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Commercial feasibility of a new freeze crystallization plant for small-scale potable water production

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ABSTRACT

Water desalination can be an important method to ensure that people receive potable water, and simultaneously strengthens their economic situation. Different water purification processes such as thermal evaporation and reverse osmosis are widespread. However, both methods have the disadvantage of the necessary use of chemicals, and they are hardly operable by renewable energies. Consequently, freeze desalination could be an innovative alternative. Most freeze desalination plants use water washing and are not economically efficient. Therefore, no working plants are installed besides research plants. Thus, this study introduces a new design, which uses pressing instead of washing, and investigates its economic efficiency. Every expense is described in detail. Water production costs of 2.705 €/m³ for a plant manufactured in Germany and 2.160 €/m³ for that manufactured in China are feasible. Overall, the results show that a freeze desalination plant can be competitive with common plants but has a better ecological footprint.

Keywords: Economic efficiency; Freeze desalination; Renewable energies; Water treatment

1. Introduction

The current world population is estimated at more than 7 billion, and is expected to increase to 10.1 billion in the next 90 years [1]. In addition, research studies also predict that two-thirds of the world population will not have access to clean water by the year 2025 [2]. Although the United Nations declared the year 2003 as the International Year of Freshwater, and the years from 2005 to 2015 as the International Decade for Water, such initiatives had little consequences, implying that more countries than ever continue to suffer from water shortages [3,4]. In addition, with the existing climate changes, an improvement in water supply should not be expected [5,6]. In addition to areas like Southeast Europe, the Middle East, and the West Coast of North America, which have good preconditions caused by a high wealth, there are also areas with less opportunities, such as North Africa, Southwest Asia, and the Southwest Coast of South America [7,8]. A possible improvement in the water availability could be the transportation of water between places. However, this would have a high environmental impact, and may incur

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high costs for bottles, transport and energy. In addition, the transport is limited to within continents only. The invention of an artificial unit called Virtual Water could prevent the trade of products that require significant amounts of water for production, to countries that already have abundant water [9–11]. However, despite offering a better water distribution system, this method would cause losses for the local industry, which would in turn have to be restructured, eventually decreasing the GDP of the state [12]. Thus, these disadvantages make the use of Virtual Water rather unpopular and unrealistic for the next decades. Desalination plants could possibly be considered a technology to help people directly by supplying them with fresh water [13]. Important factors for realization depend heavily on the desalination process and its workability. However, afford ability and environmental friendliness are at least as important as technical issues. The existing plants are mainly based on processes like reverse osmosis or evaporation. However, both technologies have the disadvantage of requiring a significant use of different chemicals, rendering them unsuitable for operations in isolated islands or areas [14]. Furthermore, they are expensive when combined to renewable energies. Only a few plants are powered by sunlight or wind. For instance, the stepwise replacement of oil-based power plants with wind energy has been realized in the Canary Islands. But costs are still too high to operate without government funding [15,16]. Further, limitations in downscaling have restricted the use of renewable energies for bigger desalination plants and countries with a large amount of waste energy or money [17]. One disadvantage is that most countries suffering from water scarcity do not have a wealthy population, except oil-exporting countries, but they do have a significant solar incident [17,18]. This fact should be considered to operate desalination plants powered by photo voltaic or solar thermal energy [14]. Accordingly, an alternative and prospective technology solution can be desalination by freeze crystallization [19]. With less energy consumption, lack of necessary chemicals, the possibility to use photo voltaic energy in combination with heat pumps, and the chance of arbitrarily scaling the process looks ideal to generate potable water in remote areas. This process can be used to supply water to small family communities, villages, and hotel complexes with environmental consciousness [20,21]. Furthermore, the process includes heat pumps to use the energy conversion from electrical to thermal energy. Thus, the advantage of little temperature gradients through heat recovery, leads to a high coefficient of performance (COP), which in turn results in smaller photo voltaic plants, thereby reducing the investment costs [22]. Existing plants powered by alternative energies to save carbon dioxide are based on combinations of thermal desalination and nuclear power plants. Therefore, waste steam or power is used. Renewable energies are mainly used in reverse osmosis plants [14]. Water production costs of 3.14 €/m³ to 9.00 €/m³ are already reported [16,23]. Thermal desalination plants powered by renewable energies use sunlight to evaporate water; however, this process is realized at a laboratory-scale only [14,24]. Usually, such systems comprise a collector and an evaporator, although the collector can be a concentrator. The production costs are between 3.50 €/m³ and 8.00 €/m³ [15]. The above mentioned plants in the Canary Islands, which are partly powered by wind energy, incur production costs worth 1.00 €/m³ to 5.00 €/m³ [15]. However, using renewable energies poses some challenges, such as additional investment costs, and the variable availability of wind or sunlight, which are the main factors for non-implementation. Therefore, plants should be bigger in dimension to compensate for the fluctuating energy supply, to produce the same amount in less time. Alternatively, electric storage devices should be installed to maintain power supply. However, both methods incur higher water costs [14]. Thus, this study introduces and describes in detail the feasibility of a freeze crystallization plant for the continuous production of potable water. The remainder of the paper is structured as follows. Section 2 describes the plant design, specifying and monetarily quantifying all plant parts. Next, Section 3 presents the cost estimations, wherein the total costs of the plant are calculated and compared to other desalination plants powered by renewable energies. Section 4 evaluates the costs for potential fields of applications, and finally, Section 5 presents the conclusion of the study.

2. Plant design

A freeze desalination system usually needs a combination of different technical plant components. This includes crystallization, separation, and post-treatment steps, of which the last step presents the biggest challenge. Although many crystallization processes are known to work with diverse post-treatment technologies, the end product always has a high monetary value, like pharmaceuticals. Water, in comparison, has a low monetary value, and thus needs competitively cheap processes. Wasting products by washing the polluted ice is therefore not a good option. Rather, pressing the ice could be a better alternative because applying mechanical force presses the liquid with all pollutants out of the ice, leaving only the pure ice [19]. The liquefaction of the ice due to the pressure can thereby be neglected [19]. This post-treatment step combined with a crystallization plant allows the design of a continuous production plant to produce potable water with low wastage of products and energy, and is also combinable with renewable energies. Fig. 1 shows all the main steps in such a freeze crystallization plant. First, a cooled vessel is installed, where the crystallization occurs. This vessel is in contact with a cooling plant, typically a compressor unit with a vaporized/condensed coolant. Next, the crystals are separated from the surrounding brine by pressing the ice together. The brine can then be collected and pumped back into the sea. The ice is melted and can be stored as potable water. The bound cooling energy obtained from melting the ice and heating the brine and potable water can be used for heat integration. Electrical power is delivered by solar modules and an inverter transforming solar radiation into energy.

The small-scale plant that will be analyzed in this paper is based on a screw press crystallizer. The special feature of this design is that ice can form on the inner surface of the tube, and is scraped away and transported toward the upper end. Through forced conveyance, the ice is pressed through a conical, perforated funnel which separates the ice and brine. Ice can then be collected and melted to obtain potable water. The development of the plant and the results that show that test water contaminated with 4 wt% NaCl and seawa-

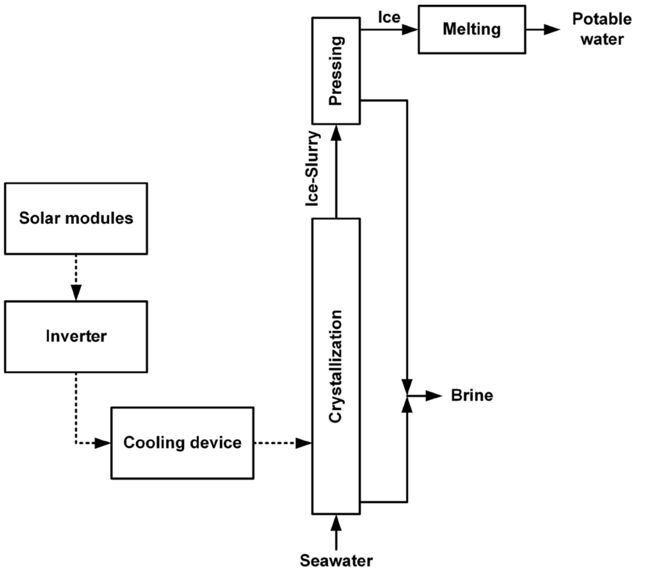


Fig. 1. Freeze crystallization plant: Schematic flow diagram with main process steps.

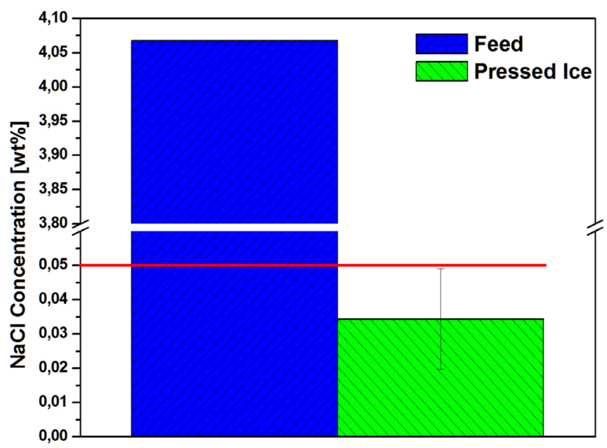


Fig. 2. NaCl concentration of the feed and the pressed ice with a screw rotation speed of 30 rpm, a coolant inlet temperature of –8°C and a coolant flow rate of 880.5 l/h (red line - limit concentration of NaCl in potable water).

ter obtained from the Atlantic Ocean can be desalinated to obtain potable water as required by the drinking water ordinance [25], will be, due to conciseness, described elsewhere. Nevertheless, Fig. 2 shows the results, which were exemplarily achieved using such a freezing crystallization plant with a test solution of 4.07 wt% NaCl. Basic experimental results of desalination with freezing crystallization in combination with a press can be looked up in our previous paper [19].

The experiments showed that with Eq. (1) from Stein [26] the heat transfer within the crystallizer can be accurately calculated [Eq. (2)], assuming a spiral agitator instead of a screw. This equation was then used for the upscaling.

$$Nu = 0.48 * Re^{\frac{2}{3}} * Pr^{\frac{1}{3}} * \left(\frac{\eta_f}{\eta_w}\right)^{0.14} \tag{1}$$

$$\alpha = \frac{Nu * \lambda}{d_i} \tag{2}$$

Nu Nusselt number; *Re* Reynolds number; *Pr* Prandtl number; η_f Dynamic viscosity fluid; η_W Dynamic viscosity fluid close to wall; α_i heat transfer coefficient; λ thermal conductivity; d_i inner diameter

Fig. 3 depicts the design of the main parts of the plant. The size of the plant can be scaled from single-person (>100 m³/a) to multi-person (>400 m³/a) households.

2.1. Screw

The most important part of the plant is the screw, which will scrape the ice layer and force it into the conical funnel (Fig. 4). The screw is made of stainless steel. To connect the screw to the motor and to distract the forces, one axial and two radial roller bearings, and a coupling are used. The motor with transmission has a maximum torque of 250 nm and a maximum rotation speed of 60 rpm. The slip between the screw and tube is approximately 2 mm.

2.2. Press section

The funnel is designed to press the ice slurry (Fig. 5). On an average, this slurry comprises pure ice (37.5 wt%) and concentrated brine (62.5 wt%). The funnel is constructed to

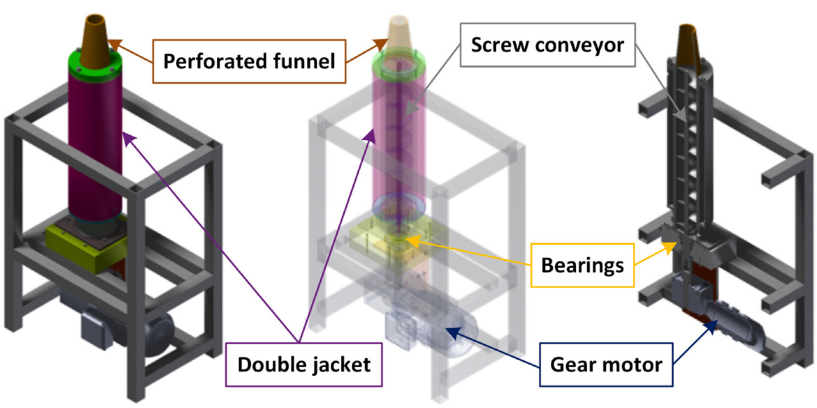


Fig. 3. Construction design of a screw press crystallizer [whole design (left), semitransparent (middle), cross-section (right)].

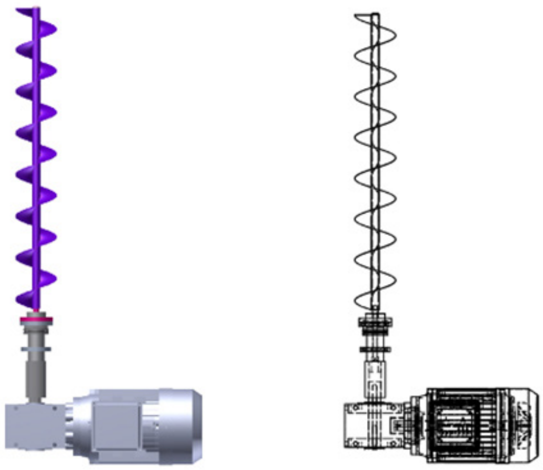


Fig. 4. Design of the screw with additional connections.

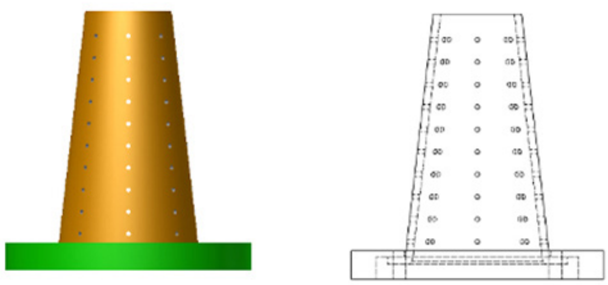


Fig. 5. Design of the straining conical funnel.

apply a defined separation time with the necessary change of ice volume from the entry to the outlet. The brine leaves the cone through holes and flows counter current to the ice.

2.3. Heat transfer surface

The cooling section is double walled and has a heat transfer area of 0.14 m² (Fig. 6). Between the outer and inner pipes, a defined volume is enclosed, which is used to pump a cooling liquid through or to use it as an evaporator for a heat pump. The inner wall is more than two times thicker than the outer one, guaranteeing the necessary absorption of the force generated by pressing of the ice. All walls are even, implying that no ribs are mounted. The outer pipe is shorter to leave space for connections for the purge and the feed.

2.4. Miscellaneous

A steel frame stabilizes the whole plant. The upper part is separately placed on the steel frame, detaching the motor from the opposing force. A heat pump as well as solar modules and related electronic devices can be considered merchantable as long as they fit the requirements. In addition to these parts, liquid pumps, water hoses, and a heat exchanger should be mounted as well.

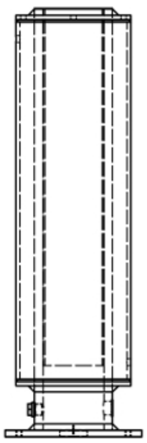


Fig. 6. Heat transfer surface in terms of pipes with different diameters.

3. Individual cost estimation

If not otherwise mentioned, all the following costs are obtained via quotations from either German or Chinese suppliers. Therefore, a quantity of 100 pieces is requested to obtain a more realistic price range, and only the cheapest suppliers are used for further calculations. No extra charges for delivery are included because transportation costs to the yet unknown final destination cannot be estimated. For the Dollar to Euro conversion, an exchange rate of 1.0669/€ is assumed. Furthermore, all calculations are performed considering that the plant components must handle a larger water volume than only potable water (Ice), caused by the overall seawater (SW) consisting also of concentrated brine (Brine) that has to be cooled and pumped as well (Eqs. (3) and (4)). The production rate is based on an operating time of 10 h per day. This is due to the dependence on the solar radiation, which is not constant during the day. The assumed sun hours are realistic for countries with water scarcity. The ice/brine mass ratio, to calculate cooling energy, for example, is based on seawater with a concentration of 4 wt%. Another source as feed with lesser salinity, for example, brackish water, could change the ice/brine mass ratio, and therefore influence the costs positively.

$$\dot{m}_{SW} = \dot{m}_{Brine} + \dot{m}_{Ice} = (1-x) * \dot{m}_{SW} + x * \dot{m}_{SW} \tag{3}$$

$$\dot{Q} = \dot{m}_{SW} * c_{P,SW} * \Delta T_1 + \dot{m}_{Ice} * \Delta h_m + \dot{m}_{Ice} * c_{P,Ice} * \Delta T_2 + \dot{m}_{Brine} * c_{P,Brine} * \Delta T_2 \tag{4}$$

where $\dot{m}$ is mass flow rate, C_p is specific heat capacity, $\dot{Q}$ is thermal energy, ΔT is temperature difference, Δh_m is melting enthalpy, and x is mass fraction.

For calculating the amount of potable water produced, the parameters given in Table 1 were calculated from the measured data obtained from the laboratory scale plant. The difference in the heat transition of the German (Ger) and Chinese (CN) plants is due to the different wall thickness of the pipes produced in China, and therefore a different inner diameter, resulting in a smaller crystallization surface.

Table 1
Calculated parameters and resulting water yield

Description	German plant	Chinese plant
Heat transition water/ice [W/(m²*K)]	897.27	873.10
Heat transition refrigerant [W/(m²*K)]	1130.41	1130.41
Heat transition wall [W/(m*K)]	15.00	
Wall thickness [mm]	3.00	4.00
Heat transition coefficient [W/(m²*K)]	500.20	492.58
Seawater temperature inlet [°C]	20.0	
Brine/Ice temperature outlet [°C]	–3.4	
Coolant vaporization temperature [°C]	–10.0	
Coolant overheating [K]	3.0	
COP [–]	5.86	
Specific energy demand [kWh/m³]	55.69	52.93
Seawater inlet [m³/a]	377.8	346.1
Potable water outlet [m³/a]	141.7	129.8

Table 2
Cost overview of heat transfer and crystallization pipes

Description	Price [€/(m³/a)]
Outer pipe, Germany [27]	3.479
Inner pipe, Germany [27]	3.076
Outer pipe, China [28]	2.495
Inner pipe, China [28]	2.187
Inner pipe-anticorrosion, Germany [29], [30]	5.924

The detailed description of each part of the plant and the cost structure is provided in the following subsections.

3.1. Pipes

The easiest way to construct a crystallization vessel is to use two pipes combined to one double-walled vessel. The heat transfer surface and force absorption are realized via different diameters and wall thicknesses. Prices based on the annual production volume are given in Table 2. Pipes from Chinese suppliers are less expensive than those by German suppliers are, thus resulting in a significant difference when ordered in large quantities. Considering standard pipes with corrosion protection would raise the price instead of lowering it. A lower k-value (497.83 W/(m²*K)) is caused by a larger wall thickness of standard steel, and by an additional layer of anti corrosive with low heat conductivity. The lower price and the better heat conductivity of standard steel cannot outweigh the lower production volume and the expensive anti corrosion, thus concluding in a higher final price.

3.2. Screw

The screw is made of stainless steel because of the pressing force that has to be transferred through it, particularly through the flights and the shaft connection of the screw. In contrast to pipes, screws from China are not necessarily cheaper than those made of Titanium (Table 3). Polymer screws are even up to twice as expensive as screws made of stainless steel.

Table 3
Cost overview of screws

Description	Price [€/(m³/a)]
Stainless steel, Germany [31]	2.711
Stainless steel, China [32]	3.375
Titan, China [33]	1.993
Polyoxymethylene, Germany [34]	5.426

3.3. Heat pump

A heat pump removes the heat from seawater. This provides an advantage because of the conversion from electrical to cooling energy quantified by the COP. For all calculations without heat integration, a COP of 5.86 is calculated. Furthermore, all heat pumps operate with alternating current because large heat pumps with direct current are not yet available. Thereby, the heat pump is designed depending on the accumulation of salt in brine, thus changing the ice/brine mass ratio and the freezing temperature. The accumulation based on experiments is 6.0 wt%. The connected electrical load is approximately 3 kW, considering a buffer for heat losses. The prices for different heat pumps are given in Table 4.

3.4. Perforated funnel

To separate the ice from the attached and included brine, a conical, perforated funnel is fixed by a flange on top of the pipes. Besides stainless steel, high-strength Alumina can be used. An advantage of Alumina is its lower price because of a lower production time on the lathe due to the excellent machine ability. The prices are given in Table 5.

3.5. Motor, pump, water hose, and miscellaneous

The motor is responsible for transport and pressing of the ice via the screw. Furthermore, it is inevitable to have good turbulence within the crystallizer to ensure good heat transfer. The demand on the motor is therefore high. Consequently, it should have sufficient power with compatible gearing for the right rotational speed, torque, and electrical data to operate it with power from solar modules. Pumps are necessary to ensure that water does not have to be transported manually, so that people can invest time to improve their standard of living, rather than for procuring potable water. For this, three submersible pumps (feed, brine, and potable water) with suitable flow rates and anti corrosive materials have been selected. Similar to the heat pump, the motor, water hose, and pumps have to be chosen to suit the ice/brine mass ratio. To provide the plant with seawater and to return the brine to the sea, plastic hoses instead of pipes will be used to ensure resistance, easy exchange ability, and cost effectiveness. Every installation place will be differ-

Table 4
Cost overview of heat pumps

Description	Price [€/(m³/a)]
Heat pump, Germany [35]	10.455
Heat pump, China [36]	7.017

Table 5
Cost overview of perforated, conical funnels

Description	Price [€/(m³/a)]
Funnel, Germany [37]	5.294
Funnel, China [38]	2.123
Funnel-Alumina, Germany [39]	3.088

ent; therefore, a standard length of 200 m is assumed. Advantageously, this desalination plant design does not require several bearings, fittings, other similar connections, or even automation equipment, because of which they are omitted in the cost estimate. The long-term weather-resistant frame is made of galvanized steel, and can be easily repaired if damaged. All costs are presented in Table 6.

Table 6
Cost overview of motors, pumps, and miscellaneous

Description	Price [€/(m³/a)]
Motor, Germany [40]	1.377
Motor, China [41]	1.397
Pumps, Germany [42]	2.943
Pumps, China [43]	1.733
Water hose, Germany [44]	0.918
Water hose, China [45]	0.881
Frame, Germany [46]	0.278
Frame, China [47]	0.076

3.6. Solar modules and inverter

The solar modules have to deliver the power to the heat pump, liquid pumps, and motor. Costs for solar modules are set at a rate of 0.54 €/Wp [48]. Until now, this is the price in the world market. Because electrical parts are not working with direct current, an inverter is also necessary. Regarding all other plant parts, no transport or assembly costs are included and the efficiency depending on the solar irradiation, location, and the choice of modules are neglected. The assumed efficiency is 95% for the inverter, motor, and the liquid pumps, and 90% for the heat pump. The solar modules and the inverter are also slightly oversized for flexibility in case of optimizations and heat losses. The costs are presented in Table 7.

Table 7
Cost overview of solar modules with inverter

Description	Price [€/(m³/a)]
Solar modules, Germany	7.469
Solar modules, China	7.706
Inverter, Germany [49]	6.946
Inverter, China [50]	6.903

4. Total cost estimation

Following cost estimations show the total costs with and without heat integrations as well as with battery operation.

4.1. Water costs without heat integration

Considering all individual costs, an overview shows at what price for a cubic meter potable water can be obtained. All parts and their costs, together with the total price are given in Table 8.

For this kind of investigation, assuming a realistic repayment of investment after 10 years, the prices that can be obtained are given in Table 9. Compared to the present costs of desalination plants, the water price is commensurable for a combination with renewable energies. The overall costs regarding the size of the plant are rather good.

A detailed analysis of the cost overview shows that the main cost factors are the heat pump, the solar modules, and the inverter (Fig. 7). Furthermore, the relative costs of each individual part are almost equal whether they are made of German or Chinese parts, and only the absolute numbers differ.

4.2. Water costs with heat integration

All main parts, related to the costs, depend directly on the necessary thermal and thus electrical energy. Therefore, it is both ecologically and economically reasonable to include heat integration. Energy can hereby be saved by regaining the sensible and latent heat of the ice and the sensible heat of the brine. It can then be used to cool the feed and/or the refrigerant. Possible options for heat integration are shown in Fig. 8.

4.2.1. Water costs with single heat integration

Melting energy from ice can be used to cool down the feed. Therefore, the ice should always be mixed with a small amount of liquid potable water to guarantee a good heat transfer within the heat exchanger. This produces no loss of product, but rather only an offset when starting the production. Theoretically, the bound cooling energy can be used to not only cool down but also crystallize the feed partially. This would lead to a blocked heat exchanger. Therefore, the heat integration is not completely realized but is calculated to cool down the feed before crystallization starts. The single heat integration positively affects the production rate when ensuring the same cooling energy. This is realized by adjusting the evaporation temperature of the coolant (Table 10).

Thereby, the COP drops to 4.96 and increases the electrical energy demand, and thus the solar installation. Furthermore, costs for an additional heat exchanger should

Table 8
Individual and overall costs

Description	Price German plant [€/(m³/a)]	Price Chinese plant [€/(m³/a)]
Pipe	3.479 (outer) /3.076 (inner)	2.495 (outer) /2.187 (inner)
Screw	2.711 (stainless steel)	1.993 (titan)
Heat pump	10.455	7.017
Funnel	3.088 (alumina)	2.123 (stainless steel)
Motor	1.377	1.397
Pumps	2.943	1.733
Water hose	0.918	0.881
Frame	0.278	0.076
Solar modules	8.240	8.547
Inverter	6.946	6.903
Total	43.510	35.353

Table 9
Water costs per cubic meter

Country of production	Price [€/m³]
Germany	4.351
China	3.535

be considered. The changed costs are given in Table 11. Despite the fact that more solar modules, a bigger inverter, and an additional heat exchanger are necessary, the higher production rate significantly reduces the costs.

The relative cost estimations differ only marginally compared to the ones without heat integration (Fig. 9). This is due to the small difference of the COP for the plants with and without heat integration.

4.2.2. Water costs with double heat integration

Double heat integration can be realized by combining the product with the refrigerant stream and the brine with the feed stream. The feed can thereby not be cooled as with the single heat integration because of the less bound energy in the brine stream. However, because of the precooled refrigerant, the COP increases to 7.63. Adjusting the evaporation temperature until the same cooling energy is achieved increases the overall production rate (Table 12).

The higher COP lowers the necessary number of solar modules and thus the costs. Nevertheless, the smaller production rate, compared to single heat integration, and the two additionally installed heat exchangers raise the overall costs, whereby the costs are higher than for single heat integration. Specifically, the refrigerant/ice-heat exchangers affect the costs due to the large area that is necessary because of the low k-value of the condenser.

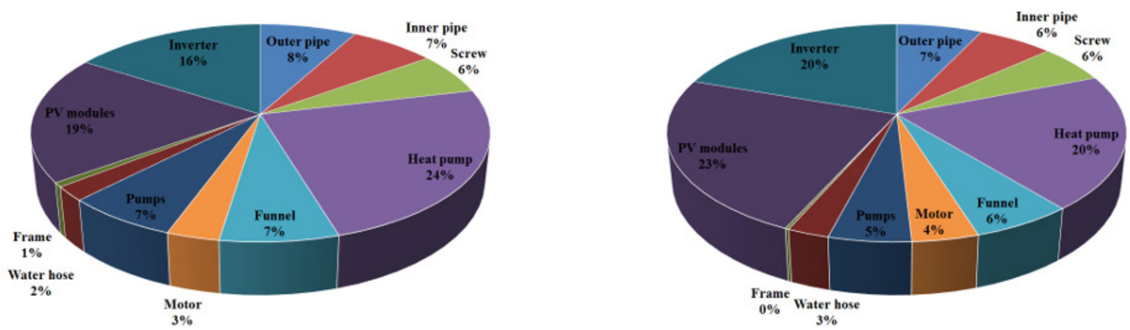


Fig. 7. Individual costs of German (left) and Chinese (right) plants.

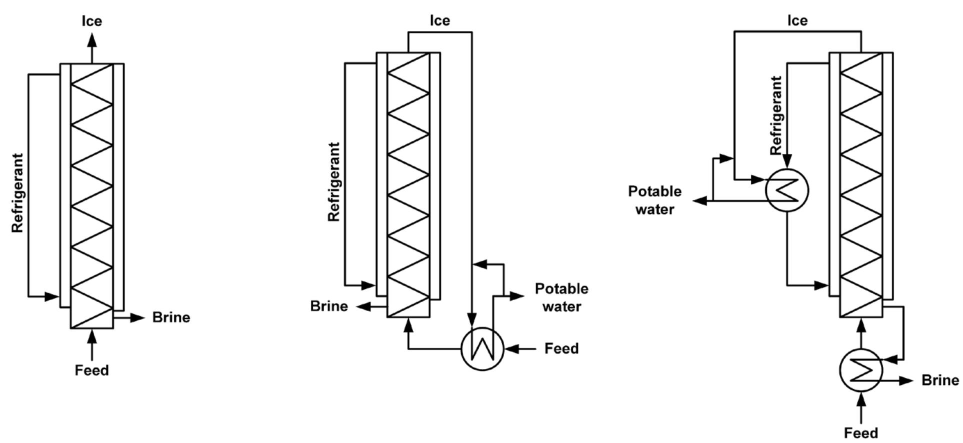


Fig. 8. Schematic flow chart of the plant without (left), with single (middle), and double (right) heat integration.

Table 10
Calculated parameters and resulting water yield with single heat integration

Description	German plant	Chinese plant
Seawater temperature inlet [°C]	–2.0	
Brine/Ice temperature outlet [°C]	–3.4	
Coolant vaporization temperature [°C]	–16.8	
Coolant overheating [K]	3.0	
COP [–]	4.96	
Specific energy demand [kWh/m³]	36.18	34.26
Seawater inlet [m³/a]	644.0	590.1
Potable water outlet [m³/a]	241.5	221.3

Table 11
Individual and overall costs with single heat integration

Description	Price German plant [€/(m³/a)]	Price Chinese plant [€/(m³/a)]
Pipe	2.040 (outer) /1.804 (inner)	1.464 (outer) /1.283 (inner)
Screw	1.590 (stainless steel)	1.169 (titan)
Heat pump	6.132	4.116
Funnel	1.811 (alumina)	1.141 (stainless steel)
Motor	0.808	0.820
Pump	1.726	1.017
Water hose	0.538	0.517
Frame	0.163	0.045
Solar modules	5.352	5.532
Inverter	4.074	4.049
Feed/brine heat exchanger	1.014 [51]	0.445 [52]
Total [€/(m³/a)]	27.055	21.596
Total [€/m³]	2.705	2.160

As shown in Fig. 10, the relative ratio of solar modules compared to the overall costs is quite smaller than it was before the heat integration. Yet, renewable energies and the heat pump are still the largest portion of the costs.

4.3. Water costs for battery operation

Raising the working hours of the plant by installing battery packs could be another option to optimize the plant operation due to an increasing production rate. Up to now, costs of 300 $/kWh for Lithium-ion batteries are available, and are considered to decrease further [54]. Nevertheless, more installations of solar modules and inverters are considered necessary to store surplus energy during the day. Besides additional expenses, adding a solar storage device increases the produced water amount, so that more families can benefit from one plant. Table 14 shows how costs change when plants are additionally powered by batteries. Compared to plants with heat integration (HI) and no batteries, costs are higher in plants with batteries.

This is owing to additional solar modules and inverters that are, apart from the batteries, the main cost factors when plants are powered by renewable energies. Together, solar modules, inverters, and batteries are responsible for 66% to 82% of the overall costs (Figs. 11 and 12).

Table 12
Calculated parameters and resulting water yield with double heat integration

Description	German plant	Chinese plant
Seawater temperature inlet [°C]	6.6	
Brine/Ice temperature outlet [°C]	–3.4	
Coolant vaporization temperature [°C]	–13.5	
Coolant overheating [K]	3.0	
COP [–]	7.63	
Specific energy demand [kWh/m³]	35.97	34.38
Seawater inlet [m³/a]	504.4	462.2
Potable water outlet [m³/a]	189.2	173.3

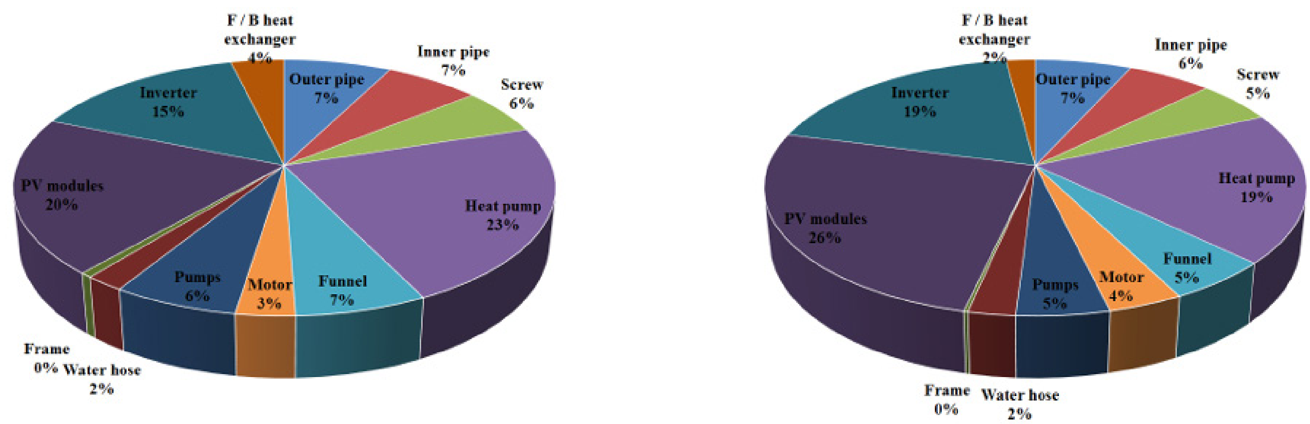
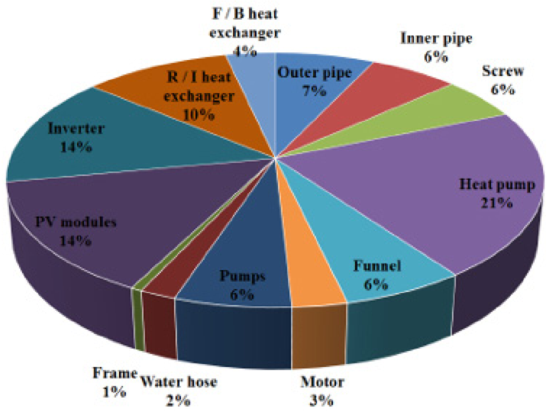


Fig. 9. Individual costs of German (left) and Chinese (right) plants with single heat integration.

Table 13
All costs and overall manufacturing costs with double heat integration

Description	Price German plant [€/(m³/a)]	Price Chinese plant [€/(m³/a)]
Pipe	2.605 (outer) /2.303 (inner)	1.868 (outer) /1.638 (inner)
Screw	2.030 (stainless steel)	1.493 (titan)
Heat pump	7.829	5.255
Funnel	2.313 (alumina)	1.590 (stainless steel)
Motor	1.032	1.046
Pump	2.204	1.298
Water hose	0.687	0.660
Frame	0.208	0.057
Solar modules	5.322	5.552
Inverter	5.202	5.170
Refrigerant/ice slurry heat exchanger	3.817 [53]	2.596 [52]
Feed/brine heat exchanger	1.295 [53]	0.568 [52]
Total [€/(m³/a)]	36.847	28.789
Total [€/m³]	3.685	2.879



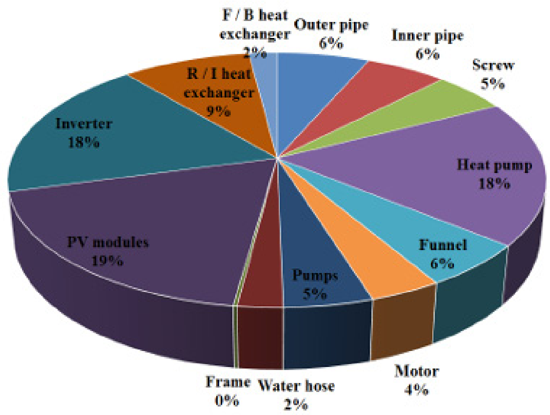


Fig. 10. Individual costs of German (left) and Chinese (right) plants with double heat integration.

Table 14
Calculated parameters and resulting water yield and costs for battery operation

Description	Single HI		Double HI	
	Germany	China	Germany	China
Seawater temperature inlet [°C]	4.4		6.6	
Brine/ice temperature outlet [°C]	–3.4			
Coolant vaporization temperature [°C]	–14.2		-13.5	
Coolant overheating [K]	3.0			
COP [-]	5.27		7.63	
Specific energy demand [kWh/m³]	32.59	30.42	26.04	24.46
Seawater inlet [m³/a]	1,283.1	1,175.6	1,210.7	1,109.3
Potable water outlet [m³/a]	481.2	440.9	454.0	416.0
Cost of battery [€/(m³/a)]	17.060		12.482	
Cost of plant parts [€/(m³/a)]	18.578	15.821	20.023	16.647
Total [€/(m³/a)]	35.638	32.881	32.505	29.129
Total [€/m³]	3.564	3.288	3.250	2.913

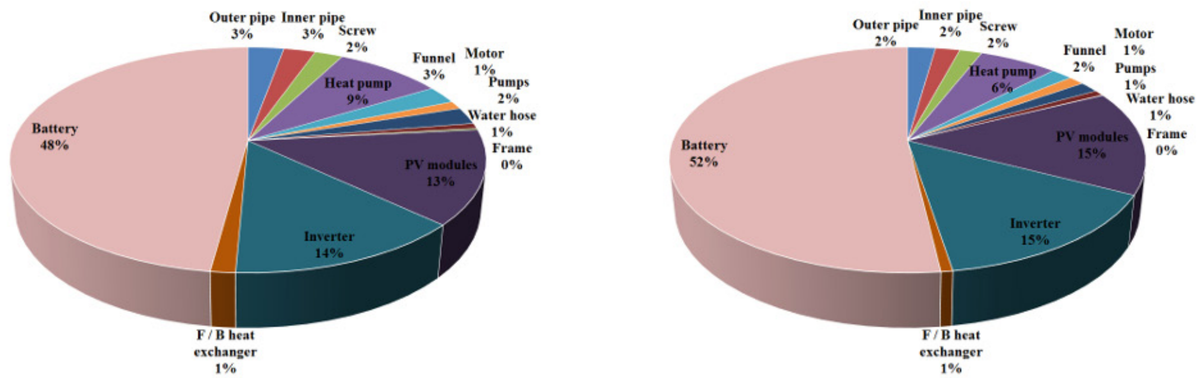


Fig. 11. Individual costs of German (left) and Chinese (right) plants with single heat integration and storage battery.

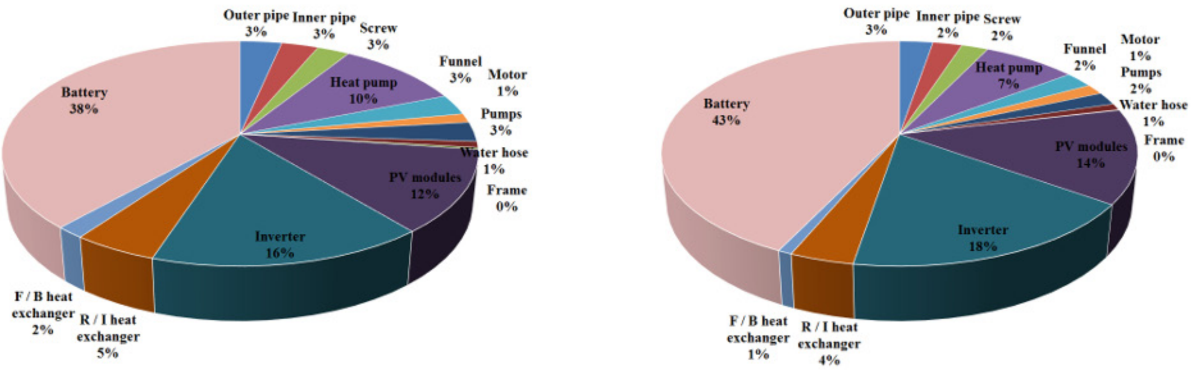


Fig. 12. Individual costs of German (left) and Chinese (right) plants with double heat integration and battery.

Double heat integration is even less expensive than single heat integration, which is in contrast to operation without batteries. The combination of double heat integration with a higher COP and batteries improves the overall efficiency.

5. Economic efficiency

The proposed plant in this study cannot compete, in terms of water costs, with the existing desalination plants with large production rates of thousands of cubic meters. However, systems powered by renewable energies, to be used in remote areas are less developed, and because of the lower production rates, they are more expensive. Water costs for such small plants are typically estimated at around 5.50 €/m³ [15,23].

5.1. Private applications

The costs calculated up to now exceed these for a freeze desalination plant with single heat integration with 2.705 €/m³ for a German plant and 2.160 €/m³ for a Chinese plant, respectively. Depending on the salt concentration of seawater, costs could even decrease for lower concentrations using brackish water because of the increasing ice/brine mass ratio. The main remaining problem is the receivable investment that has to be made. Usually, people who need such a plant are unable to afford it. Therefore, an investor is necessary. With a lending interest rate of 7.5% (i.e., Panama, 2016 [55]), the price for a plant with single heat integration and a 10 year payment would rise to 3.942 €/m³ and 3.146 €/m³, respectively. This would mean a not-tolerable price increase. Hence, a financial solution should be of interest to the WHO and other organizations with a long-term-investment strategy, especially if people are able to help themselves for producing their own food and becoming independent of aid transports or funds.

5.2. Industrial applications

Powering the plant using conventional power sources instead of renewable energies, if available, results in a higher production rate. Eliminating the costs of the inverter, solar modules, and batteries generates costs for a plant with single heat integration of 0.886 €/m³ for a German plant and 0.604 €/m³ for a Chinese plant, assuming an electricity price of 0.1983 $/kWh (produced with diesel in the Canary Islands, for instance [16]). Assuming a water tariff of 1.72 €/m³ (i.e., Canary Islands, 2014 [56]) for water supply, the dynamic amortization would be 0.61 y for both plants with single heat integration. With no renewable energies, the price of the plant is so low that it would be profitable from the first year. Water costs generated with conventional power can compete with water gained from even bigger desalination plants. Thereby, this plant can be used for different purposes such as delivering potable water to hotels and small beverage industries. It can also be used to save ground water or to regenerate water reservoirs.

6. Conclusions

Analyzing a freeze desalination plant for small water amounts in terms of economic efficiency shows that such plants can operate with renewable energies, and can be competitive with other plants within this scale. Specifically, when used in remote areas, these plants can help provide families and groups of families with potable water to become independent of already existing structures. Based on 4 wt% salt in seawater, water production costs of 4.531 €/m³ for an in Germany produced plant and 3.535 €/m³ for an in China produced plant with no heat integration are feasible. A plant optimization, like double heat integration, cuts the costs to 3.685 €/m³ and 2.879 €/m³, respectively. Nonetheless, the costs of the two additional heat exchangers in combination with a lower production rate prevent lower costs. A single heat integration conversely reduces the costs to 2.705 €/m³ and 2.160 €/m³, respectively. This is due to a higher production rate decreasing the costs even with a poor COP. Operating the plant with conventional power shows that the main costs are based on the conversion of solar energy into electrical energy even by using a heat pump. Costs would then be 0.886 €/m³ and 0.604 €/m³, respectively, which is within the range of common desalination plants. Increasing the production rate by installing battery packs to raise the working hours of the plant, leads to higher costs due to additional installations of expensive solar modules and inverters. Besides these cost arguments, the lack of necessary chemicals enables people to produce self-sufficient, clean, and ecological water. Because of the small size of the plant, even with solar modules, the plant can be installed anywhere with a good solar incident and is fully scalable within limits. Changing the parameters of the plant allows the operator to produce water with a higher concentration than is necessary for potable water, thereby increasing the ice/brine ratio to gain more water for planting fruits or vegetables. Advantageously, the plant is easily repairable and has no special parts that would be difficult to replace, simultaneously improving the long-term stability. This enables people to repair their own plant without any special, qualified personnel. It can even be installed and supervised by one technical person to reduce further installation costs. Many parts are available worldwide, thus reducing the transportation costs and the carbon footprint as well. As another ecological effect, in contrast to plants with large production rates, brine is only released in small amounts and only at different places, preventing natural damage through high salt concentration. Further optimizations could be to store excessive cooling energy in a thermal storage device, like the brine, instead of as electrical energy in a battery. It could then be pumped through the plant when the solar radiation is too low to operate the heat pump but high enough for the motor and pumps. The working hours and hence the production rate could be extended. Saved costs for the battery have to be offset against a more complex plant design and automation. Considering the current costs for thermal or electrical storage devices, the proposed plant design appears reasonable. However, it is not possible to enumerate a fixed price because too many conditions depending on the installation location have to be considered. For the pricing, a few simplifications are assumed, which have to be proofed. Material costs as insulation, filters, and automation as well as profit and overheads are neglected. Furthermore, up to now, no long-term experiences regarding the stability of the plant are investigated by estimating any operating expenses.

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