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Concepts and economic analysis of a crystallizer for a solar thermal powered desalination plant

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ABSTRACT

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Concepts and economic analysis of a crystallizer for a solar thermal powered desalination plant

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This Bachelor’s thesis deals with the physical and economic examination of different concepts to implement it in a modular constructed solar thermal powered desalination plant to reduce the waste of it. During this analysis the concepts are developed and compared to each other via a scoring model. Here, two different concepts are selected. The first concept consists of a direct solar thermal heated crystallizer and the second concept is an industrial crystallizer. The following step is a physical and thermodynamic analysis. This shows the probable scale and the required heat flow to run the concepts. Furthermore, the concepts are analysed in an economic way. The result of this is a diagram where the costs are as a function of the scale of the desalination plant. Here, it is shown, that the direct crystallizer is much cheaper in a scale of 1 to 60 desalination applications but becomes more expensive above 60.

In dieser Bachelorarbeit werden verschiedene Konzepte zur Reduzierung des Abfalls einer modular aufgebauten und solarthermisch betriebenen Entsalzungsanlage untersucht. Hierzu werden die Konzepte zuerst entworfen und im Anschluss untereinander verglichen. Dies geschieht mit Hilfe einer Nutzwertanalyse. Zwei Konzepte werden ausgewählt. Eines der Konzepte ist ein direkt solarbetriebener Verdampfer und das Zweite ein industrieller Verdampfer. Als Nächstes werden die Konzepte physikalisch und thermodynamisch untersucht. Hier werden die Abmessungen grob dargestellt und die benötigte Wärmemenge berechnet. Darauf folgt die Wirtschaftlichkeitsbetrachtung, welche ein Diagramm aufzeigt, in welchem die Kosten der Konzepte in Abhängigkeit zur Größe der Entsalzungsanlage dargestellt sind. Das Ergebnis zeigt, dass der direkte Verdampfer bei einem Maßstab der Entsalzungsanlage zwischen 1 und 60 Modulen günstiger zu betreiben ist als der industrielle Verdampfer. Bei über 60 Modulen wird jedoch der industrielle Verdampfer günstiger.

Key words: solar energy, evaporation, crystallization, economic analysis

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Δh_C	Enthalpy of crystallization, [kJ/kg]
ΔH_C	Molar enthalpy of crystallization, [kJ/mole]
ΔH_S	Molar enthalpy of solution, [kJ/mole]
ΔT_b	Boiling point elevation, [K]
ΔT_m	Temperature difference between condensate and boiling solution, [K]
Δx	Thickness of metal layer, [m]
A	Heat transfer area, [m²]
B	Molality, [mole/kg]
C	Costs for equipment and installation, [€]
C_e	Equipment costs, [€]
$C_{e,\ i,\ CS}$	C estimated with carbon steel, [€]
$C_{p,\ F}$	Specific heat capacity of the input to the crystallizer, [kJ/kg*K]
$c_{p,\ S}$	Specific heat capacity of sodium chloride crystals, [kJ/kg*K]
c_{Solids}	Concentration of the salt solution, [kg/m³]
D	Diameter direct crystallizer, [m]
F	Lang-Factor, [-]
f_c	Factor civil, [-]
f_{el}	Factor electrical, [-]
f_{er}	Factor equipment erection, [-]
f_i	Factor instrumentation and control, [-]
f_l	Factor lagging and paint, [-]
f_m	Factor materiel, [-]
f_p	Factor piping, [-]
f_s	Factor structures and buildings, [-]
G	Mass fraction [g/kg]
H	Height direct crystallizer, [m]
h	Convective heat-transfer coefficient, [W/m²K]
h_{CO}	Enthalpy of condensate, [kJ/kg]
h_F	Enthalpy of the input to the crystallizer, [kJ/kg]
h_S	Enthalpy of solids leaving the crystallizer, [kJ/kg]
h_{SI}	Enthalpy of entered steam, [kJ/kg]
h_V	Enthalpy of the vapor leaving the crystallizer, [kJ/kg]
I	Imputed interest, [€/a]

k_{eb}	ebullioscopy constant, [K*kg/mole]
L	Labour costs, [€/a]
M	Molar mass, [kg/mole]
m_{CO}	Mass flow condensate, [kg/h]
m_{Feed}	Mass flow of the input to the crystallizer, [kg/h]
m_{SI}	Mass flow steam in, [kg/h]
m_{So}	Mass of solvent, [kg]
m_{Solids}	Mass flow of the salt leaving the crystallizer, [kg/h]
m_{Steam}	Mass flow steam, [kg/h]
m_{SteamA}	Mass flow available steam, [kg/h]
m_{SteamR}	Mass flow required steam, [kg/h]
m_{Vapor}	Mass flow of the vapor leaving the crystallizer, [kg/h]
n	Amount of substance, [mole]
$\dot{Q}$	Heat flow, [W]
$\dot{Q}_L$	Heat losses, [W]
t_a	Air temperature, [°C]
t_w	Casing temperature crystallizer, [°C]
$\dot{V}_{Feed}$	Volume flow, [m³/h]
λ	Thermal conductivity, [W/m²*K]
ρ	Density [kg/m³]

1 Introduction

The worlds and humans most important resource is water. Without water there can be no life on earth. Although the worlds surface area consists of 70,8 % of water, it is not always potable and available for humans. Especially in dry and coastal areas fresh and clean water sources get very rare. Reasons for that are a depletion of the available sources as well as an increase of pollution. On top of that the worlds fresh water demand raises with the growth of the world's population. Therefore, the desalination of seawater and polluted waste water is becoming more popular and important every year. But right now, desalination processes like reverse osmoses is related to high energy consumption. This energy consumption could lead to a bad economic yield. Which means that the plants are not rentable for the provider.

What kind of energy could decrease the costs for the energy supply of desalination plants? Here, the solar thermal powered desalination plants become important. Solar energy is free of charge and actual available everywhere. Especially in dry countries where desalination plants are needed immediately. The processes which could be operated by solar thermal power are the distillation processes like solar distillation, humidification-dehumidification, multiple effect and multistage flash distillation and some more. The disadvantages of these types are the long process time and therefore the low mass flow. Because of that there is also the problem with the economic yield. Although the energy is free of charge, the plants could not generate enough fresh water to drive such plants economically. One possibility to make these plants more economical is the crystallization of the waste of the desalination process. Particularly, if the desalinated water is seawater the salt can be crystallized and probably sold. The energy for the evaporation could also come from the sun. Are there possibilities to do the crystallization and how could they be connected to a desalination plant? And does it affect the economics? (Belessiotis, Kalogirou and Delzannis 2016, 1–6; Zheng 2017, 2–21)

1.1 Aim of the thesis and description of conditions

The questions above allows a glimpse of the topic that will be elaborated in this work. More explicit, the work will consider a solar concentrator but especially one application for it. This application will desalinate sea or waste water to produce drinkable water in countries like Namibia, Tunisia or Kenya. The aim is to establish different concepts for minimizing the waste of the desalination process. The salt in the solution shall be crystallized so that the volume of the waste decreases concluding in lower costs for disposing the waste. This is a good opportunity for locations where it is difficult to dispose the

waste. Otherwise, the salt solution could damage the environment if it is not treated carefully. The crystallizer shall minimize this hazard to the environment. The concepts are to be analysed in a physical and thermodynamic way to get an idea of the needed energy and the scale of the application. According to that, an economic analysis of the concepts shall show the cost differences between the concepts for different scales of a desalination plant. As a result, it will be shown at what point which concept is more profitable related to the scale of the desalination plant. This can be done in a rough overview to get an idea of the possible matters of expanse.

The designs for a desalination application are already done. This application is working with a solar concentrator which is designed and also built by the company *Solar Fire Concentration Oy*. This concentrator exists of a mirror surface with a scale of 6 m * 6 m. It is possible to focus the sunlight of a 36 m² area to a small point above the mirrors. The idea of the solar concentrator is to heat up different forms of applications at this focal point. The application possibilities are variegated. Therefore, one idea is to use the solar concentrator to crystallize the salt. This idea shall be as simple as possible to keep low investment costs.

The designs of the solar concentrator and the desalination application of the company *Solar Fire Concentration Oy* are confidential and cannot be shown here. Generally, the working mechanism of the solar concentrator can be compared with a parabolic solar concentrator and this of the desalination application with a multi stage flash distillation.

Some properties of the desalination waste and other values which will be illuminated in this thesis are given by the company and are listed in the following table.

Table 1: Pre-existing values for the project

Input crystallizer	0,1 – 0,2 m³/h
Concentration of input	120 – 200 kg(salt)/m³
Input desalination	4 m³/d; 0,614 m³/h
Solar concentrator area	36 m²
Diameter of possible crystallizer	30 – 50 cm
Focal temperatures	up to 600 °C
Costs per solar concentrator	2000 – 5000 € (India – Europe)

Benefiting from this work will be mainly the company *Solar Fire Concentration Oy*. The thesis will be very theoretical because there is no intention to build such a desalination plant soon.

Beside the pre-existing values some simplifications are made. At this stage it is inexplicit which kind of solutions will be treated in the desalination plant. Therefore, the solution is fixed as seawater. Furthermore, the ingredients of the seawater are assumed as sodium chloride only. This simplicity should be exactly enough to get significant results.

1.2 Course of action

The course of action of this thesis is as follows. After the introduction to the topic and the theory which is needed for working on this topic, the concepts are mentioned. Here, they are described in a short and simple way. The principle should just become apparent. Important issues for each concept are considered as well as some simple technical parts in this section. Furthermore, the implementation in a desalination plant is described and shown in figures. Three concepts are developed and analysed in a scoring model. This scoring model compares the concepts via different criteria to select two of them for the ongoing process. Some criteria are simplicity, maintenance, labour and investment costs for example.

The main part of the thesis is the physical, thermodynamic and the economic analysis. First, the concepts are calculated and described in a physical and thermodynamic way. Here, subjects like the solution properties, solar radiation and the required energy for the evaporation are determined. This is done for both concepts so that they can be economical analysed in the next part.

The economic analysis shows a rough overview about the probable costs for implementing the crystallizer concepts in a desalination plant. In the end, the question, at what time which concept is more rentable related to the scale of the desalination plant, is answered with a diagram. The conclusion about the results complete the thesis.

1.3 Company introduction

The company, who provides the topic, is called *Solar Fire Concentration Oy* and is based in Tampere. It is a small company with a work range from thermal and optical modelling across control and automatization for optical or thermal systems. Furthermore, CAD construction designs up to data visualization and web design are fields of their work. Their main technology is a solar concentrator in different scales that is used for generating steam and power to run different applications. This thermal power can be used in many different industry fields. Processes like pasteurization, distillation or canning can benefit from that thermal power. Moreover, options for mechanical powering via steam engine or turbine are possibilities for their technology. Another major aspect is the foundation of

the *GoSol* initiative. Projects in Africa especially in Tanzania and Kenya where they build the solar concentrators to drive ovens, dryers and roasters are the main working field of the initiative.

2 Theory

The following section is about the required theory of this work. Each topic is described to the extent that is needed for this thesis. The subjects of solar energy and solar concentrators are mentioned to get to know the possible amount of solar energy and how it can be used from solar concentrators. Besides that, the theory about the properties of aqueous salt solutions is described to understand why and which values are changed compared to water for example. After that separation processes and heat transfer is listed in the theory. Here, the reader shall get an idea about the processes and how they are used and work. More information about the subjects can be found in the given references.

2.1 Solar energy and solar concentrators

Solar energy is the energy delivered by the sun. It is transported by photons and is converted mainly into thermal energy when the photons hit any kind of material. When the energy is emitted by the sun the energy flow density is equal to 6,15 * 10^7 $\frac{W}{m^2}$ but it loses energy at the way to the earth. The so called solar constant is the energy flow density which arrives the earth surface area before entering the atmosphere. This constant is about 1367 $\frac{W}{m^2}$ which is validated by the *World Radiation Center* (Zheng 2017, 49–52).

After the solar energy hits the atmosphere, it is absorbed, scattered and reflected by molecules and particles in it. The overall energy density which reaches the ground on cloudless days is only 70 % from the energy density outside the atmosphere. On cloudy days the absorption, scattering, and reflecting portion rises to 90 %. Besides that, solar radiation can be differed to a diffuse and direct part when it enters the atmosphere. Some reasons for that are shown in figure 1. So, direct solar radiation is the energy which arrives the ground without any direction change and diffuse means the solar energy which changed direction after hitting clouds or particles.

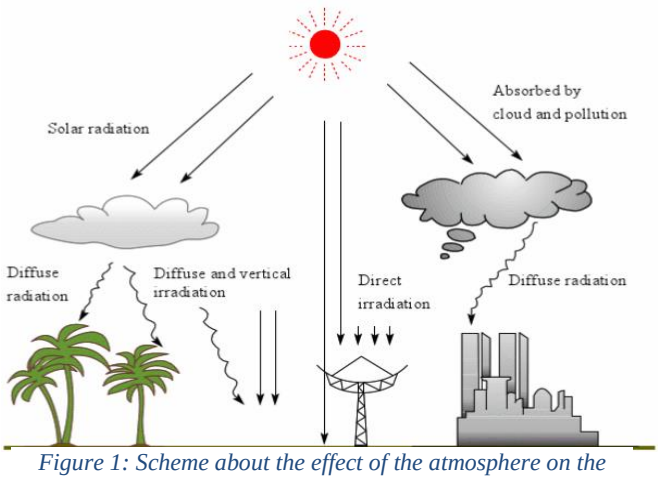

Figure 1: Scheme about the effect of the atmosphere on the solar energy (Zheng 2017, 54)

Diffuse radiation is mainly weaker than the direct one since it has already hit molecules or particles. The ground reaching energy then can be used to generate thermal power for different kind of processes. The maximum energy flow density on the earth's ground is between 800 and 1000 $\frac{W}{m^2}$ on good weather days (Ibid., 53–55).

Figure 2: Parabolic dish concentrator (Zheng 2017, 54)

The collecting methods for solar energy can be divided in solar concentration and nonconcentration. The main difference between them is that the solar concentration applications can only collect direct solar irradiance and the nonconcentration can collect both, diffuse and direct irradiance. But the advantage of the solar concentration is the high thermal efficiency with focal temperatures up to 4000 °C. Examples for the solar concentrations are parabolic dish or parabolic trough concentrators. And examples for nonconcentration is the flat-plate or vacuum tube collector. The parabolic dish concentrator is using a lot of mirrors which are concentrating the sunlight to a small focal point where water or any other fluid is heated (figure 2). Since the solar concentrators can only collect direct radiation the applications must be added with a solar-tracking system. So that the direct radiation can be collected the whole day (Ibid., 58–62).

2.2 Properties of aqueous salt solutions

An aqueous salt solution includes one or several dissolved salts in a solvent which is mainly water. The properties of these solutions differ from pure water due to the ionic composition. One example of an aqueous salt solution is seawater. And one important property of seawater is the salinity for example. It shows the mass fraction in the solution. So, it is defined as the mass of the dissolved material per mass of the solution. The salinity has impact on other properties of those solutions. For example, the density, the pH, the thermal conductivity, the boiling point, the heat capacity and a lot more. The salinity of seawater compounds a lot of different salts. The composition of it is shown in table 2. The relative portion is determined with the values of appendix A (Belessiotis, Kalogirou and Delzannis 2016, 34–40).

Table 2: Relative portion of the main ionic components of seawater

Component		Molar Mass [g/mole]	relative portion [-]
Chloride	Cl	35,453	0,550
Sodium	Na	22,99	0,306
Sulphate	SO4	96,065	0,077
Magnesium	Mg	24,305	0,037
Calcium	Ca	40,078	0,012
Potassium	K	39,098	0,011
Bicarbonate	HCO3	61	0,004
Bromide	Br	79,904	0,002
Boric acid	H3BO3	61,8	0,001
Strontium	Sr	87,62	0,0004
Fluoride	F	18,988	0,00004

The density of salt solutions depends on the temperature and the salinity. This density can be calculated with the help of different theoretical equations by Gibbs, Grunberg or Isdale and Morris for example. The validation of these equations is between a salinity of 10 to 160 $\frac{g}{kg}$. Therefore, it cannot be used for every situation. Another possibility to estimate the density is doing measurements with the required values. But in general, the density rises with the increase of the salinity and it decreases with higher temperatures (Ibid., 41–52).

The other important property is the boiling point elevation. This phenomenon appears because of the change of the vapour pressure of the solution due to the change of the ionic composition. The dissolved particles have either a stronger or a weaker force to other particles in the solution compared to the forces to the same particles. If the force is stronger, the partial pressure of the components and the total pressure is less. And if the force is weaker, the pressure is higher. This is one reason why the boiling point rises and the freezing point drops of salt solutions for example. Here, the vapor pressure of the salt is quite low and the total pressure is nearly the same as the partial pressure of the solvent. But nonetheless, the small pressure difference leads to a higher boiling point and a lower freezing point. The vapor pressure is, due to the stronger forces in the solution, smaller. This is shown in figure 3. Because of that it is more energy required to reach the atmospheric pressure. Where the solvent is vaporized.

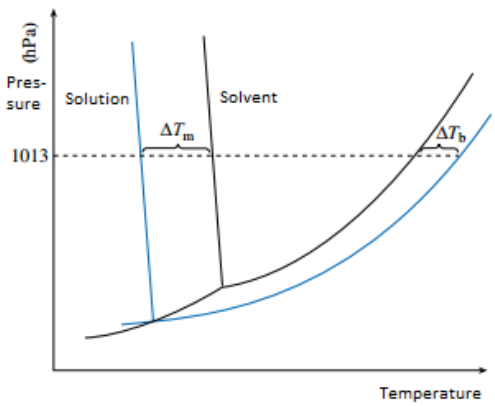

Figure 3: Vapor pressure reduction of a salt solution compared to the solvent (Binnewies, et al. 2016, 204)

The expression of the boiling point elevation is as follows.

$$\Delta T_b = k_{eb} * b \quad (1)$$

Here, ΔT_b is the boiling point elevation in K, k_{eb} is the ebullioscopy constant for the respective solvent and b is the molality of the solution. The molality is the amount of substance of the dissolved solids per kilogram of the solvent. The expression for the freezing point reduction is the same except of the ebullioscopy constant. Here, the cryoscopy constant for the respective solvent is used.

So, the elevation and reduction are only depended on the solvent and the number of dissolved solids, but it does not matter which particles are dissolved (Binnewies, et al. 2016, 203, 204).

2.3 Separation processes and heat transfer

This section is about the theoretical basics of separation processes like evaporation and crystallization as well as heat transfer concepts.

2.3.1 Evaporation and crystallization

Evaporation describes the process of heating up an aqueous solution until it begins to vaporize. During this process water is removed from the solution. And the result is a higher concentrated solution. Normally, the higher concentrated solution is the product and the vaporized water is a kind of energy as well as waste of the process. Evaporators are big heat exchangers, powered by steam. The main areas of application are sugar, salt, glycerol, glue, milk and orange juice production (Geankoplis, Hersl and Lepek 2018, 32.1; Schwister and Leven 2013, 278–280).

The equipment possibilities for evaporation are big. Examples for the equipment is the open pan, horizontal- or vertical-tube natural circulation or the forced-circulation-type evaporator. The last one has a good heat-transfer coefficient due to the fact of the forced circulation. Thus, the heat transfer area can be smaller. This type is good for the crystallization process. Furthermore, the process can be differed in single or multiple-effect evaporators. Single-effect means, that there is only one evaporator used. This is good for small scaled operations and with low energy costs for the required steam. Figure 4 shows a simple overview of a single-effect evaporator. Here, it is presented which flow rates enters the evaporator and which ones are leaving it. The whole calculations of an evaporator are concentrated to the mass and

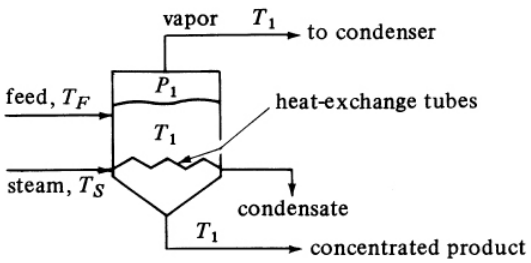

Figure 4: Simplified figure of a single-effect evaporator (Geankoplis, Hersl and Lepek 2018, 32.2B)

energy balance of it. So, entering materials or energies are equal to the leaving materials or energies. Besides that, the following equation is required to calculate the needed heat transfer area of an evaporator for example.

$$\dot{Q} = U * A * \Delta T_m \tag{2}$$

In this equation $\dot{Q}$ is the rate of heat transfer, U is the overall heat-transfer coefficient, A is the heat transfer area and ΔT_m is the temperature difference between the condensing steam and the boiling liquid (Geankoplis, Hersl and Lepek 2018, 32.s–32.4; Schwister and Leven 2013, 281–285).

Crystallization is another separation process. Here, the application is concentrated on solid-liquid separation. More detailed, it is about the crystallization of solids which are dissolved in a solvent. After the solute concentration reaches the maximum of solubility in a specific solvent, crystals begin to grow and the solid comes out of the solvent. Mainly, this process is used in the food and pharmaceutical industries (Geankoplis, Hersl and Lepek 2018, 29.1).

Crystallization is based on the solubility of a material and saturation of a solution. And there are different possibilities to reach the saturation. Depending on the solubility curves of the material the solution can be either cooled down or evaporated to go beyond the point of maximum solubility. Solubility means, how much material can be dissolved in the solvent before it is saturated. For example, the solubility of NaCl in water is 39,2 g salt/ 100g water (Binnewies, et al. 2016, 928).

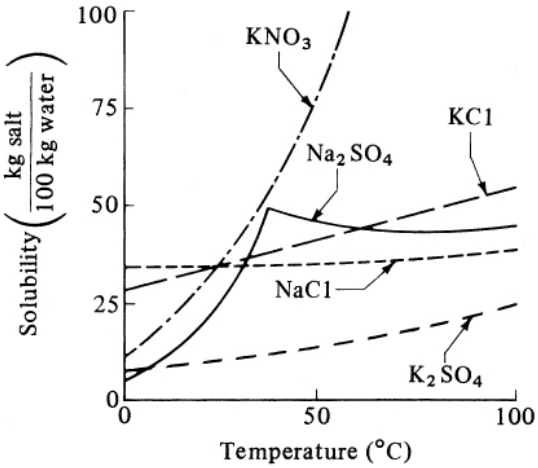

Figure 5: Solubility curves for different salts (Geankoplis, Hersl and Lepek 2018, 32.1B)

Figure 5 shows the solubility curves for some salts in water. For example, NaCl must be evaporated because the solubility at a temperature range of 100 °C is nearly constant. So, an overrun of the curve by cooling down the solution would not be a possibility to crystallize the salt. But Na_2SO_4 has a very low solubility in the temperature range from 0 to 30 °C for example. Here, it would be possible to crystallize the salt be cooling down the solution under 30 °C (Geankoplis, Hersl and Lepek 2018, 29.1–29.2).

2.3.2 Heat transfer

Heat transfer means the transportation of thermal energy from one material to another. These materials could be solids, liquids or gases. The transfer direction is always from the higher temperature to the colder one. And it stops when the temperatures are equal. Heat transfer can be differed to conduction, convection and radiation.

Conduction

Conduction is taken place on the molecular layer of solids, liquids and gases. Here, the thermal energy is transported from particle to particle of the material. Conduction occurs only in the same material and not from one material to another. An example for it is the conduction through a metal layer from a heat exchanger. The heat flow by conduction is calculated as the following equation:

$$\dot{Q} = -\lambda * A * \frac{\Delta T}{\Delta x} \tag{3}$$

$\dot{Q}$ is the heat flow, λ is the thermal conductivity of the material, A is the heat transfer area, ΔT is the temperature difference from the warmer side to the colder side of the material and Δx is the thickness of the layer (Wagner 2011, 17–21).

Convection

Convection is also a heat transfer mechanism and it occurs only in liquids and gases. The energy transportation is taken place due to flow phenomena. That means, that the warmer part heats the colder part because of the movement of the molecules. Convection is differed in free and forced convection. Free convection is without any outer influence and forced means, convection due to mechanical work from fans or pumps.

But convection is also a part of the heat exchange of a liquid or gas to a solid surface. The equation to calculate the amount of the heat flow is:

$$\dot{Q} = h * A * \Delta T \tag{4}$$

$\dot{Q}$ is again the heat flow, h is the convective heat-transfer coefficient, A the heat-transfer area and ΔT is the temperature difference between the solid surface and the liquid or gas (Ibid., 67, 68).

Radiation

Radiation is the last mechanism of heat transfer. It occurs in every material. Liquids, gases and solids can radiate heat. This heat radiation consists of electromagnetic waves and can be absorbed from other materials which are not permeable for radiation. Due to the absorption of the waves, the material becomes warmer because it receives the energy. One example for transfer of energy via radiation is the sun (Ibid., 159).

2.4 Economic analysis

In this chapter are the used economic methods described. First, the Cost Comparison Method is mentioned and explained in a theoretical way. And after that, the Factorial Method to estimate the probable fixed capital cost is defined.

2.4.1 Cost Comparison Method

The Cost Comparison Method (CCM) is a static procedure to look at the costs of different implementations of an investment project. Static means that the projects are considered in a fixed period. This period can be as long as possible, but the disadvantage of this static view is a loss of statement for a long-time period. In contrast, the advantage is a simple, fast and especially for the beginning of a project a good method to get a rough overview of possible costs for an investment (Töpfer 2007, 972).

The main element of the CCM is the comparison between two or even more cost listings. These listings consist only of the arising costs of a concept and not of the possible revenue. So, it is a method which is used to compare concepts which have the same quantitative and qualitative output. Therefore, the yield of the concepts is the same and can be ignored for the calculations (Ibid., 972, 973).

Following types of costs are considered in this determination. First, the operational costs which consist of labour, material, repairing, room and energy costs. These are also called variable costs which appears every period again. Second, the capital costs which are composed of the imputed depreciation and the imputed interest. The imputed depreciation is calculated with the equipment costs minus the left worth of the application after its lifetime, divided by the expected useful life. And the imputed interest is calculated either

$$I = \frac{(fixed\ capital\ cost + residual\ value\ befor\ last\ year\ of\ use)}{2} * interest\ loan \tag{5}$$

if the repayment is not continuously and only done in the end of each year or

$$I = \frac{(fixed\ capital\ cost + residual\ value\ after\ useful\ life)}{2} * interest\ loan \tag{6}$$

when the repayment is done continuously. The imputed interest represents the possible profit if the money from a project is invested in the capital market instead of finance a project.

Every cost point is summarized to a value in relation to a specified period. The concept with the lowest cost per period should be used for the project (Ibid., 974).

2.4.2 Estimating installed costs: Factorial Method

Estimating the installed costs are very important for a project in the early beginning. Only knowing the equipment costs for a plant is insufficient. The main additional costs to that are the civil works, pipe systems, instrumentations or electrical works to implement the transaction. All these costs can be calculated with a factor which is then multiplied with the equipment costs. This methods accuracy is as good as the accuracy of the cost data of the equipment. But generally, the result of this estimation is rough and should only be used for the early economic calculations (Towler and Sinnott 2013, 328).

The first type of factors is called Lang factors and they evolved from economics in the 1940s. This installation factor is multiplied with the total costs of the main equipment items. Lang defined the factors generally in F = 3,1 for plants with solid materials, 4,74 for fluids and 3,63 for mixed fluids-solids processing plants (Towler and Sinnott 2013, 329).

Another more detailed factorial estimation is shown in the following figure. Here, each equipment type is calculated on its own instead of summarizing the whole equipment costs and use only one factor. Towler and Sinnott (2013) explain that this method is more detailed and reliable, nonetheless only applies for the beginning of a project.

Equipment Type	Installation Factor
Compressors	2.5
Distillation columns	4
Fired heaters	2
Heat exchangers	3.5
Instruments	4
Miscellaneous equipment	2.5
Pressure vessels	4
Pumps	4

Figure 6: Installation factors for the capital cost estimation (Towler and Sinnott 2013)

There are lot more different factor methods which become more reliable by splitting the factors in more stages. So, that each step and each equipment have its own factor. Here, one more method shall be described. It is called materials factors. The old factors consider only carbon steel items. This method includes a factor for special materials like stainless steel. Also factors for the equipment erection, piping, instrumentation and control, electrical, civil, structures, building, lagging and paint work are available. This method is more separated. That way, it is easier to see which step is considered in the calculations. Additional to that, the offsite costs, design and engineering work as well as the contingency can be estimated separately to the capital costs with the factors given in appendix B. The equation for estimating the capital costs is as follows:

$$C = C_{e,i,CS} * ((1 + f_p)f_m + (f_{er} + f_{el} + f_i + f_c + f_s + f_l)) \quad (7)$$

C is the equipment and installation costs for the project but without engineering work offsite and design costs and the contingency. $C_{e,i,CS}$ is the cost for the equipment in carbon steel. And f_m is the material factor which is listed in appendix B as well as all the other factors (Towler and Sinnott 2013, 329–332).

3 Concepts

In this chapter the possible concepts for minimizing the waste of the desalination plant are shown and described. Here, the theoretical structure and functions are mentioned. The whole analysis and calculations for the concepts are shown in chapter 5 if the concept is selected by the scoring model in chapter 4.

3.1 First concept: Crystallizer directly on the solar concentrator

The first concept for a crystallizer which shall minimize the waste of the desalination plant is to put the crystallizer directly on the solar concentrator. That means, that the crystallizer is placed about four meters vertically above centre of the solar concentrator area. After the desalination process the high concentrated salt solution gets to the crystallizer which evaporates the water to minimize the volume of the waste. The product is crystallized salt with the ingredients of the used salt or industrial waste water.

The crystallizer is directly heated from the energy of the solar radiation. Hence, the focal point of the solar concentrator should be on the bottom of the crystallizer to make sure that the needed temperature will be reached. To find out whether the temperature at the focal point is high enough, the boiling point elevation and the resultant energy need must be compared with the energy of the solar radiation of a 36 m² area.

Important for a good heat transfer is the movement of the solution. For keeping the movement, the crystallizer could include a screw.

Another issue to preserve the heat transfer is the maintenance of the crystallizer. A layer of salt on the bottom of the crystallizer disturbs the heat transfer between the solution and the case of the crystallizer. To keep the heat transfer, the maintenance should be very simple because of that the crystallizer is designed as a simple cylinder which includes a maintenance flap to remove the salt easy and fast. The maintenance should be done each day. During this maintenance, the salt is collected and stored in a tank. Possibilities to treat the salt are mentioned in chapter 6.4.

Now, the physical part is described in a few very rough sentences. The physical idea is that the sun shall heat the salt solution above the boiling point of the solution. Here, it is

important to calculate the new boiling point of the solution. Like mentioned in chapter 2.2 the boiling point rises with one mole of a dissolved solid in the solution. In order to calculate the new boiling point, the dissolved solids in the water must be known. The elevation is calculated in chapter 5.1.

Figure 7 shows a very simple model of the first concept. The mirror area which is about 36 m² focus the shafts of sunlight to a little point on the bottom of the crystallizer. This called focal point provides the heat exchange from the sun to the solution.

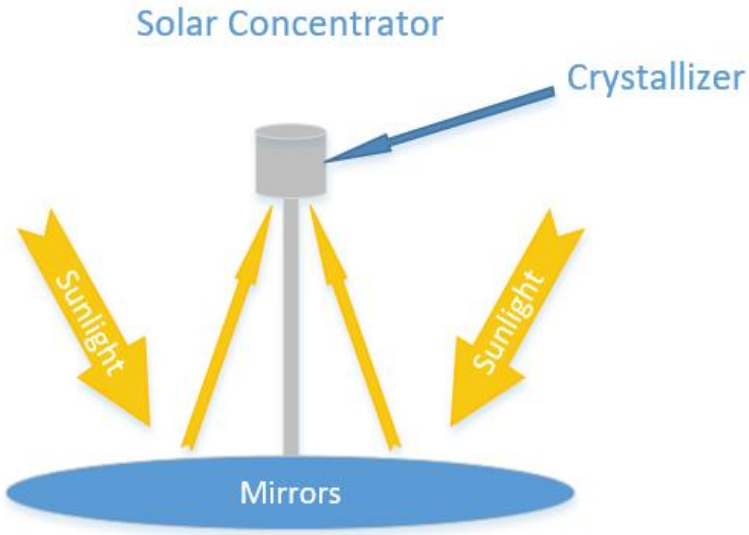

Figure 7: First concept: Crystallizer directly on the solar concentrator

3.2 Second concept: Collecting salt solution and use of a pan evaporator

The second concept consists of a very simple pan evaporator. The desalination plant is built like using the direct crystallizer but here, the waste of the process is collected by pipes from each solar concentrator. The salt solution is pumped into a big pan where the water can evaporate to the air. The pan is built like a rectangle and can be made of concrete. The aim is to have a large volume with a high area where the air is in contact with the salt solution.

For this concept a long pipeline system is needed, especially for big scaled plants. Furthermore, pumps are needed to transport the salt solution to the pan. It is important to use steel which is not vulnerable to corrosion because of the high concentration of salt.

The idea of using this principle of the evaporation is very old. It was, and it is still used to produce sea salt. The seawater is collected in huge ponds where it is kept for several days until the water is evaporated and the salt is left. In this concept, the idea is the same. The high salt solution is collected in a big pond(pan) and will stay there until the water is

left. After that only the solids of the saltwater are left over. The volume of waste is minimized and can be disposed cheaper and easier. The salt can be directly collected from the pan and can be stored in waterproofed tanks.

The advantage of this concept is the simplicity. In warm countries with high sunlight hours it should be possible to drive this concept without any extra energy. In countries with less sunlight there is the opportunity to use an electric heater so that the temperature of the solution is higher and equal to the evaporation rate.

Disadvantages of this concept are on the one hand the long pipeline system which is needed for the transport and on the other hand the inefficiency when the humidity of the air is quite high, and the sun is not shining. For example, when it is raining.

The size of the pan evaporator is connected to the size of the desalination plant and the evaporation rate of the water. After the evaporation rate and the volume flow of the desalination plant is calculated, the size could be estimated. Keeping a continuous production, two pan evaporators should be built. First, one pan is filled. After an estimated time, the pan is closed, and the other pan is started to fill up. During that time the water in the first pan will be evaporated and the pan can be cleaned until the other pan is loaded. After that it starts from the beginning.

Figure 8 represents the second concept. The blue quadrate illustrates the solar concentrator including the desalination application. The brown lines are the pipes which connect the desalination application with the pan evaporator (grey). This figure is a very simple visualization of this concept. The aim of it is only a better understanding of the idea.

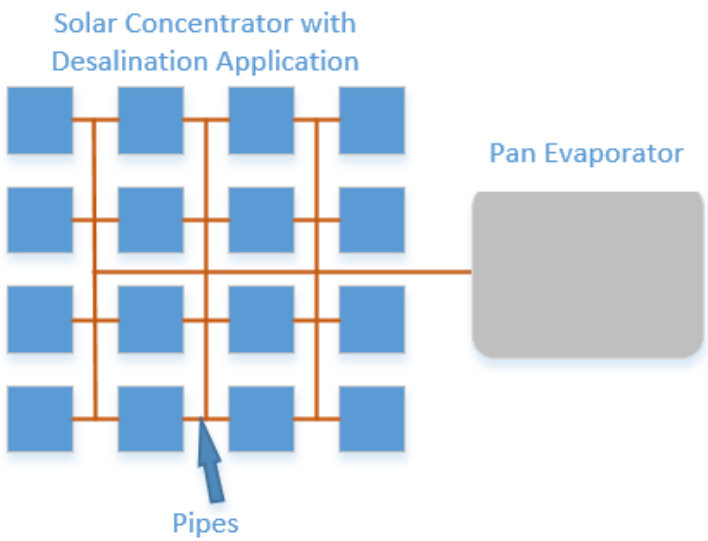

Figure 8: Second concept: Pan evaporator for the whole desalination plant

3.3 Third concept: Circulating-liquid evaporator-crystallizer

The third concept is using an industrial evaporator-crystallizer. This evaporator shall be integrated in the whole desalination plant. That means, there is one evaporator for the whole plant. Like for the second concept, there must be pipes and pumps which will transport the salt solution to the evaporator. Here, it is important to say that the evaporator works like a circulating-liquid evaporator and it is a single-effect continuous process. This type of evaporator needs an own energy source to heat the solution. At the figure, steam is used for that. However, there is no steam directly available during the desalination process which can be used for it. One opportunity is to produce it separately, this way more solar concentrators could be used to generate steam for the crystallization. Another opportunity is to use electricity to broil the solution. Electrical heating is combined with high costs whereas generating steam with solar concentrators would only increase the investment costs but not the operating costs. The continuous process is limited for the sunlight hours per day if steam is used. In the night it must be shut down or if there is still liquid waste left, the possibility of an electrical heater could be used.

The circulating-liquid evaporator works with a pump like pictured in figure 9. The pump circulates the liquid between the steam heater, the vapor space and the bed where the crystals can grow (Geankoplis, Hersl and Lepek 2018, Chapter 29.1D).

The structure of this evaporator compared to the pan evaporator or the direct crystallizer is quite complicated, but it can be compensated with lower maintenance and process time. Because of that the size of the evaporator can be estimated smaller than the size of the pan evaporator for example. Nonetheless, the investment costs are probably higher in comparison to the other concepts because of the complicity of this concept.

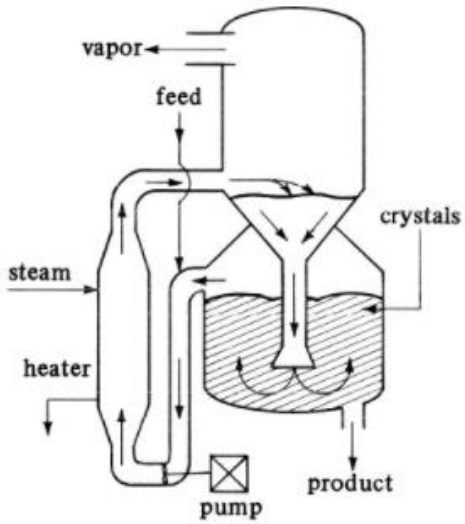

Figure 9: Circulating-liquid evaporator-crystallizer (Geankoplis, Hersl and Lepek 2018, 29.1D)

4 Scoring model of the concepts

The scoring model serves as a numerical process to compare the different concepts which are mentioned before. With the help of a points rationing scheme the concepts are analysed with different criteria. After that it is possible to make a statement which one is the most efficient and best to implement due to the score of the concept.

4.1 Criteria for concepts

The criteria are essential for the scoring model. They must be chosen to differentiate between the concepts. For this reason, the criteria must differ between itself to cover a large scale of possible differences.

Labour costs

Labour cost means the number of workers which are needed to drive the whole desalination plant. Included in that is the serviceability of the concept. Depending on the service time of the machine more workers are needed to do the work on time.

Investment costs

The investment costs include all the building and infrastructure costs for the concept. First, the machine itself but also kind of pipe systems or construction work to place the machines. The investment costs should be as low as possible to build such plants also in poor and dry countries.

Flexibility of energy source

This criterion is focused on the ability to change the energy source from the solar thermal power to any other one. For example, electricity or fossil fuels. That means if it is possible to include an electrical heater in the machine and use it if the sun does not shine. This could be important for days when the sun disappears during the process. To finish the process then, an electrical heater could be used.

Simplicity

Simplicity reflects the complicity of the concept. So, issues as, it is easy to build, only a few components are needed and the whole calculation is simple, are considered in this criterion. This is important if the desalination plant is built in a very small scale and in countries without funds to buy complex machines like Namibia or Kenya.

Required space

The larger the required area for the desalination plant the larger the costs. So, this criterion considers the amount of space. Construction size and additional needed solar concentrators are the main points of interest.

Maintenance costs

Maintenance costs mirror the costs of repairing damage. The components should be very simple to replace them cheap and fast. More complexity means higher maintenance costs and in worst case longer repairing time. It should be possible to buy the materials in the country where the plant is built, and they should be available fast and in large amounts in best case. The result of this could be low maintenance costs.

Process time

The process time of the crystallizer should be short to process the waste as fast as possible. Especially if the sun is used for powering the machine, the process should be done until the sun sets. It should be avoided that the salt solution must be stored. Storing tanks and other facilities must be built then and with that more costs appears.

4.2 Course of action

After naming the criteria they must be compared to each other to get the weighting of them. Here, it is done like shown in appendix C. Each criterion is compared directly to all others. If the criterion on the left side is more important than the other one on the top row it gets a “3”. If they are both as important as the other one, they are numbered with a “2” and if it is less important a “1” is used. After that the rows are summarized and the sum of the used points as well.

Now the weighting is calculated by dividing the points for each criterion by the sum of the total points. The results are listed in table 3 in per cent. Besides that, the points for each concept are mentioned. The points are awarded between one to ten. One is the worst number and ten the best. This model is highly affected by the own opinion of the person who does it, but it is good for the first part of a project and to select the concepts in the first part (Kühnapfel 2014, 14–19).

Table 3: Points for the concepts in the scoring model

Criteria	Weighting [%]	Concepts		
		Direct crystallizer	Pan evaporator	Industrial crystallizer
labour cost	16,7	3	5	7
investment costs	17,9	8	5	4
flexibility of energy source	8,3	1	1	8
simplicity	20,2	10	6	2
required space	10,7	3	5	7
maintenance cost	16,7	9	7	5
process time	9,5	7	1	8

Table 4 shows the results of the scoring model after the points of the concepts were multiplied with the weighting of each criterion and summarized to the numbers below. The concept with the highest number suits best. So, the selected concepts for the next chapters are the direct crystallizer and the industrial crystallizer. The whole table of the points for each concept and criterion is represented in appendix C.

Table 4: Results of scoring model

Direct crystallizer	Pan evaporator	Industrial crystallizer
652,4	482,1	529,8

5 Physical and thermodynamic analysis of the concepts

After the scoring model the concepts are analysed and calculated in a physical and thermodynamic way in this chapter. The crystallizer which is directly on the solar concentrator and the industrial crystallizer are mentioned. Important issues like the required energy or the scale of the crystallizer are estimated here. Therefore, the energy and mass balance of the processes are shown. Before that, the general topics which concern both concepts are determined.

Density of the solution

Starting with the density of the salt solution. The pre-existing property of the salt solution is, that it has a concentration of 200 $\frac{kg}{m^3}$. This value cannot be used to estimate the boiling point or the mass flow rate of the solution. The value which is important for the analysis is the mass fraction and the mass flow rate. For this it is necessary to approximate the

solutions density. In appendix D is a report for a density measurement of a 200 $\frac{kg}{m^3}$ concentrated and 20 °C tempered sea salt solution. This is the fastest and most exact way to get the value. Unfortunately, it is the wrong temperature. Better would be the temperature of its boiling point. Nevertheless, the final density of a 100 °C warm solution can be approximated with the help of Perry's and Green's (1997) tables of the density of an aqueous sodium chloride solution by different mass fractions. It is also listed in appendix D.

The resultant diagram of the table is shown in figure 10. For working with this diagram, the mass fraction must be calculated first with the density measurement of the experiment.

Mass fraction: $g = \frac{200000\frac{g}{m^3}}{1126{,}1\frac{kg}{m^3}}$ = 177,6 g(salt)/kg(solution) = 17,76 %

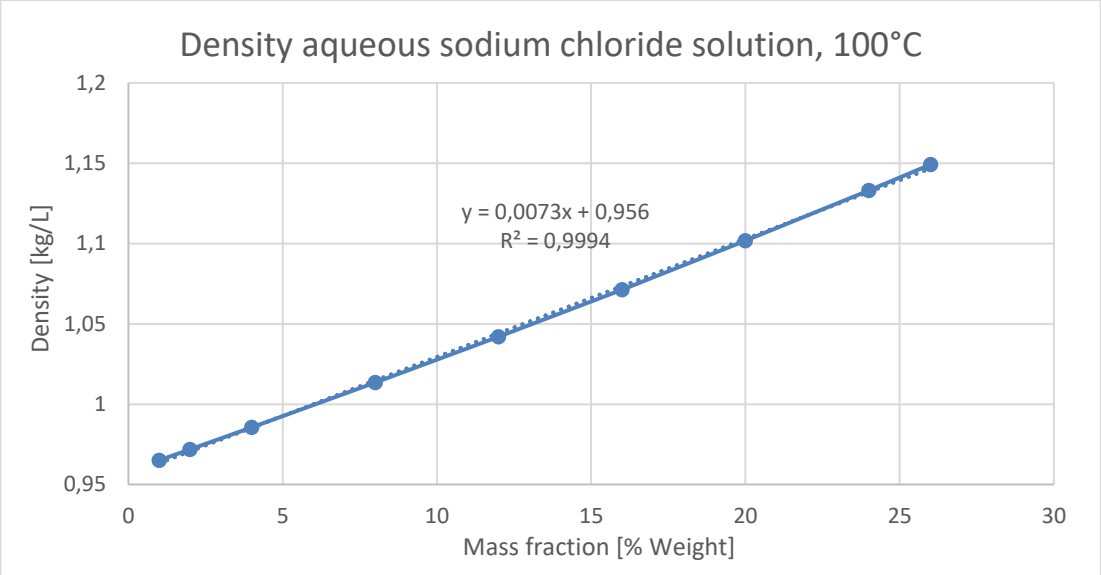

Figure 10: Density of aqueous sodium chloride solution with a temperature of 100 °C as a function of the mass fraction

Figure 10 shows a linear dependency and with the function $y = 0{,}0073 * x + 0{,}956$ the new density of the solution can be determined. After that the new mass fraction is calculated and again the new density with the old mass fraction. Between step 3 and 4 in table 5 is almost no more change of the density. The density value which is used in the following calculations has a value of 1,09 $\frac{kg}{l}$.

Table 5: Approximation results for the density of the aqueous sodium chloride solution

Step	Density (g = 17,76%) [kg/l]	Mass of solution [kg]	New mass fraction g (100°C and old density) [%]
1	1,0856	1,0856	18,42
2	**Density (g = 18,42 %) [kg/l]**		**g (100°C and old density) [%]**
	1,0905	1,0905	18,34
3	**Density (g = 18,34 %) [kg/l]**		**g (100°C and old density) [%]**
	1,0899	1,0899	18,35
4	**Density (g = 18,35 %) [kg/l]**		**g (100°C and old density) [%]**
	1,0900	1,0900	18,35

Boiling point elevation

The next property which should be calculated before the analysis of the concepts, is the boiling point elevation of a 200 $\frac{kg}{m^3}$ concentrated salt solution. Especially, for the energy balance the boiling point of the solution is very important. Here, it is separated in the boiling point of the entered solution and the boiling point of the saturated solution. After the saturation the boiling point does not increase because the maximum of dissolved solids is reached. In chapter 2.2 the compounds of the seawater and their relative portion are listed. Furthermore, the calculation of the boiling point elevation is shown in chapter 2.2 as well. The result of the density calculation which is shown earlier in this chapter is that the mass fraction of the salt solution entering the crystallizer has a value of 18,35 %. That is 183,5 $\frac{g(salt)}{kg(solution)}$. But for the boiling point elevation the value of the salinity is needed. The equation $\frac{1000g(Solvent)}{1-0,1835}$ estimates the mass of a solution with 1 kg of water included the salt. The result is that 224,74 g salt is dissolved in one kilogram water. Now, the mass per component can be estimated and thereby the elevation per component.

The mass per component is the relative portion of each component multiplied with the total mass of dissolved solids. The results are listed in table 6. The elevation is calculated as follows for the component chloride with the equation 1:

$$\Delta T_b = 0{,}512 \frac{K * kg}{mol} * \frac{\left(\frac{123{,}71 g}{35{,}453 \frac{g}{mol}}\right)}{1\ kg} = 1{,}79\ K$$

Here, the molality is replaced with the amount of substance divided by the mass of solvent and the amount of substance is determined with the mass of the substance divided by the molar mass.

The overall elevation is the sum of the single elevations. Table 6 shows the elevation per component and the overall elevation. On top of that there is the comparison with a pure sodium chloride solution. The difference between these two values is only 0,28 K. So, it is proved, that the difference between the salt water and a sodium chloride solution has an acceptable magnitude. Nevertheless, the following determinations are done with a boiling point of 103,66 °C for the salt solution which enters the crystallizer.

Table 6: Boiling point elevation of the salt solution entering the crystallizer

Component		Molar Mass [g/mole]	Relative portion in seawater [-]	Mass [g]	Elevation [K]
Chloride	**Cl**	35,453	0,550	123,71	1,79
Sodium	**Na**	22,99	0,306	68,80	1,53
Sulphate	**SO4**	96,065	0,077	17,26	0,09
Magnesium	**Mg**	24,305	0,037	8,29	0,17
Calcium	**Ca**	40,078	0,012	2,61	0,03
Potassium	**K**	39,098	0,011	2,48	0,03
Bicarbonate	**HCO3**	61	0,004	0,91	0,01
Bromide	**Br**	79,904	0,002	0,42	0,00
Boric acid	**H3BO3**	61,8	0,001	0,17	0,00
Strontium	**Sr**	87,62	0,0004	0,087	0,00
Fluoride	**F**	18,988	0,00004	0,008	0,00
Sum					**3,66**
Sodium Chloride	**NaCl**	58,45	1	224,74	**3,94**

For the boiling point elevation of the saturated salt solution it is assumed that the salt consists only of sodium chloride. This simplicity is chosen because every salt has its own solubility thereby it would be difficult to estimate the exact mass of ions which are dissolved in the solution. Moreover, sodium chloride has a relative portion of 85,6 %. The other elements have not a very high influence on the elevation like it is shown by the low elevation difference of 0,28K. For this application it is exactly enough to calculate with 100 % sodium chloride. The saturation of sodium chloride in water at a temperature of 100 °C is 39,2 $\frac{g(NaCl)}{100g(water)}$ (Binnewies, et al. 2016, 928). The result of the elevation of a

saturated sodium chloride solution is 6,87 K. Here, it is important to multiply the equation of the boiling point elevation by two because Na^+ and Cl^- are dissolved in the water. So, the double number of ions are rising the boiling point. The resultant boiling point at atmospheric pressure is 106,87 °C.

Solar radiation

The following topic is the solar radiation which represents the used energy in this work. To mention any usable and real solar radiation data a place in Namibia is chosen. On the part of *Solar Fire Concentration Oy*, the place is not more concretized so, the place is selected spontaneous and not considered to any real project. To keep it realistic, a free area close to Windhoek is picked. There the needed infrastructure, possible consumer of fresh water and industry who could provide the desalination plant with contaminated water are available. Beyond that, the needed data is available for this place.

To make a statement of the possibility to implement the concepts, the needed energy must be compared with the available energy which comes from the sun. Like mentioned in chapter 2.1, solar concentrators can only collect direct solar irradiance. Hence, it is important to consider only this one instead of the global irradiance which consist also of a diffuse irradiance part. In appendix E is the irradiance data of the selected area listed. One datasheet is about the month with the highest average direct irradiance and one sheet about the lowest average direct irradiance. Namibia is placed on the southern hemisphere, so, October is the month with the highest irradiance and June with the lowest. In October the highest value of direct irradiance is 879 $\frac{W}{m^2}$ at UTC time of 09:45 which is 10:45 local time. In June at UTC time 10:45 the direct radiation has its highest value of 635 $\frac{W}{m^2}$. These values are results of calculations of the interactive tool of the *Photovoltaic Geographical Information System* (European Union, Photovoltaic Geographical Information System 2017). Mostly, the used data comes from geostationary meteorological satellites and they are using data of the atmosphere to calculate the solar radiation at ground level of the earth (European Union, Overview of PVGIS data sources and calculation methods 2017). Furthermore, it is important to say, that the values are only averaged. On top of that they have a high fluctuation due to weather conditions like cloudy or sunny days. The value can be lower or even higher than the mentioned numbers.

Nevertheless, it is possible to determine the available thermal output now. One solar concentrator has a mirror area of 36 m². For the month with the highest irradiance the maximum thermal output can be up to:

$$\dot{Q} = 879\frac{W}{m^2} * 36m^2 = 31644\ W = 31{,}6\ kW$$

For the month with the lowest value the thermal output can be 22,9 kW. In this work these values are accepted as the thermal output of the solar concentrators for the location in Namibia. For more precise values the commercial providers *SolarGIS* or *Meteonorm* could be used to get more accurately measurements of the solar irradiance.

5.1 Crystallizer directly on the desalination application

The first concept which will be analysed is the crystallizer which works directly with the solar concentrator. Like described in chapter 3.1 the idea is to crystallize the salt in a cylindrical container which is four meters above the centre of the mirror area. Now the question is, whether the solar concentrator can focus enough solar thermal energy to evaporate the whole water from the salt solution.

In a desalination plant a continuous fresh water production can only occur if one part of the solar concentrators works with the desalination application and the other part with the crystallizer. The idea is to evaporate the water of the salt solution simultaneous to the desalination process.

Like mentioned in chapter 1.1, the crystallizer should have a diameter between 30 and 50 cm. Besides that, the crystallizer is opened on its top so that the water can evaporate to the air. The volume of the crystallizer is defined with 120 litres. This volume should be big enough to carry the solids of one day. The water evaporates continuously only the solids will be left. For the volume estimation, the daily working time of the solar concentrator is fixed with 6 hours and the density of the salt, here for simplicity considered as sodium chloride, is 2170 $\frac{kg}{m^3}$ (National Center for Biotechnology Information n.d., 4.2.7). 6 hours multiplied with 40 $\frac{kg(salt)}{h}$ is 240 kg salt per day. Divided by 2170 $\frac{kg}{m^3}$ is a volume of 0,11 m³. So, the crystallizer should have a volume of 0,11 m³ to carry the salt of one day. Of course, the volume of the crystallizer should be much bigger to carry the salt and to keep a simultaneous mixing of the solution. But it must be considered, that the amount of 240 kg salt is the absolute maximum at one day. The solar radiation fluctuates and has its maximum only for a short time. Therefore, the constantly evaporation of 0,2 $\frac{m^3}{h}$ and thus a production of 40 $\frac{kg}{h}$ salt cannot be reached anyway. Consequently, the volume for the next calculations is fixed by 0,12 m³. With this volume the height (*H*) is calculated for three different diameters. This is important to have a comparison of the heat transfer

area and how this affects the crystallizer. The following equation shows the volume of the crystallizer (0,12 m³)

$$H_1 = \frac{0{,}12\ m^3}{\pi * (0{,}15\ m)^2} = 1{,}70\ m$$

$$H_2 = \frac{0{,}12\ m^3}{\pi * (0{,}2\ m)^2} = 0{,}96\ m$$

$$H_3 = \frac{0{,}12\ dm^3}{\pi * (0{,}25\ m)^2} = 0{,}61\ m$$

The actual crystallization process shall work in batch to keep a simple design. The salt solution should enter the crystallizer continuously, but the output is not collected until the evaporation is done. Therefore, the size of the crystallizer is getting very big and a manual removable version by a labourer is impossible. Nonetheless, the maintenance shall be very simple to have low labour costs. For this the crystallizer shall contain a maintenance flap. After the process the labourer can open the flap and collect the salt from the crystallizer manually. The salt is collected and can be treated in different ways to be more economical.

The transportation between the desalination application and the crystallizer could work with a pipe system so that the salt solution can be pumped continuously to the crystallizer. Important for that are short ways to keep the material costs and the heat losses during the transportation low. Let's assume that each desalination process needs its own crystallizer. So, the modules should stand directly side by side to have short pipe ways.

According to Mersmann, Kind and Stichlmair (2005, 423), the movement of the solution during the evaporation must be ensured. No movement means that the salt will accumulate at the heat transfer area of the crystallizer and that stands for a worse heat transfer. To prevent the accumulation a screw is placed from the top into the crystallizer. The design should imply a fixture for the engine of the screw. For the dimensioning a specific power of the screw of 0,5 $\frac{W}{kg}$ is accepted (Mersmann, Kind and Stichlmair 2005, 477).

The focus of this work is on the economical and physical point of view because of that the design is not more detailed and shown. For example, the design of the maintenance flap must consider that the flap must be waterproofed, and the heat losses are not rising compared to the rest of the wall.

5.1.1 Energy and mass balance

In figure 11 the energy and mass balance are shown for this concept. Feed represents the high concentrated salt solution from the desalination process. Vapor is the evaporated

water during the process. In optimum conditions this is the mass water which enters the crystallizer to the salt solution. Solids are the crystallized salt. Same as the vapor, in optimum conditions salt is the mass solids which arrives the process to the salt solution. The energy and mass balance are important to figure out the needed heat flow which is represented by $\dot{Q}$. After this it is possible to compare it with the provided energy from the sun.

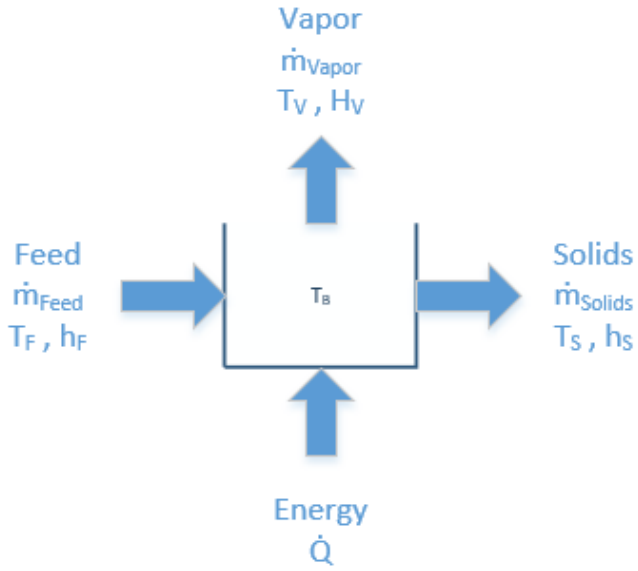

Figure 11: Energy and mass balance of the direct crystallizer

In chapter 1.1 the values of the desalination process and the values of the crystallizer are mentioned. For the analysis the higher values are considered for reaching a validation for the whole scale.

Mass balance

Pre-existing values are: $c_{Solids} = 200\ \frac{kg}{m^3}$; $\dot{V}_{Feed} = 0{,}2\ \frac{m^3}{h}$

$$\text{Mass balance: } \dot{m}_{Feed} = \dot{m}_{Vapor} + \dot{m}_{Solids} \tag{8}$$

First, $\dot{m}_{Solids}$ is calculated with the equation:

$$\dot{m}_{Solids} = c_{Solids} * \dot{V}_{Feed} = 200\ \frac{kg}{m^3} * 0{,}2\ \frac{m^3}{h} = 40\ \frac{kg}{h} \tag{9}$$

Here, c_{Solids} is the concentration of the salt solution which enters the crystallizer. This is multiplied with the flow rate of the input.

$\dot{m}_{Feed}$ can be estimated with $\dot{V}_{Feed}$ and the density of the solution. To get the density of the salt solution which enters the crystallizer, the density of a 200 $\frac{kg}{m^3}$ concentrated salt solution at a temperature of 20°C was measured. But for the following calculations the density of a boiling salt solution with 200 $\frac{kg(salt)}{m^3}$ is needed. The measurement and the

approximation of the density is shown in a previous section and in appendix D. The density is approximately 1090 $\frac{kg}{m^3}$ at a temperature of 100°C.

$$\dot{m}_{Feed} = \dot{V}_{Feed} * \rho = 0{,}2\frac{m^3}{h} * 1090\frac{kg}{m^3} = 218\frac{kg}{h} \tag{10}$$

The result of that is, that the mass flow of the solvent and the vapor is

$$\dot{m}_{Vapor} = \dot{m}_{Feed} - \dot{m}_{Solids} = 218\frac{kg}{h} - 40\frac{kg}{h} = 178\frac{kg}{h} \tag{11}$$

For this special case it is simplified assumed that $\dot{m}_{Vapor} = \dot{m}_{Solvent}$. All the water (solvent) shall be evaporated during the process and no salt leaves the crystallizer by the vapor.

Energy balance

$$\dot{Q} + \dot{m}_{Feed} * h_F = \dot{m}_{Vapor} * h_V + \dot{m}_{Solids} * h_S + \dot{m}_{Solids} * \Delta h_c + \dot{Q}_L \tag{12}$$

Here, $\dot{Q}$ represents the needed heat flow, h_F is the enthalpy of the input, h_V of the vapor which leaves the crystallizer, h_S the enthalpy of the crystals and Δh_c the enthalpy of crystallization. The last value, $\dot{Q}_L$, are the heat losses.

First of all, it is important to know the temperatures of the different components for calculating the enthalpies. It is accepted, that the salt solution (Feed) enters the crystallizer with its boiling temperature of 103,66 °C and will not lose any heat during the transportation. The temperature of the vapor and the solids are the same. It is the temperature of the boiling point of the saturated salt solution. Like described earlier, the boiling point elevation is 6,87 K so, the temperature is 106,87 °C.

Enthalpies

Now, the enthalpies of the different components are estimated. Beginning with the enthalpy of the feed.

$$h_F = c_{p,F} * \Delta T = 3{,}61\frac{kJ}{kg * K} * 103{,}66\ K = 374{,}21\frac{kJ}{kg} \tag{13}$$

At this point, $c_{p,F}$ is the specific heat capacity of the solution. For simplicity and adequate accuracy for this case the heat capacity is calculated with the mass fraction of sodium chloride and water, multiplied with their respective heat capacities. The heat capacity of sodium chloride is 0,8699 $\frac{kJ}{kg*K}$ (Korth Kristalle GmbH 2018) at a temperature of 0 °C and of water at 103,66 °C it is approximately 4,22 $\frac{kJ}{kg*K}$ (VDI-Gesellschaft 2013, 178).

$$c_{p,F} = 0{,}1835 * 0{,}8699 \frac{kJ}{kg * K} + (1 - 0{,}1835) * 4{,}22 \frac{kJ}{kg * K} = 3{,}61 \frac{kJ}{kg}$$

The next value is the enthalpy of the vapor (h_V). This is normal saturated water vapor. With the help of the steam table the enthalpy can be determined. It is 2685,29 $\frac{kJ}{kg}$ at a temperature of 106,87 °C (VDI-Gesellschaft 2013, 178).

The enthalpy of the sodium chloride crystals is calculated also with the equation 13. But instead of the heat capacity of the solution, the heat capacity of sodium chloride is used.

$$h_S = c_{p,S} * \Delta T = 0{,}8699 \frac{kJ}{kg * K} * 106{,}87\ K = 92{,}97 \frac{kJ}{kg}$$

In very simple words, the enthalpy of crystallization (h_c) is the negative value of the enthalpy of solution. This one is the difference between the heat of formation of the solid state and the aqueous state. Because sodium chloride dissolves in water and here, energy is released while the salt is burst in the ions Na^+ and Cl^-. The statement that energy is needed can be proved with the following equation (Lucas 2008, 217, 218). The heat of formation of the aqueous sodium chloride is -97,324 $\frac{kcal}{mole}$ (is equal to -407,20 $\frac{kJ}{mole}$) and of the solid one -98,321 $\frac{kcal}{mole}$ (is equal to -411,38 $\frac{kJ}{mole}$) (Perry and Green 1997, 2-193).

$$\Delta H_s = -407{,}20 \frac{kJ}{mol} - (-411{,}38) \frac{kJ}{mol} = 4{,}18 \frac{kJ}{mol}$$

$$\Delta H_c = -\Delta H_s = -4{,}18 \frac{kJ}{mol}$$

The algebraic signs show that energy is needed to dissolve the sodium chloride and energy is released while the sodium chloride crystallizes. For the energy balance the specific enthalpy of crystallization is needed. So the molar enthalpy divided by the molar mass is equal to the specific enthalpy: $\Delta h_c = \frac{\Delta H_c}{M} = \frac{-4{,}18 \frac{kJ}{mol}}{0{,}05845 \frac{kg}{mol}} = -71{,}48 \frac{kJ}{kg}$. (14)

Heat losses

The last point of the energy balance are the heat losses of the system. Heat losses appears from the wall of the crystallizer to the air. Without any insulation the temperature of the wall can be assumed with approximately 106,87 °C. Heat transfer mechanisms have already been described in chapter 2.3.2. So, convection is one of the reasons for heat losses. Here, if moving or still air is around the application depends on the weather. And this is already one reason why the estimation of heat losses is quite difficult and not exact. It is combined with huge fluctuation which cannot be estimated in all its range. Nonetheless, should it be considered to some degree. Geankoplis, Hersl and Lepek (2018) says that the convective heat-transfer coefficient (h) is approximately 55 $\frac{W}{m^2 * K}$ for moving air and 23

$\frac{W}{m^2 * K}$ for still air (Geankoplis, Hersl and Lepek 2018, 12.4B). For the calculation, the value for moving air is used because it is higher. Therefore, the heat losses are higher which covers then the worst case. The area A is the circumference area of the crystallizer. And t_w, t_a mirrors the assumed wall temperature of the crystallizer and the air temperature. Exemplarily determined for a crystallizer diameter of 50 cm. The area is $A = 2 * \pi * 0{,}25\ m * 0{,}611\ m = 0{,}96\ m^2$ and the following formula is based on the equation 4.

$$\dot{Q}_L = h * A * (t_w - t_a) = 0{,}055 \frac{kW}{m^2 * K} * 0{,}96\ m^2 * (106{,}87 - 15)\ K = 4{,}85\ kW$$

This estimation is done for a day with 15 °C air temperature. And table 7 shows the heat losses for larger crystallizers with smaller diameters.

Table 7: Scale and heat losses of the direct crystallizer

D [m]	H [m]	A [m²]	$\dot{Q}_L$ [kW]
0,3	1,7	1,60	8,1
0,4	0,96	1,21	6,1
0,5	0,61	0,96	4,85

Besides that, there are more potential heat losses. The surface of the focal point is getting very hot. The heat loss potential is quite high because the temperature difference between the surface and the air is high. Right now, the temperature of the focal point is unknown. Therefore, this will not be considered here.

Now, equation 12 can be changed to the following equation:

$$\dot{Q} = \dot{m}_{Vapor} * h_V + \dot{m}_{Solids} * h_S + \dot{m}_{Solids} * h_c + \dot{Q}_L - \dot{m}_{Feed} * h_F \qquad (15)$$

$$\dot{Q} = 178 \frac{kg}{h} * 2685{,}29 \frac{kJ}{kg} + 40 \frac{kg}{h} * 92{,}97 \frac{kJ}{kg} + 40 \frac{kg}{h} * (-71{,}48) \frac{kJ}{kg}$$
$$+ (4{,}85 * 3600) \frac{kJ}{h} - 218 \frac{kg}{h} * 374{,},21 \frac{kJ}{kg} = 414723{,}44 \frac{kJ}{h}$$
$$= 115{,}2\ kW$$

The required energy for evaporating the whole water is 115,2 kW. Now, it is interesting to know which temperatures are needed to achieve this performance. The heat transfer area is quite small, and the salt layer could cause problems after a while. So, the next section is considering the heat transfer through the crystallizer wall.

Heat transfer

The heat transfer is important for calculating the temperatures which must be reached to achieve the determined performance.

First, there is a kind of conduction from the outside to the inside surface of the wall. After that it continuous with the convection from the inside surface to the solution. But the only

temperature which is known right now, is the solution temperature of 106,87 °C. So, the first calculation is the convection from the inner surface to the solution. The theory and the equation are already mentioned in chapter 2.3.2. For the equation the values have already been specified in the previous section. But additional to the information above, it is important to know that the convective heat-transfer coefficient (*h*) includes a lot of different properties of the system, like the geometry of the application, fluid properties, flow velocity and temperature differences during the process (Geankoplis, Hersl and Lepek 2018, 12.4). For not doing it too complicated, *h* is chosen from a table by Geankoplis, Hersl and Lepek (2018, 12.4). For boiling liquids *h* is between 1.700 to 28.000 $\frac{W}{m^2K}$. The estimation is done with 1,7 $\frac{kW}{m^2K}$. The energy flow can be looked up in the earlier section and the heat-transfer area is the surface from the bottom of the crystallizer: $A = \pi * r^2$. The equation 4 for calculating the convection (section 2.3.2) is reformed as follows:

$$\Delta T = \frac{\dot{Q}}{h * A} = \frac{115{,}2\ kW}{1{,}7\,\frac{kW}{m^2K} * 0{,}196\ m^2} = 345{,}74\ K \tag{16}$$

In table 8 the heat difference values for the different scales of the crystallizer are shown. With them it is possible to estimate the temperature of the inner surface. The result of adding 106,87 °C to the heat difference is the surface temperature which is needed to transfer the energy to the solution.

Table 8: Convective heat transfer results for the direct crystallizer

D [m]	A [m²]	ΔT [K]	t [°C]
0,3	0,071	958,7	1065,5
0,4	0,126	539,3	646,1
0,5	0,196	345,7	452,6

After that the heat difference between the outer and inner surface of the heat-transfer area can be estimated. The mechanism is called conduction and it depends on the thermal conductivity of the material. The equation 3 for the conduction is reformed as follows:

$$\Delta T = -\frac{\dot{Q} * \Delta x}{\lambda * A} = \frac{115{,}2\ kW * 0{,}003\ m}{0{,}0211\,\frac{kW}{mK} * 0{,}196\ m^2} = -83{,}4\ K \tag{17}$$

Here, *Δx* is the thickness of the material. The material is chosen from *Solar Fire Concentration Oy* and it is called Lean Duplex Stainless Steel. $\dot{Q}$ and *A* is the same as earlier and *λ* is the thermal conductivity of the material. For *Lean Duplex Stainless Steel 2304* it is 21,1 $\frac{W}{m*K}$ at a temperature of 500 °C (Action Stainless KwaZulu Natal 2018). The algebraic sign is only for the direction of the heat transfer and it means, that the temperature

decreases from the outer to the inner surface. Table 9 shows the results for the different scales.

Table 9: Conduction heat transfer results for the direct crystallizer

D [m]	A [m²]	ΔT [K]	t [°C]
0,3	0,071	-231,7	1297,3
0,4	0,126	-130,3	776,5
0,5	0,196	-83,4	535,4

Consequently, the temperature at the focal point should be 535,4 °C minimum.

But here it must be considered that one solar concentrator cannot reach a thermal power of 115,2 kW. So, the heat transfer and the resultant temperatures should also be calculated for the possible generated thermal power of 31,6 kW. The results for that are listed in table 10. It is shown that the focal temperature for a 30 cm diameter application is under 600 °C. So, it would be also possible to build the application with this size.

Table 10: Heat transfer results for one solar concentrator with a thermal power of 31,6 kW

Convection			
D [m]	A [m²]	ΔT [K]	t [°C]
0,3	0,071	263,0	369,8
0,4	0,126	147,9	254,8
0,5	0,196	94,7	201,5
Conduction			
0,3	0,071	-63,6	433,4
0,4	0,126	-35,8	290,5
0,5	0,196	-22,9	224,4

5.1.2 Conclusion

In this section the concept is evaluated, and possible improvements or changes are mentioned and discussed.

The idea to design a crystallizer and put it just above the centre of the mirrors, sounds very simple and easy to implement. But in reality, it is not that basic. A lot of circumstances must be considered, and the problem is, that a lot of them cannot be calculated like they really are. The density or the heat capacity of the salt solution for example. Furthermore, the weather conditions are fluctuating and can change every day. Here, things can be determined for good or even optimal conditions but if there is a year with a lot of rainy days everything changes, and the calculations are not authentic. Nevertheless, it is important to start with a set point even though if there must be made some simplicities for striking a statement.

The values which could be imprecise are the heat losses for example. Only the heat losses due to the wall of the crystallizer are considered. Possible further heat losses could arise

at the bottom of the crystallizer. The focal surface is getting very hot. So, the temperature difference between the air and the focal surface are very high and heat losses to the air appears. In addition, the heat losses to the wall could be higher than estimated. Since the temperature of the wall could be higher than the fluid temperature because the very high temperatures of the focal point at the bottom of the crystallizer could heat the whole application most likely above the boiling point. But in this work, it is assumed to be exactly enough if the heat losses are approximated in a realistic degree like it has been done here. Because of this calculation it can be said that an insulation around the crystallizer would be helpful to increase the energy efficiency.

The overall heat flow is calculated with 115,2 kW. This can be compared to the thermal performance of the sun. The result of this during the best month and a mirror area of 36 m² is 31,6 kW. The difference between the available and needed thermal power is -83,6 kW. So, one solar concentrator cannot supply enough energy to achieve the crystallization of an input of 200 $\frac{L}{h}$ salt solution. Four solar concentrators are needed to accomplish the process. One assumption out of it could be, that the output of the desalination application is not realistic. Because the desalination process needs even more energy to distil 4000 $\frac{L}{d}$ than the crystallizer and the maximum available energy of one solar concentrator is only 31,6 kW. Unfortunately, there are no more public properties available about the desalination application. So, it is not possible to validate the data which are mentioned in table 1. The proportion of one desalination application to four crystallizers seems out of scale. Especially because the aim of the plant is generating fresh water and not salt. However, the investment could be still rentable. Options to change the rate could be to reduce the input to the desalination application. The result would be also a decreasing of the input to the crystallizer. So, if the reduction was a fourth to the beginning, only one solar concentrator could evaporate the waste. Ultimately, the production of fresh water and salt decreases as well. The right balance of the parameters is important.

Another change could be to increase the mirror area. So, that only two solar concentrators are needed to get a thermal output of 115,2 kW. The mirror area per solar concentrator must be approximately 65,5 m² or the evaporation rate could be decreased. That means, not the whole water is evaporated but only a part of it. The disadvantage is, that the waste is not minimized and there is still water left in the salt solution.

Nonetheless, the economic analysis in chapter 6 considers the estimated rate of one desalination application to four crystallizers. This seems economically possible because the solar concentrators are made from cheap and easy available materials.

In the end, the input to the crystallizer must be reduced to circa a fourth of the previous value anyway. With this decrease, the size, the heat losses and the needed temperatures are changing. In table 8 and table 9 are the temperatures due to convection and conduction mentioned for a thermal power supply of 115,2 kW. Since one solar concentrator cannot reach such a supply, table 10 shows the required focal temperatures for a thermal power of 31,6 kW. The highest temperature is 433,4 °C by a diameter of 30 cm. The result is that the critical temperature for the material (Lean Duplex Stainless Steel) of 550 °C (Action Stainless KwaZulu Natal 2018) and the possible focal temperature of the solar concentrator of 600 °C is not reached. The crystallizer can be built with a diameter of 30 cm. The resultant height with a volume of 40 dm^3 is than 0,57 m. With 40 dm^3 there is still enough space left in the end of a day to mix the salt.

5.2 Circulating-liquid evaporator-crystallizer

This chapter focuses on the thermal and physical analysis of the second concept. This concept considers an industrial evaporator. The idea has already been described in chapter 3.3. The used evaporator should be a forced circulating-liquid evaporator like shown in figure 9. Additionally, there could be a solid-liquid separator which selects the salt crystals out of the solution. After that the crystals can be dried to minimize the humidity and the weight of them (Wankat 2016, 17.1.1). After the separation the solvent can enter the crystallizer again to the feed flow. In theory, this can be done until no solvent is left. For the lay out design it is assumed that the solvent is completely evaporated during the process. In real cases, the solids must be dried after the process to get a product without any solvent in it.

According to Geankoplis, Hersl and Lepek (2018) this type of evaporator is quite good for viscous liquids. Which will be the salt solution after the salt starts to crystallize. Due to the forced circulation the heat-transfer coefficient is kept high (Geankoplis, Hersl and Lepek 2018, 32.2A). Thereby, heat losses are less because the temperature can be lower. The energy source should be steam which can be generated by solar concentrators. Thus, the energy costs are zero but instead of that, costs for the investment and labour appears to implement the additional solar concentrators. Furthermore, this concept needs a more complicated infrastructure. This consists of pipe systems from the desalination application to the evaporator and a second pipe system from the steam generating solar concentrators to the evaporator. Nonetheless, only one evaporator is used for a whole desalination plant and especially for big scaled plants it could be an efficient solution.

For the dimensioning the key values are the mass flow rate of the feed, the vapor and the solids. Everything of it is the same like in chapter 5.1. The evaporator should work in a continuous process. That means, that the whole waste enters the crystallizer directly from the desalination application. Here, it must be considered, that the size of the evaporator changes with the scale of the desalination plant. So, every calculation must be made for each scale. To get reliable results the scale of the desalination plant is defined in one, ten, 30, 50 and 100 desalination applications. The whole desalination plants are even bigger because of the needed extra solar concentrators to generate the steam or to drive the direct crystallizers.

Subsequently, the energy and mass balance of the industrial evaporator is mentioned.

5.2.1 Energy and mass balance

Figure 12 shows the balances of the industrial crystallizer. The vapor, feed and the solids represent the same parameters like in the chapter above. The main differences are “steam in” and “condensate out”. This is the energy source which heats up the salt solution in an extra heat exchanger. The energy difference between the steam and condensate is the heat flow to the salt solution ($\dot{Q}$). The steam is saturated water vapor at atmospheric pressure and the mass flows are changing depending on the scale of the desalination plant. Calculation examples are done for one desalination application. The results for more applications are shown in table 11.

With the help of the mass and energy balance it should be possible to determine how many solar concentrators are needed to generate the required amount of steam. Furthermore, the size of the crystallizer, and the needed heat-transfer area can be estimated.

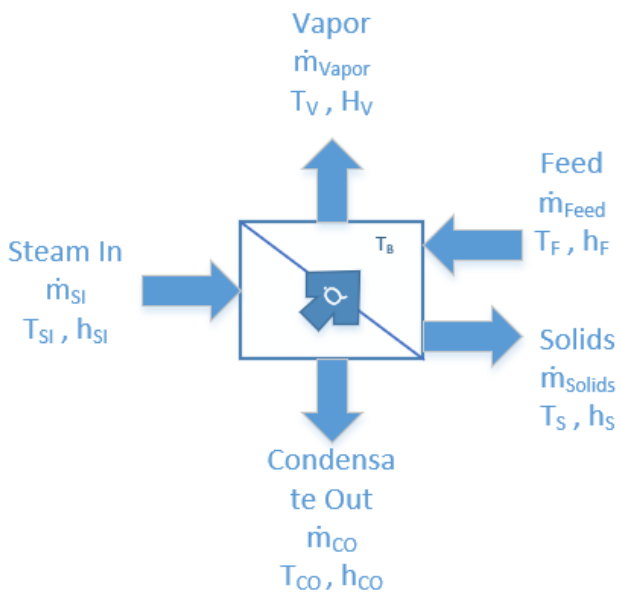

Figure 12: Energy and mass balance of the industrial crystallizer

Mass balance

Here, there are two different mass and energy balances. One for the side of the steam and one for the salt solution.

The mass balance of the salt solution is shown in chapter 5.1.1. The results for the different scales are listed in the following table.

Table 11: Mass flows of the industrial crystallizer salt solution-sided

Scale	$\dot{m}_{solids}$ [kg/h]	$\dot{m}_{feed}$ [kg/h]	$\dot{m}_{vapor}$ [kg/h]
1	40	218	178
10	400	2180	1780
30	1200	6540	5340
50	2000	10900	8900
100	4000	21800	17800

The mass balance steam-sided is quite simple but cannot be calculated right now.

$$\dot{m}_{SI} = \dot{m}_{CO} = \dot{m}_{Steam} \tag{18}$$

Energy balance

The salt solution-sided energy balance is the same as equation 12:

$$\dot{Q} + \dot{m}_{Feed} * h_F = \dot{m}_{Vapor} * h_V + \dot{m}_{Solids} * h_S + \dot{m}_{Solids} * \Delta h_c + \dot{Q}_L$$

The only difference in the energy balance compared to the direct crystallizer are the heat losses. This should be higher than the heat losses from the direct crystallizer. Because additional to the heat losses through the wall, the pipes are being prone to lose energy. Although, they have mostly a good insulation. Besides that, the peripheral area of the heat exchanger plus the crystallizer is larger than of the direct crystallizer. All in all, the heat losses cannot be calculated exactly because not even the dimension of the crystallizer is known. Therefore, the heat losses are assumed as nearly big as the heat losses from the direct crystallizer. So, $\dot{Q}_L$ = 5 kW.

$$\dot{Q} = \dot{m}_{Vapor} * h_V + \dot{m}_{Solids} * h_S + \dot{m}_{Solids} * h_c + \dot{Q}_L - \dot{m}_{Feed} * h_F$$
$$= 115{,}35\ kW$$

With a required heat flow of 115,35 kW, the mass flow of the steam can be determined. In addition, the heat flow, the enthalpy of saturated water vapor and boiling water are needed.

The enthalpy of the saturated steam which enters the crystallizer (h_{SI}) is equal to 2724,7 $\frac{kJ}{kg}$ and the enthalpy of the condensate (h_{CO}) is equal to 561,43 $\frac{kJ}{kg}$. These values are collected from the steam table at 3 bars. The resultant boiling point of water at 3 bars is 133,54 °C (Siemens Building Technologies 1998). A pressure of 3 bars is necessary to

have a temperature difference between the saturated salt solution (boiling point 106,78 °C) and the steam respectively the condensate.

Steam-sided energy balance:

$$\dot{m}_{Steam} * h_{SI} = \dot{Q} + \dot{m}_{Steam} * h_{CO} \tag{19}$$

$$\dot{m}_{SteamR} = \frac{\dot{Q}}{(h_{SI} - h_{CO})} = \frac{(115{,}35 * 3600)\frac{kJ}{h}}{(2724{,}7 - 561{,}43)\frac{kJ}{kg}} = 192\frac{kg}{h} \tag{20}$$

Equation 20 shows the determination of the required steam flow to the crystallizer. So, 192 $\frac{kg}{h}$ steam is needed to transfer the heat flow of 115,35 kW. The equation is formed by the energy balance of equation 19.

Now, the steam generation per solar concentrator is calculated. The thermal output of one solar concentrator is 31,6 kW. Equation 20 can be used again. The condensate and the solar thermal power enters the evaporator and steam comes out.

$$\dot{m}_{SteamA} = \frac{\dot{Q}}{(h_{SI} - h_{CO})} = \frac{(31{,}6 * 3600)\frac{kJ}{h}}{(2724{,}7 - 561{,}43)\frac{kJ}{kg}} = 52{,}59\frac{kg}{h}$$

The result is an available steam flow for one solar concentrator of 52,59 $\frac{kg}{h}$.

The calculations are done for the smallest scale. Therefore, table 12 represents the results of the required steam flow for different scales of a desalination plant. The needed thermal output increases with the number of the used desalination applications, so do the required steam.

Table 12: Results of the required steam flow for an industrial crystallizer

Scale	$\dot{Q}$ [kW]	$\dot{m}_{SteamR}$ [kg/h]	Additional solar concentrators
1	115,35	192	4
10	1153,5	1920	37
30	3460,5	5759	110
50	5767,5	9598	183
100	11535	19196	365

To calculate the extra needed solar concentrators, the required steam must be divided by the generated steam per solar concentrator. After that the heat transfer area must be determined for the cost estimation in chapter 6. For calculating the heat transfer area, equation 2 is reformed to the following equation.

$$A = \frac{\dot{Q}}{U * \Delta T_m} \tag{21}$$

$\dot{Q}$ is shown in table 12 for the different scales. U is the heat transfer coefficient for a long-tube vertical, forced circulation evaporator and has a value of 2300 $\frac{W}{m^2 * K}$ (Geankoplis, Hersl and Lepek 2018, 32.3). ΔT_m represents the temperature difference between the condensate and the boiling salt solution.

$$\Delta T_m = 133{,}54\ °C - 106{,}78\ °C = 26{,}76\ K$$

Therefore, A is for the smallest crystallizer

$$A = \frac{115{,}35\ kW}{2{,}3 \frac{kW}{m^2 * K} * 26{,}76\ K} = 1{,}9\ m^2$$

The heat transfer area for the other scales is written down in table 13.

Table 13: Required heat transfer area for the industrial crystallizer

Scale	A [m²]
1	1,9
10	18,7
30	56,2
50	93,7
100	187,4

5.2.2 Conclusion

The energy and mass balance of the industrial crystallizer shows that the crystallizer must have different sizes depending on the scale of the desalination plant. Here, the scale of ten, 30, 50 and 100 desalination applications were chosen. For this, the crystallizer must handle a feed flow rate of 2180 $\frac{kg}{h}$, 6540 $\frac{kg}{h}$, 10900 $\frac{kg}{h}$ and 21800 $\frac{kg}{h}$. For only one desalination application there is a flow rate of 218 $\frac{kg}{h}$ like the same rate for the direct crystallizer.

The required thermal power is also the same. It increases with the amount of the desalination application. To have more detailed energy calculations, the used crystallizer must be known exactly for example. Only than it should be possible to estimate the heat losses. Additional to that, the heat losses due to the pipe system must be considered in a more detailed view of the whole desalination plant.

Table 12 points the required steam for running the evaporation but also the necessitated number of solar concentrators to generate the steam. Compared to the direct crystallizer, there is the same ratio between the desalination application and the solar concentrator of 3,65. This value is due to the required steam flow of 192 $\frac{kg}{h}$ and an available steam flow

per solar concentrator of 52,59 $\frac{kg}{h}$. That means, for one application are four solar concentrators required.

Consequently, it would be good for this concept to reduce the flow rate of the desalination plant to a fourth. So, that there are not so many additional solar concentrators needed. Nonetheless, the economic analysis is made with the previous determined values.

6 Economic analysis

This chapter shall show which concept is cheaper in relation to the size of a possible desalination plant. The used method for the economic analysis is called Cost Comparison Method. This type of procedure was chosen because the expected revenue of the crystallizer concepts is the same. Only the investment and the current costs differ. Besides that, the capital costs are estimated for both concepts with the help of the factorial method. This is good for the beginning of a project and it shows a rough overview about the probable costs. The whole calculation is done with the fact that four additional solar concentrators are required to evaporate the salt solution.

6.1 Cost calculations direct crystallizer

For the Cost Comparison Method, the costs of the direct crystallizer is estimated first. These costs consist roughly of the capital costs, labour costs and maintenance costs.

Capital Costs

The capital costs compound of the inside battery limits, the engineering, construction and possible contingency charges. The inside battery limits include the equipment and the summarized installation costs. Furthermore, the equipment costs consist of the costs for the solar concentrators and the costs of the crystallization application. The last parameter, installation costs, include charge for the piping, instrumentation, electrical, civil, lagging and paint work.

For estimating the equipment costs it is important to know the charge for one solar concentrator and the material costs of *Lean Duplex Stainless Steel 2304*. Beforehand the required material for one crystallizer must be determined. The design is not fixed in this step of the possible desalination plant. So, it is assumed as a simple cylindrical container with a diameter of 30 cm and a height of 57 cm like analysed in chapter 5.1. The total area of the cylindrical casing is the circle area from the bottom plus the casing area of the height. The result is $A = (\Pi * r^2) + (2 * \Pi * r * h) = 0{,}61\ m^2$. After that it is multiplied with its thickness (3mm). The volume is equal to 1,83 dm^3 and multiplied with the density

of the steel (7,8 kg/dm³ (Action Stainless KwaZulu Natal 2018)). The resultant mass of one crystallizer is 14,27 kg. The stainless-steel costs are 3600 $\frac{€}{t}$ referred to a price information of the company *Outokumpu Europe Oy*. This information is in appendix F. The material costs then consist of the probable production costs for the crystallizer and the stainless-steel costs. The production costs are mentioned with a factor of three which was given by the company *Solar Fire Concentration Oy*. The next cost aspect are the solar concentrators. The cost of production and material are assumed as 2000 € per concentrator because the financial situation in Namibia is more like in India than in Europe. This cost parameter is a given value of *Solar Fire Concentration Oy*. The results of the costs are listed in table 14 for different scales of a desalination plant. Only the additional concentrators are considered for the calculation of the concentrator costs

Table 14: Equipment costs for the direct crystallizer

Scale desalination plant [units]	Additional concentrators [units]	Concentrator costs [€]	Material Costs [€]	Sum equipment costs [€]
1	4	8.000	617	8.617
10	37	74.000	5.704	79.704
30	110	220.000	16.958	236.958
50	183	366.000	28.211	394.211
100	365	730.000	56.268	786.268

Now, the installation costs can be multiplied with the factorial method. The equation 7 shows the total fixed capital costs including all steps mentioned before. The factors come from the first table in appendix B middle column for the liquid and solid material. For illustration the calculation is done for the smallest size of a desalination plant.

$$C = 8.617\ € * \big((1 + 0{,}6)1{,}3 + (0{,}5 + 0{,}2 + 0{,}3 + 0{,}3 + 0{,}2 + 0{,}1)\big) = 31.709\ €$$

For the material factor 1,3 is chosen because the plant must consist mainly of stainless steel instead of carbon steel to be protected against the salt. The results for the inside battery limits are shown in table 15.

In addition to the installation costs the engineering, design, offsite and possible contingency costs must be considered. Adding these factors, the fixed capital investment costs are completed. The values of the last factors and the equation used in the next step are listed in the first table of appendix B as well.

$$C = 31.709\ € * \big((1 + 0{,}4) * (1 + 0{,}25 + 0{,}1)\big) = 59.930\ €$$

The fixed capital costs for different scales of the desalination plant are presented in table 15.

Table 15: Results of the installation and the fixed capital costs for the direct crystallizer concept

Scale desalination plant [units]	Equipment and installation costs [€]	Fixed capital costs [€]
1	31.709	59.930
10	293.310	554.356
30	872.004	1.648.087
50	1.450.697	2.741.817
100	2.893.467	5.468.652

Labour costs

For the overview about the possible costs for the direct crystallizer, the labour costs must be estimated. Labour costs include the required working hours to do the daily work on the crystallizer. That means, to collect the salt from the crystallizers after they evaporated the solution. In addition to that, they must be cleaned from the salt and prepared for the next day.

The theoretical estimated time for preparing one crystallizer per day is one hour. Here, it is considered, that the crystallizer is fixed 4 m above the mirror area and that the whole work must be done manually. In the calculation of the labour costs only the additional required solar concentrators are integrated.

The labour costs for Namibia come from the Namibia Statistics Agency (2015). Here it is said that the average monthly wage for a worker in the water supply and related industries is 8.813 N$ (Namibia Statistics Agency 2015, 63). With the assumption of 8 hours per day five times a week the average hourly wage is 55,1 N$. The currency factor is 0,06676 (30.04.2018) from Namibian dollar to Euro (Oanda Corporation 2018). The resultant average hourly wage is 3,68 €.

The labour costs are estimated for a period of one year. With this information the labour costs are approximated for the smallest scale like followed:

$$L = 4\,units * 1\frac{h}{unit * d} * 3{,}68\frac{€}{h} * 365{,}25\frac{d}{a} = 5.372\frac{€}{a}$$

The required solar concentrators are multiplied with the assumed working time of one hour and the average hourly wage. In the end, the days per year are added to the equation to get the costs for the whole year. The results are shown in the following table.

Table 16: Labour costs per year for the direct crystallizer concept

Scale desalination plant [units]	Additional concentrators [units]	Labour costs [€/a]
1	4	5.372
10	37	49.695
30	110	147.742
50	183	245.788
100	365	490.234

Maintenance costs

The last point of the cost estimation is the maintenance costs to prevent downtime of the crystallizers. Included in that is normal repairing costs which arise due to the time. Towler and Sinnott (2013) consider maintenance costs as a factor of the equipment plus the summarized installation costs (table 15). The crystallized salt can wear the crystallizer quite fast down. So, the factor is assumed with 5 % (Towler and Sinnott 2013, 377).

The results are listed in table 17.

Table 17: Maintenance costs for the direct crystallizer concept

Scale desalination plant [units]	Maintenance costs [€/a]
1	1.585
10	14.666
30	43.600
50	72.535
100	144.673

6.2 Cost calculations industrial crystallizer

Now the costs for the industrial crystallizer are estimated. These costs consist again of the capital, labour and maintenance costs.

Capital Costs

The capital costs of the industrial crystallizer are different to the direct one. Here, the main part of the capital costs is the cost for the crystallizer itself. This matter of expanse cannot be cited with reliable information. So, it is estimated with the help of cost curves described by Towler and Sinnott (2013, 321). These cost curves follow the equation

$$C_e = a + b * S^n \tag{22}$$

The factors for this equation is shown in appendix G. There the values for the vertical tube evaporator are used to estimate the equipment costs for the industrial crystallizer. The vertical tube evaporator is accepted because it is a very close machine to the mentioned crystallizer. Furthermore, this thesis is the very first analysis of this topic and this estimation can give a reliable first impression about the possible costs.

$$C_e = 330 + 36000 * (18{,}7m^2)^{0{,}55} = 180.555\ \$$$

With the currency factor 0,82424 (Oanda Corporation 2018, 30.04.2018) from US$ to € the equipment costs for the evaporator can be approximated. The example is shown for a desalination plant with ten desalination applications. And the heat transfer area is listed in table 13.

The results are presented in the following table. For the smallest crystallizer 100.000 € is assumed. For such small crystallizers are no data available so that, the price must be estimated.

Table 18: Results of the fixed capital costs for the industrial crystallizer concept

Scale desalination plant [units]	Additional concentrators [units]	Concentrator costs [€]	Crystallizer costs [€]	Equipment and installation costs [€]	Fixed capital costs [€]
1	4	8.000	100.000	397.440	751.162
10	37	74.000	148.821	819.980	1.549.763
30	110	220.000	272.361	1.811.889	3.424.470
50	183	366.000	360.695	2.674.239	5.054.312
100	365	730.000	527.963	4.629.303	8.749.382

The rest of the calculations are the same as these for the direct crystallizer. The concentrator costs and the crystallizer costs are summarized and multiplied with the factors mentioned in the previous chapter. The result is the equipment and installation costs. Thus, multiplied with the engineering, design and contingency costs are equal to the fixed capital costs. All findings are mentioned in table 18.

Labour costs

The labour costs for the industrial crystallizer are less than these of the direct crystallizer. Here, everything is automated and there are only a few people required to check the process during the day. The solar concentrators which are producing the steam must not be cleaned like the crystallizers in the other concept. So, the labour costs are reduced at a fraction. It is assumed that one worker is needed to drive the smallest crystallizer. Two workers are needed to drive the crystallizer at a plant with ten and 30 applications. For the 50-application plant three workers are required and for the biggest four. Consequently, the following labour costs are estimated for this concept. The estimation is done with the same hourly wage for one year.

Table 19: Labour costs for the industrial crystallizer concept

Scale desalination plant [units]	Required worker	Labour costs [€/a]
1	1	10.753
10	2	21.506
30	2	21.506
50	3	32.259
100	4	43.012

Maintenance costs

The maintenance costs are calculated again with 5 % of the equipment and installation costs (table 18). The crystals in the crystallizer could wear the machine down quite fast whereby it is more reliable if the maintenance costs are considered with 5 % instead of 3%. The results are mentioned in table 20.

Table 20: Maintenance costs for the industrial crystallizer concept

Scale desalination plant [units]	Maintenance costs [euro/a]
1	19.872
10	40.999
30	90.594
50	133.712
100	231.465

6.3 Cost comparison of the concepts

In this chapter the Cost Comparison Method is used to show which concept is more economic related to the scale of a desalination plant. The labour and maintenance costs are calculated earlier. Now, the imputed depreciation and the imputed interest must be determined. For the imputed depreciation it is assumed, that the machine has no more value after its lifetime and the using time for the concepts is 3 years for the direct crystallizer and 5 years for the industrial crystallizer. This is accepted due to the reason that the direct crystallizer is exposed to high temperature ranges. The material embrittles and must be replaced after a period. Furthermore, the high concentrated salt solution destroys the material after a while. The industrial crystallizer does not work with such high temperatures whereby the material can used longer. The following equation shows the calculation for the depreciation. It is done for the direct crystallizer and the smallest plant scale. The fixed capital costs from table 15 and table 18 are divided by the useful life.

$$Imputed\ depreciation = \frac{Fixed\ capital\ costs}{Useful\ life} = \frac{59.930\ €}{3\ a} = 19.977\frac{€}{a} \qquad (23)$$

And the imputed interest is calculated like mentioned in chapter 2.4.1. The residual value after useful time is again zero and the interest is assumed with 10%. The fixed capital costs are the same as before. The following equation is based on equation 5 and 6.

$$Imputed\ interest = \frac{59.930\ €}{2} * 0{,}1 = 2.997\ €$$

The results for these values are presented in table 21 for the direct crystallizer concept and in table 22 for the industrial crystallizer concept.

Table 21: Cost listing per year for the direct crystallizer concept

Direct crystallizer					
Scale desalination plant [units]	**1**	**10**	**30**	**50**	**100**
Labour costs [€/a]	5.372	49.695	147.742	245.788	490.234
Maintenance costs [€/a]	1.585	14.666	43.600	72.535	144.673
Imputed depreciation [€/a]	19.977	184.785	549.362	913.939	1.822.884
Imputed interest [€/a]	2.997	27.718	82.404	137.091	273.433
Sum [€/a]	**29.931**	**276.864**	**823.109**	**1.369.353**	**2.731.224**

Besides the imputed depreciation and interest the labour and maintenance costs are listed in these tables. All costs are summarized to the last row which represents the total estimated annual costs for the concepts.

Table 22: Cost listing per year for the industrial crystallizer

Industrial crystallizer					
Scale desalination plant [units]	**1**	**10**	**30**	**50**	**100**
Labour costs [€/a]	10.753	21.506	21.506	32.259	43.012
Maintenance costs [€/a]	19.872	40.999	90.594	133.712	231.465
Imputed depreciation [€/a]	150.232	309.953	684.894	1.010.862	1.749.876
Imputed interest [€/a]	37.558	77.488	171.223	252.716	437.469
Sum [€/a]	**218.415**	**449.946**	**968.218**	**1.429.549**	**2.461.823**

In the end, figure 13 shows the annual costs as a function of the desalination plant scale. The blue line stands for the direct crystallizer and the red one for the industrial one.

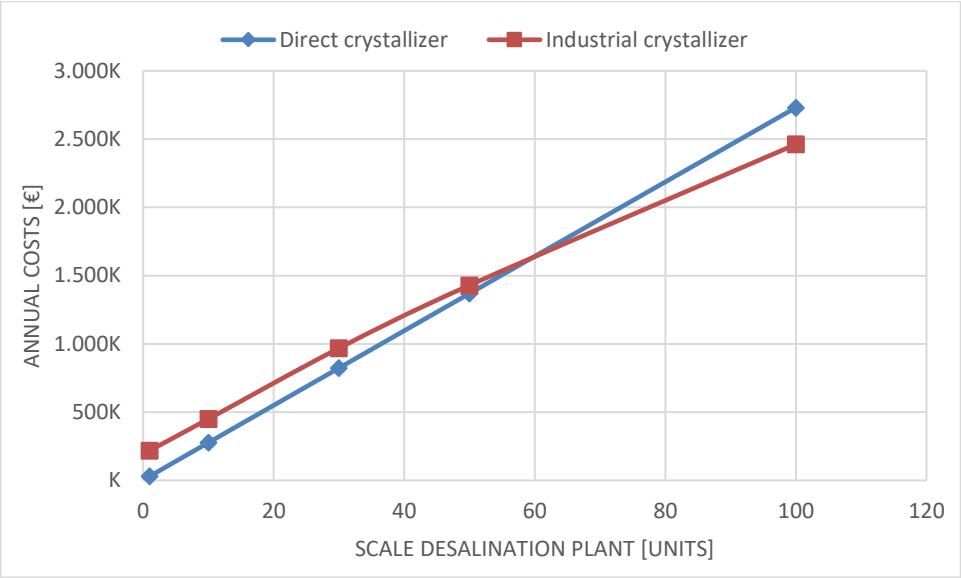

Figure 13: Annual cost comparison of the concepts

The analysis and interpretation of this figure is in the conclusion of this work.

6.4 Possible revenue

Besides the cost listings of the concept it is also important to know which earnings can be reached. The main income of a desalination plant would be the fresh water but due to the reason of using a crystallizer, the possible income of the salt should be mentioned as well. Here, it depends which kind of water is treated with the desalination application. Possible solutions could be different kinds of industrial waste waters or seawater. In the case of the industrial waste water no statement can be made at this stage because no ingredients are known. For calculating the possible revenue of the crystallization, it must be known which product appears. Furthermore, the waste water could be contaminated with ingredients who cannot be sold after the crystallization. There, more costs would accumulate to get rid of the waste.

In the case of desalinating seawater, a rough overview about possible benefits can be presented. For example, the U.S. Geological Survey (2017) presented a price for "Solar salt" of 90 $\frac{\$}{t}$. This is the price for the United States and not Namibia but to get an overview this price prospect should be good. The currency is determined in euro again with the factor 0,82424 $\frac{€}{\$}$. The amount of salt is calculated with an average working time per day for one solar concentrator of 6 hours the whole year (365,25 d). This is multiplied with $\dot{m}_{Solids}$ = 40 $\frac{kg}{h}$ and the scale of the desalination plant. The results are shown in table 23.

Table 23: Possible revenue for the salt per year

Scale desalination plant [units]	Salt [kg/a]	Salt benefit [€/a]
1	87660	6.503
10	876600	65.028
30	2629800	195.083
50	4383000	325.138
100	8766000	650.276

7 Conclusion

The aim of the thesis was to analyse different kind of concepts for a waste treatment of a desalination plant. The results of this analysis shall be presented in this conclusion.

First, a few words about the physical and thermodynamic analysis. A crystallizer directly heated by solar radiation and an industrial crystallizer are analysed. After some calculations about the salt water properties and the available solar radiation the direct crystallizer is analysed with an energy and mass balance. The available solar thermal power for one solar concentrator with a mirror area of 36 m² is determined with 31,6 kW. Here, it must be considered, that this is the total maximum on a full sunny day in summer. This maximum is only available for a few minutes. Referred to appendix E, before the maximum and after it the energy is less and is getting nearly useless just three to four hours before and after it. Due to the point that the crystallization and the desalination is powered by solar thermal energy it is not important to consider the fact of fluctuation. Because if the radiation decreases, the waste production drops as well and with it the required energy to evaporate the waste. Hence, the calculations are done with the maximum of radiation to find out the total possible maximum.

The result of the energy and mass balance for both concepts is, that 115,2 kW thermal power is required to crystallize the waste. Therefore, four solar concentrators are needed to provide this amount of thermal power.

After a heat transfer calculation for the direct crystallizer from the outer to the inner surface and a resultant focal temperature of 433,4 °C, the diameter and the volume are fixed to 30 cm and 40 dm³. The resultant height is 0,57 m. Here, the volume of the crystallizer seems a little bit too small related to the probable volume of the salt (27,65 dm³) at the end of the day. However, this volume is a disproportionate maximum and will not be reached to the fact that this amount is calculated with a constant waste production of 200 $\frac{l}{h}$. But this amount cannot be constantly provided because of the fluctuation of the solar

radiation. For a more precise result of the amount of salt and available and required thermal energy these calculations must be done with long-time measured solar radiation data for each hour for example.

In chapter 5.2 the physical and thermodynamic analysis of the industrial crystallizer is shown. The crystallizer shall be powered by steam, generated by solar concentrators. The required steam flow is 192 $\frac{kg}{h}$ and one solar concentrator can provide 52,59 $\frac{kg}{h}$. The result is again that four concentrators are needed to evaporate the waste from one desalination application. Another important issue for the cost estimation is the heat transfer area. It differs between 1,9 m² to 187,4 m² depending on the scale of the desalination plant. Results are listed in table 13.

Now, the economic analysis is evaluated. In the first part, the costs for the direct crystallizer are estimated. This is done with a factorial method for the fixed capital costs. Due to the factorial method this estimation is only a first overview about the possible amount of the costs and only good for the first phase of the project. For the biggest plant with 100 desalination applications the fixed costs are 5,47 million € for example. To get a better estimation, the crystallizer concept should be more precise and already mentioned with real designs. Next point is the labour costs. In this concept the labour costs are the crux. Because it is affected by high labour time. In African countries like Namibia where the wages are very low, it has not such an influence but in European countries it has. There, the labour costs could become far too expensive to run such a plant economically. The estimated labour costs for the biggest plant are 490.234 $\frac{€}{a}$. In contrast are the maintenance costs. These are very low because of the small equipment costs. For the biggest plant it is 144.673 $\frac{€}{a}$.

Besides the direct crystallizer is the industrial one. Here, the equipment costs are first estimated with a cost curve. The cost curve stands for a vertical tube evaporator. In the future the costs could be calculated with real offers from supplier companies. This would be more precise than the cost curve. Nonetheless, for the first phase the cost curve presents a good and fast overview about the possible costs. After that the fixed capital costs are estimated with the same factorial method than before. One validation of the cost curve could be that the fixed capital costs are much higher than of the direct crystallizer. The higher fixed capital costs were expected and arise due to the complexity of an industrial crystallizer. In contrast are the labour costs. These are estimated quite small. The crystallizer size rises with the mass flow but neither does the labour time. This is relative constant. The estimate of four workers for the biggest crystallizer are rough values. This must

be proofed in the future. But here, it is intent to keep the labour costs small to show the big difference of the concepts. The direct crystallizer is high dependent on the labour costs and the industrial crystallizer is high dependent on the fixed capital costs. The fixed capital costs reach 8,75 million € and the labour costs 43.012 €.

The Cost Comparison Method shows the development of the costs related to the scale of the desalination plant. Here it is assumed that the industrial crystallizer has a longer useful life than the direct crystallizer. Only with this assumption, the industrial crystallizer has a chance to be more economic than the direct crystallizer. The result is shown in figure 13. The industrial crystallizer gets more economic by a scale of circa 60 desalination applications. This result appears since the costs of the direct crystallizer increase linear. And the cost increasing rate of the industrial one decreases with the size of the crystallizer. So, with bigger scales the cost increasing drops. But this estimation is done with different useful life values. If the direct crystallizer should work longer than expected it is more economically to use this one instead of an industrial one in any scale.

All in all, this work outlines the possibilities to evaporate the waste of a desalination plant. Furthermore, it presents the possible costs and helps to decide which crystallizer should be used for which scale of a desalination plant. Nonetheless, the whole estimation is very approximate and if there should be any project in the future the calculations should be redone with more precise data. But this work could be used as a basic form for future development.

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APPENDICES

Appendix A

Table 24: Mean ionic composition of seawater (Belessiotis, Kalogirou and Delzannis 2016, 336)

Ions	Ions	Normal Seawater
Chlorides	Cl^-	19.3605
Sodium	Na^+	10.7678
Sulfates	SO_4^{2-}	2.7017
Magnesium	Mg^{2+}	1.2975
Calcium	Ca^{2+}	0.4081
Potassium	K^+	0.3876
Bicarbonates	HCO_3	0.1425
Bromides	Br^-	0.0659
Boric acid	H_3BO_3	0.0265
Strontium	Sr^{2+}	0.0136
Fluorides	F^-	0.0013

Appendix B

Item	Process Type		
	Fluids	Fluids–Solids	Solids
Major equipment, total purchase cost	C_e	C_e	C_e
f_{er} Equipment erection	0.3	0.5	0.6
f_p Piping	0.8	0.6	0.2
f_i Instrumentation and control	0.3	0.3	0.2
f_{el} Electrical	0.2	0.2	0.15
f_c Civil	0.3	0.3	0.2
f_s Structures and buildings	0.2	0.2	0.1
f_l Lagging and paint	0.1	0.1	0.05
ISBL cost, $C = \Sigma C_e \times$	3.3	3.2	2.5
Offsites (OS)	0.3	0.4	0.4
Design and Engineering (D&E)	0.3	0.25	0.2
Contingency (X)	0.1	0.1	0.1
Total fixed capital cost $C_{FC} = C\ (1 + \text{OS})(1 + \text{D\&E} + \text{X})$			

Figure 14: Factors for estimation of the fixed capital costs of a project (Towler and Sinnott 2013, 331)

Material	f_m
Carbon steel	1.0
Aluminum and bronze	1.07
Cast steel	1.1
304 stainless steel	1.3
316 stainless steel	1.3
321 stainless steel	1.5
Hastelloy C	1.55
Monel	1.65
Nickel and Inconel	1.7

Figure 15: Material cost factors relative to carbon steel for the factorial capital cost estimation

Appendix C

Table 25: Calculation of the weighting for the criteria at the scoring model

	labour costs	investment costs	flexibility of energy source	simplicity
labour cost		2	3	1
investment costs	2		3	2
flexibility of energy source	1	1		1
simplicity	3	2	3	
required space	1	1	3	1
maintenance cost	2	2	3	1
process time	1	1	2	1
Sum				

Table 26: Calculation of the weighting for the criteria at the scoring model (continued)

	required space	maintenance cost	process time	Sum
labour cost	3	2	3	14
investment costs	3	2	3	15
flexibility of energy source	1	1	2	7
simplicity	3	3	3	17
required space		1	2	9
maintenance cost	3		3	14
process time	2	1		8
Sum				84

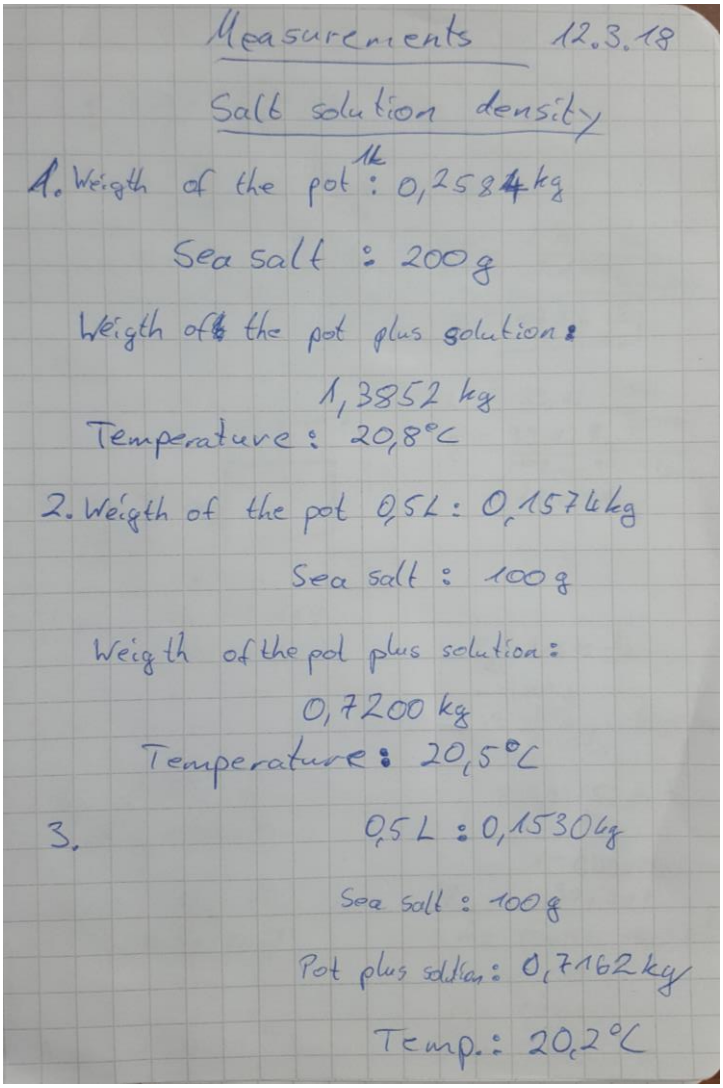
Table 27: Results of the scoring model for each concept

Criteria	Concepts		
	Direct crystallizer	Pan evaporator	Industrial crystallizer
labour cost	50,0	83,3	116,7
investment costs	142,9	89,3	71,4

flexibility of energy source	8,3	8,3	66,7
simplicity	202,4	121,4	40,5
required space	32,1	53,6	75,0
mainte-nance cost	150,0	116,7	83,3
process time	66,7	9,5	76,2
Sum	652,4	482,1	529,8

Appendix D

For calculating the density of the salt solution which enters the crystallizer, the density of a 200 $\frac{kg}{m^3}$ concentrated salt solution at a temperature of 20 °C is measured. With that the mass fraction is calculated. Afterwards, the new density of a 100 °C salt solution is estimated with the help of the density values from Perry and Green, visible in Table 29.


Measurements 12.3.18

Salt solution density

1. Weigth of the pot 1L: 0,2584 kg

Sea salt : 200 g

Weigth of the pot plus solution:

1,3852 kg

Temperature: 20,8°C

2. Weigth of the pot 0,5L: 0,1574 kg

Sea salt : 100 g

Weigth of the pot plus solution:

0,7200 kg

Temperature: 20,5°C

3. 0,5 L : 0,1530 kg

Sea salt : 100 g

Pot plus solution: 0,7162 kg

Temp.: 20,2°C

Figure 16: Measurement density of a 200 kg/m³ salt solution

Table 28: Results of the density measurement

Measurement	Mass of the solution [kg]	Density [kg/L]
1	1,1268	1,1268
2	0,5626	1,1252
3	0,5632	1,1264
Average		1,1261

Table 29: Density of an aqueous sodium chloride solution with a temperature of 100 °C and different mass fractions (Perry and Green 1997, 2-105)

Mass fraction [% Weight]	Density at 100°C [kg/L]
1	0,9651
2	0,9719
4	0,9855
8	1,0134
12	1,042
16	1,0713
20	1,1017
24	1,1331
26	1,1492

Appendix E

Daily irradiance data from Windhoek, Namibia. The data are collected from PVGIS-5 geo-temporal irradiation database for the months June and October (European Union, Photovoltaic Geographical Information System 2017).

European Commission

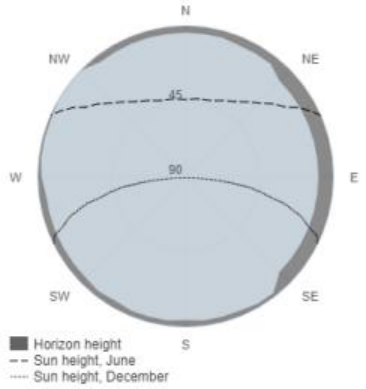
Daily irradiance data

PVGIS-5 geo-temporal irradiation database

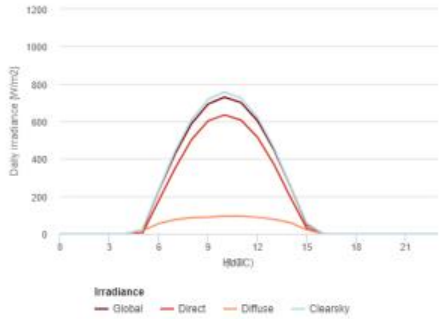
Provided inputs

Latitude/Longitude:	-22.573, 17.027
Horizon:	Calculated
Database used	PVGIS-CMSAF
Month:	June

Outline of horizon at chosen location:



Daily average irradiance on fixed plane with slope 0° and azimuth 0°



Irradiance on a fixed plane

Time	00:45	01:45	02:45	03:45	04:45	05:45	06:45	07:45	08:45	09:45	10:45	11:45	12:45	13:45	14:45	15:45	16:45	17:45	18:45	19:45	20:45	21:45	22:45	23:45
G	0	0	0	0	0	16	231	427	589	693	730	701	605	450	255	49	0	0	0	0	0	0	0	0
Gb	0	0	0	0	0	0	177	351	503	603	635	607	516	372	196	28	0	0	0	0	0	0	0	0
Gd	0	0	0	0	0	16	54	76	86	89	94	94	88	77	59	21	0	0	0	0	0	0	0	0
Gc	0	0	0	0	0	22	235	442	610	718	757	725	623	460	256	55	0	0	0	0	0	0	0	0

G: Global irradiance on a fixed plane [W/m2].
Gb: Direct irradiance on a fixed plane [W/m2].
Gd: Diffuse irradiance on a fixed plane [W/m2].
Gc: Global Clear-sky irradiance on a fixed plane [W/m2].

Joint Research Centre

Report generated on 2018/04/16

European Commission

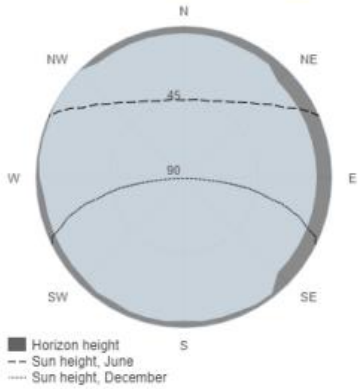
Daily irradiance data

PVGIS-5 geo-temporal irradiation database

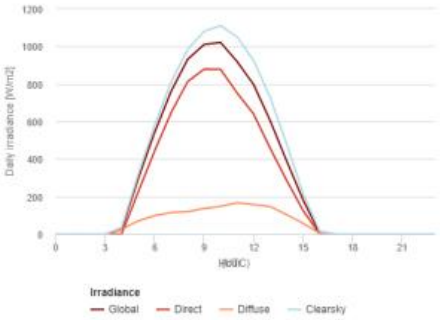
Provided inputs

Latitude/Longitude:	-22.573, 17.027
Horizon:	Calculated
Database used	PVGIS-CMSAF
Month:	October

Outline of horizon at chosen location:



Daily average irradiance on fixed plane with slope 0° and azimuth 0°



Irradiance on a fixed plane

Time	00:45	01:45	02:45	03:45	04:45	05:45	06:45	07:45	08:45	09:45	10:45	11:45	12:45	13:45	14:45	15:45	16:45	17:45	18:45	19:45	20:45	21:45	22:45	23:45
G	0	0	0	0	24	294	542	761	931	1010	1020	918	796	604	389	181	4	0	0	0	0	0	0	0
Gb	0	0	0	0	0	224	444	647	812	879	877	751	639	457	286	125	0	0	0	0	0	0	0	0
Gd	0	0	0	0	24	70	98	115	119	136	148	167	157	147	103	57	4	0	0	0	0	0	0	0
Gc	0	0	0	0	36	316	580	811	983	1080	1110	1050	924	728	480	214	15	0	0	0	0	0	0	0

G: Global irradiance on a fixed plane [W/m2].
Gb: Direct irradiance on a fixed plane [W/m2].
Gd: Diffuse irradiance on a fixed plane [W/m2].
Gc: Global Clear-sky irradiance on a fixed plane [W/m2].

Joint Research Centre

Report generated on 2018/04/16

Appendix F

Von: Pekka Heinonen <Pekka.Heinonen@outokumpu.com>

Gesendet: Freitag, 4. Mai 2018 08:48

An: Adrian Schneider <adrian.schneider@eng.tamk.fi>

Betreff: Price indication

Hi,

Here you can see price indication for grades LDX 2101 and 2304.

Thickness 3 mm
LDX 2101 Price 3050 €/t

2304 / EN 1.4362 Price 3600 €/t

This is not official offer because volume and other dimension are not available.

Price is valid 5 days

Ystävällisin terveisin / Kind regards / Med vänlig hälsning

Pekka Heinonen
Sales Manager
End user Sales Finland & Baltics
BA Europe
Outokumpu

Outokumpu Europe Oy
Salmisaarenranta 11 , 00180 Helsinki
Finland

Appendix G

Table 30: Factors for the cost curve model to estimate the equipment costs (Towler and Sinnott 2013, 323)

Equipment	Units for Size, S	S_{lower}	S_{upper}	a	b	n	Note
Dryers							
Direct contact Rotary	m^2	11	180	15,000	10,500	0.9	1
Atmospheric tray batch	area, m^2	3.0	20	10,000	7,900	0.5	
Spray dryer	evap rate kg/h	400	4,000	410,000	2,200	0.7	
Evaporators							
Vertical tube	area, m^2	11	640	330	36,000	0.55	
Agitated falling film	area, m^2	0.5	12	88,000	65,500	0.75	2
Exchangers							
U-tube shell and tube	area, m^2	10	1,000	28,000	54	1.2	
Floating head shell and tube	area, m^2	10	1,000	32,000	70	1.2	
Double pipe	area, m^2	1.0	80	1,900	2,500	1.0	
Thermosiphon reboiler	area, m^2	10	500	30,400	122	1.1	
U-tube Kettle reboiler	area, m^2	10	500	29,000	400	0.9	
Plate and frame	area, m^2	1.0	500	1,600	210	0.95	2
Filters							
Plate and frame	capacity, m^3	0.4	1.4	128,000	89,000	0.5	
Vacuum drum	area, m^2	10	180	–73,000	93,000	0.3	
Furnaces							
Cylindrical	duty, MW	0.2	60	80,000	109,000	0.8	
Box	duty, MW	30	120	43,000	111,000	0.8	
Packings							
304 ss Raschig rings	m^3			0	8,000	1.0	
Ceramic intalox saddles	m^3			0	2,000	1.0	
304 ss Pall rings	m^3			0	8,500	1.0	
PVC structured packing	m^3			0	5,500	1.0	
304 ss structured packing	m^3			0	7,600	1.0	3
Pressure vessels							
Vertical, cs	shell mass, kg	160	250,000	11,600	34	0.85	4
Horizontal, cs	shell mass, kg	160	50,000	10,200	31	0.85	4