to-grave emergy evaluations of materials or flows, which are not commonly done (Brown and Buranakarn, 2003, Ulgiati et al., 1995).

ACKNOWLEDGMENTS

The Author gratefully acknowledges the help received from The Maritime Museum “Sergeja Mašera” in Piran and its personnel in the saltpan Museum, for enabling the present research, as well as the precious assistance of the Environmental Agency of Slovenia and its unit in Portorož for providing the meteorological data.

REFERENCES


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APPENDIX A: CALCULATIONS AND REFERENCES FOR TABLE 1

1. Sunlight:
\[(\text{area of the saltpan}) \times (\text{calculated extraterrestrial radiation/m}^2; \text{in 12 days}):\]
\[19222 \text{ m}^2 \times 5.58 \times 10^8 \text{ J/m}^2 = 1.074 \times 10^{13} \text{ J}\]

2. Wind:
A) For wind-pump operation: \((\text{volume of brine at 14 Be of salinity}) \times (\text{density of brine 14 Be}) \times (\text{rise of water by means of a pump}) \times (\text{gravity}) \times (\text{efficiency of wind-pump})\):
\[2200 \text{ m}^3 \times 1000 \text{ L/m}^3 \times 1.1074 \text{ kg/L} \times 1.1074 \text{ kg/L} \times 0.4 \text{ m} \times 10 \text{ m/s}^2 \times 0.3 = 3.25 \times 10^7 \text{ J}\]
B) Energy for evaporation: According to our calculations with Penmann formula, wind contributed 8% of energy to the evaporation process, whereas the Sun contributed 71.5%. The average measured solar insulation in was 290.85 W/m² per day. Solar energy received: 290.85 W/m²*12 d*86400 sec/d*19222 m² (area of the saltpan)*0.2 (albedo) = 4.637E+12 J. If Sun contributed 71.5%, then the total energy for evaporation was 6.485E+12 J and wind contributed 5.188E+11 J.
\[3.25 \times 10^7 \text{ J} + 5.188 \times 10^11 \text{ J} = 5.188 \times 10^11 \text{ J}\]

3. Rain over land - chemical energy:
\[(\text{amount of seawater entering the production unit (L)}) \times (\text{density of evaporated water}) \times (\text{Gibbs free energy of evaporated water}) \times (\text{amount of rainfall in 12 days (m)}) \times (\text{area (m}^2)) \times (\text{Gibbs free energy of rainwater relative to seawater}):\]
\[(9.822 \times 10^5 \text{ L} \times 1000 \text{ g/L} \times 341.42 \text{ J/g}) + (0.129 \text{ dm} \times 1922200 \text{ dm}^2 \times 1000 \text{ g/dm}^3 \times 3.94 \text{ J/g}) = 3.37 \times 10^11 \text{ J}\]

\[^{10}\text{Gibbs free energy of brine at 14 Be (144963 ppm) relative to rainwater (10 ppm)}\]
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4. Rain - geopotential energy:
0 J (we are at the sea level or, more precisely, 0.6 m below it).

5. Geothermal heat:
(Area*flow per year) (Bastianoni et al., 2001; from Loddo, M. and Mongelli, F. Heat flow in Italy.
Pageoph 1978-9; 117:135-49.) *(exploitation in 12 days):
19222 m²*3.15E+06 J/m²/year*12 d/(365 d/y) = 1.99E+09 J

6a, 6b Seawater and salt dissolved in seawater:
Calculated according to the measured amount of total salt produced and known concentration of NaCl in seawater. Their transformities are theoretically 0, as rainwater is calculated relatively to Gibbs free energy of seawater.

7. Water for washing:
(measured volume of water used)*(density)*(Gibbs free energy of water):
5000 L*1000 g/L*4.94 J/g = 2.47E+07 J

8. Other goods:
(estimated quantity)*(estimated average caloric value):
2 kg*1000 g/kg*15 kJ/g = 3.0E+07 J

9a, 9b. Fuel:
(amount of fuel used)*(energy content of fuel per liter):
30 L for the motor-pump: 30 L*41 MJ/L = 1.23E+09 J
40 L used for transportation and 15 L for aggregate and other minor needs (lighting etc.):
55 L*41 MJ/L = 2.255E+09 J

10a, 10b. Woody and other tools for manual work:
Woody tools: (mass)*(exploitation in 12 days):
Wind-pump: 400 kg, estimated life-time 10 years, used half of a year.
400 kg*1000 g/kg*(12 d*2/(10*365 d/y)) = 2630 g
Other woody tools: 64 kg, estimated lifetime 5 years, used half of a year.
Gates: together 300 kg, estimated lifetime 10 years.
(64 kg*(12 d*2/(5 y*365 d/y)))+300 kg*(12 d/(10 y*365 d/y))*1000 g/kg = 1828 g
4 Heelbarrows: (mass of steel)*(exploitation in 12 days)*(transformity of steel) (Odum, 1996) + (mass of plastics)*(exploitation in 12 days)*(transformity of plastic) (Brown and McClanahan, 1996); 4 pieces, 5 kg of steel and 1/2 of plastic each, 2 years of lifetime, used half a year. 
(4*5 kg*1000 g/kg*(12 d*2/(2 y*365 d/y))*1.78E+09 seJ/g)+(4*0.5 kg*(12 d*2/(2 y*365 d/y))*1.5E+07 J/kg*34900 seJ/J) = 1.205E+12 seJ
Altogether: (2630 g+1828 g)*4.04E+08 seJ/g+1.205E+12 seJ = 3.00E+12 seJ
Wind-pump: 2630 g

11. Machinery:
(mass)*(exploitation in 12 days).
Motor pump: 20 kg, estimated lifetime 10 years: 20000 g*(12 d*2/(10 y*365 d/y)) = 1.315E+02 g.
Machines for filling sacks: 325 kg, estimated lifetime: 15 years.
Machine for sewing sacks: 5 kg, estimated lifetime: 15 years.
Wage: 25 kg, estimated lifetime: 30 years.
Aggregate: 20 kg, estimated lifetime: 15 years.
Car: 1000 kg, estimated lifetime: 10 years.
Together: \((20000 \text{ g}/10 \text{ y} + 325000 \text{ g}/15 \text{ y} + 25000 \text{ g}/30 \text{ y} + 1000000 \text{ g}/10 \text{ y})/12 \text{ d}/(365 \text{ d}/\text{y}) = 8.186E+03 \text{ g}\)

12. House:
The emergy value for the whole house in 300 years after building is:
- Walls - stones: \((88 \text{ m}^3/0.75*1950 \text{ kg/m}^3*1000 \text{ g/kg}*1 = 1.29E+08 \text{ g})\)
- Walls - concrete: \((88 \text{ m}^3/0.25*2500 \text{ kg/m}^3*1000 \text{ g/kg}*1 = 5.5E+07 \text{ g})\)
- Floor: \((15 \text{ m}^3/2500 \text{ kg/m}^3*1000 \text{ g/kg}*1 = 3.75E+07 \text{ g})\)
- Wood in the roof and interior: \((2000 \text{ kg} * 1000 \text{ g/kg} * 3 = 6.0E+06 \text{ g})\)
- Tiles: \((2.4 \text{ m}^3/2500 \text{ kg/m}^3*1000 \text{ g/kg} * 2.59E+09 \text{ seJ/g} + 6.0E+06 \text{ g}*4.04E+09 \text{ seJ/g} = 4.55E+17 \text{ seJ})\)

Estimated the transformity of a house per year is: \(6.62E+06 \text{ seJ/g}\)

13. Labor:
It is estimated to be 10% renewable and 90% nonrenewable.

Number of people * number of days (2 days were free) * 2500 kcal/day (metabolic needs):
8 people * 10 d * 2500 kcal/d/person * 4186 J/kcal = 8.37E+08 J

14. Services: They are estimated to be 10% renewable and 90% nonrenewable.

<table>
<thead>
<tr>
<th>Service</th>
<th>Cost in SEK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor pump</td>
<td>100000 SIT/12 d</td>
</tr>
<tr>
<td>Machines for filling sacks</td>
<td>150000 SIT/12 d</td>
</tr>
<tr>
<td>Machine for sewing sacks</td>
<td>30000 SIT/12 d</td>
</tr>
<tr>
<td>Wage</td>
<td>15000 SIT/12 d</td>
</tr>
<tr>
<td>Aggregate</td>
<td>100000 SIT/12 d</td>
</tr>
<tr>
<td>Car</td>
<td>2500000 SIT/12 d</td>
</tr>
</tbody>
</table>

Together in 12 days: \(40.57 \text{ €}\)

Emergy needed to perform all work, including some maintenance operation (in 12 days): \(123312 \text{ kcal}*4186 \text{ J/kcal} = 5.16E+08 \text{ J} (61.7\% \text{ of all metabolic emergy needed})

Average exchange rate between Slovenian Tolar (SIT) and Euro (€) for the year 2002 (Statistical Office of the Republic of Slovenia).
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Services for house building and renovation:
Work for building: 1 month 4 people; renovation: estimated to be 3 days per year in average; (number of days for building and preparation*metabolic energy needed*exploitation:
30 \* 8 \* (12 d/(300 y*365 d/y))*(139781 SIT/month/30 d/month)*(1 €/226.2237 SIT) = 0.54 €
Work for renovation: number of hours for renovation per year*metabolic cost* exploitation in 12 days:
3 d/y*(12 d/365d/y)*(139781 SIT/month/30 d/month)*(1 €/226.2237 SIT) = 2.03 €
Together: 48.45 €

15, 16, 17. Salt, waste salt and waste brine:
The amount of salt (NaCl) produced was around 20,000 kg, whereas the amount of waste salt was around 2,000 kg. The sum of emergy used for production was 1.44E+16 seJ. 1.31E+16 seJ were used for salt production whereas 1.31E+15 seJ were used for waste salt production.
Transformity of salt and waste salt: (emergy invested)/(weight of a product).
1.44E+16 seJ/(2.0E+07 g+2.0E+06 g) = 6.55E+08 seJ/g
Waste brine was regarded as a by-product. According to our calculation about 5500 kg NaCl and 8,000 kg of other salts were discarded. Its transformity (per gram of total salts): 1.44E+16 seJ/1.35E+07 g = 1.07E+09 seJ/g.

APPENDIX B: DIMENSIONS OF THE SALTPANS

Evaporation sage:
1\textsuperscript{st} stage of evaporation: 1993.3 m\textsuperscript{2}
2\textsuperscript{nd} stage of evaporation: 2540.2 m\textsuperscript{2}
3\textsuperscript{rd} stage of evaporation: 2948.4 m\textsuperscript{2}
4\textsuperscript{th} stage of evaporation: 3087.1 m\textsuperscript{2}
Reservoirs: 164.2 m\textsuperscript{2}
Basins receiving pumped water: 428.75 m\textsuperscript{2}
Channels: 13.6 m\textsuperscript{2}
Together for evaporation stage: 14001.4 m\textsuperscript{2}

Crystallization stage:
Pre-crystallization basins: 3121.4 m\textsuperscript{2}
Crystallization basins: 2825.8 m\textsuperscript{2}
Together for the crystallization stage: 5947.2 m\textsuperscript{2}
Together (without dams): 17122.8 m\textsuperscript{2}
Together (with dams): 19222 m\textsuperscript{2}