Fachhochschule Köln
Cologne University of Applied Sciences

UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ
FACULTADES DE CIENCIAS QUÍMICAS, INGENIERÍA Y MEDICINA
PROGRAMAS MULTIDISCIPLINARIOS DE POSGRADO EN CIENCIAS AMBIENTALES
AND
COLOGNE UNIVERSITY OF APPLIED SCIENCES
INSTITUTE FOR TECHNOLOGY AND RESOURCES MANAGEMENT IN THE TROPICS AND SUBTROPICS

Development of a low-cost, high-efficiency solar distillation unit for small-scale use in rural communities

THESIS TO OBTAIN THE DEGREE OF
MAESTRÍA EN CIENCIAS AMBIENTALES
DEGREE AWARDED BY
UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ
AND
MASTER OF SCIENCE
"TECHNOLOGY AND RESOURCES MANAGEMENT IN THE TROPICS AND SUBTROPICS"
FOCUS AREA "ENVIRONMENTAL AND RESOURCES MANAGEMENT"
DEGREE AWARDED BY COLOGNE UNIVERSITY OF APPLIED SCIENCES

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SAN LUIS POTOSÍ, MÉXICO AUGUST 2011

PROYECTO FINANCIADO POR:

APOYO PROMEP PARA EL PROYECTO RED DEL CUERPO ACADÉMICO 37, UASLP;
PROYECTO ASESORÍAS 37, UASLP.

PROYECTO REALIZADO EN:

PMPCA

FACULTAD DE CIENCIAS QUÍMICAS

UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

CON EL APOYO DE:
DEUTSCHER AKADEMISCHER AUSTAUSCH DIENST (DAAD)
CONSEJO NACIONAL DE CIENCIA Y TECNOLOGÍA (CONACYT)

LA MAESTRÍA EN CIENCIAS AMBIENTALES RECIBE APOYO A TRAVÉS DEL PROGRAMA
NACIONAL DE POSGRADOS (PNPC - CONACYT)

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Acknowledgements

During the elaboration of my Masters' thesis, I have made certainly some of the most enchanting encounters with interesting and interested persons, which not only crossed my way, but also accompanied me (not only) in the process of completing my thesis work. They were supporting me, advising, guiding, criticizing and comforting me with all the enthusiasm in their realm of possibility.

Firstly, I like to express my sincerest gratitude to the professors supervising my thesis, above all to Dr. Catalina Alfaro de la Torre, whose kind motivation and inspiration forwarded the process of writing the thesis a lot. Not to mention her personal financial "patronage" of the project, without which it would have been impossible to finish in time.

I would like to thank Dr. José Nieto Navarro for his "spontaneous" decision to join the academic committee and his constant input of important ideas, as well as his formidable support with measuring instruments for the recording of the environmental data. Dr. Michael Sturm deserves my gratitude for the structural planning of the thesis and his very valuable comments towards the methodology of realization and implementation of the prototypes. Dr. Javier Castro for his kind attention and his comments towards the present environmental situation of the study area.

I would like to address a special recognition to the engineer Jean Fritche Tamiset for his enduring support throughout the whole planning and design phase of the prototype, as well as for his practical contributions and advice towards the implementation. Also the efforts of Professor Abraham Cárdenas Tristán for providing me with a site for the outdoor experiments should not remain unmentioned.

Juan Carlos Gonzalez-Mendoza has earned my deepest respect and gratitude for his voluntary affiliation to the project, not only for his perpetual practical assistance in construction, but for the contribution of an uncountable number of valuable and elaborated ideas towards the overall realization of the entire project plan. I appreciate his "10 minutes" for doing miracles. Also Eric from the maintenance workshop of the Faculty of Chemistry deserves a big "thanks" for his practical help.

Alma Guadalupe de Lira-Santillan, for her kind attention and very fast analysis of the water samples in the Laboratory of Environmental Chemistry, Faculty of Chemistry of the UASLP.

To my colleagues from the laboratory of trace elements, René, Viki, Mayra and Adriana, I owe deep gratitude for always being there when help was needed in the process of measurements and for their kind attention towards the clarification of theoretical issues.

Maricela Rodriguez Diaz de Leon and Farah Ahmed from the Agenda Ambiental receive my deep respect and thanks for rapidly putting up a campaign for the recollection af beverage cans for the air collector of the second (lamentably not finished) prototype. I also honor their support in managing the vast amount of bureaucratic proceedings throughout the entire study period.

I want to express my gratitude to my friend Fernando Hernandez-Cruz who sacrificed his recreational periods for time-consuming solderability tests of aluminum sheets and pipes for the

primordial use in the evaporation basin. To my personal friend Miguel, who brought the raw water samples from the Altiplano region, I owe a very special thanks.

Although Victor Manuel Garza-Villa and Fidel Torres-Mata were not directly involved in the practical realization of the project, they were always present when additional help or material was needed. Therefore I owe them deep respect. Also the group of masons around Alejandro Cortina (including Raul Martinez and Alberto Lopez) deserves mentioning for their help with occasional work and their cheering presence. I appreciate their support and interest for the project very much.

At last, I would like to thank my Mexican "mother" Patricia Gonzalez-Martinez and all of her family for the material and mental support they gave me during the thesis work. Of course I also want to thank my parents for their perpetual support and their encouragement they gave me. The have done all their possible to comfort me over a very large spatial distance.

To all my friends from the city of San Luis Potosí who have participated indirectly in the project, be that by helping me obtaining material, giving advice and feedback or just comforting me, I want to express my gratitude. Your contributions are not forgotten.

Abstract

Providing access to safe drinking water becomes increasingly difficult on a worldwide level. Various regions of the Mexican Highlands have issues of groundwater contamination in terms of inorganic (e.g. arsenic or fluoride) or bacteriological parameters, which are exceeding the established limits in the Norma Oficial Mexicana (Official Mexican Standard) (NOM) for drinking water. One of the affected areas is the *Altiplano* region in the federal state of San Luis Potosí. Most of the rural communities in the region do not have access to (adequate) technology for groundwater purification and thus their inhabitants are exposed to the elevated levels of contamination which are potentially the cause for diseases, such as the *fluorosis*. Due to the facts of marginalization and poverty it is vital to investigate towards decentralized and economical technologies which can be applied on a small-scale level. A low-cost and "low-tech" approach is necessary in order to provide the people with a technology which they can construct, operate and maintain themselves. A promising approach is the technology of solar distillation for drinking water supply on domestic level, making use of the high regional potential of solar energy. It is proven that this technology is capable of removing nearly any type of contaminants (inorganic and bacterial) from the raw water. The simplest and most durable form of implementation is the passive *shallow-basin, single-slope solar still*. The mayor drawback consists in its low daily output of drinking water (about two to five liters per square meter of insolated area). In the scope of the thesis, so-called *passive energy augmentation measures* are applied to the aforementioned design, in order to raise the distillate output to an adequate level for the drinking water supply of a small family of four members with a demand of approximately eight liters per day (considering the amount of pure ingestion). A prototype unit of the passive solar still is built and its parameters of distillate output, energy efficiency and construction costs are determined, considering two different configurations. An additional analysis of the distillate quality is made. The first configuration of the prototype is mainly characterized by a low water level in the evaporation basin and raw water pre-heating, whereas the second configuration adds reflective side- and rear wall coating inside the distillation chamber. Furthermore, a prototype of an active solar still is designed, incorporating an additional energy source (solar air collector) for higher process temperatures and therefore augmentation of the daily distillate yield. The emphasis in construction was put on the use of local, economical and recycled materials as far as possible, in order to lower the costs, attain a high reproducibility and to facilitate the possibility of autonomous self-construction in rural areas. The obtained results are very satisfactory in respect to the climatological conditions of the project region and the typical efficiency and distillate output of the applied design. Mean daily distillate yields of 4.2 L (basic design) and 4.7 L (design with reflective side- and rear walls) were reached. Nevertheless, the construction of the proposed active unit is strongly recommended for the future, due to its capacity of providing a sufficient daily distillate output for the drinking water supply of a family of four members. The water was successfully liberated from contaminants and had an adequate quality for direct

ingestion after the application of marble stones (for re-mineralization) in the collection vessel. Economical feasibility is not yet given due to the use of specialized materials for evaporation basin and case.

Resumen

Proveer agua de calidad adecuada para el consumo humano es una tarea dificil a nivel mundial. Varias localidades del altiplano mexicano tienen problemas de contaminación de agua subterránea relacionados a parámetros inorgánicos (por ejemplo arsenico o fluoruros) o bacteriológicos que rebasan los límites permisibles de la Norma Oficial Mexicana para agua potable. Una de las regiones afectadas es la región del *Altiplano* en el estado de San Luis Potosí. La mayoría de las comunidades rurales no cuenta con tecnología adecuada para la potabilización de agua y por eso sus habitantes están expuestos a cantidades elevadas de contaminantes que son la causa de enfermedades como por ejemplo la *fluorosis*. Debido al alto grado de marginación y pobreza en las comunidades, es necesario proponer tecnologias económicas de fácil operación, las cuales pueden ser aplicadas a pequeña escala. Un enfoque de bajo costo y baja complejidad es necesario para ofrecer una tecnología que puede ser construida, manejada y mantenida por gente de la comunidad. Así surge la tecnología de destilación solar en escala casera, que aprovecha el alto potencial regional de energía solar. Dicha tecnología está comprobada para remover casi todos los tipos de contaminantes inorgánicos y bactarias del agua. La forma más sencilla y durable es el diseño de un destilador pasivo - tipo invernadero con charola de evaporación de poca profundidad y un solo vidrio de cobertura (orientado hacia el sur). La desventaja mayor de este tipo de destilador es su bajo rendimiento de destilado diario (2 - 5 L/m^2 de insolación). Al margen de la tesis se estudian modificaciones para el aumento pasivo de energía a un prototipo para aumentar la tasa de producción diaria de destilado con el fin de proveer una cantidad de agua suficiente para el abastecimiento de una familia de cuatro personas (aproximadamente ocho litros considerando sola la ingesta directa). En dicho prototipo se determinaron los parámetros de eficiencia energética, cantidad de destilado por día y costos de construcción - basado en dos distintas configuraciones. Además, se realizó un análisis de la calidad del destilado. La primera configuración del destilador está caracterizada por un bajo nivel de agua en la charola de evaporación y un sistema de precalientamiento de agua cruda, mientras la segunda configuración añade una capa reflectiva a las paredes interiores del destilador, guardando el mismo diseño. Además, se diseñó un prototipo de destilación activa que hace uso de una fuenta adicional de energía (colector solar de aire) para aumentar la temperatura de evaporación del agua cruda y así incrementar la cantidad de destilado. El énfasis de la construcción se pone en el uso de materiales locales, económicos y reciclados en la medida de lo posible para asegurar una buena reproducibilidad y para facilitar la posibilidad de construcción autónoma en las comunidades rurales. Los resultados obtenidos son muy satisfactorios respecto a las condiciones climáticas de la región en la cual se realiza el proyecto y respecto a los principios de funcionamiento (destilación pasiva). Se midieron valores promedios diarios de 4.2 L de destilado para la configuración básica del destilador y 4.7 L para la configuración con capa reflectiva en las paredes interiores. No obstante, la construcción del prototipo de destilación activa es altamente recomendable para investigaciones futuras, debido a su capacidad de producción de una suficiente cantidad de agua para el abastecimiento de una familia de cuatro personas. Los resultados de la calidad del destilado indicaron que la purificación de agua por este proceso es adecuada porque eliminó con éxito bacterias, tóxicos y sales. La aplicación adicional de marmolina en el recipiente del destilado asegura una calidad adecuada para la ingesta directa. El prototipo no es económicamente viable, debido al uso de materiales especiales para la charola de evaporación y la caja exterior.

Zusammenfassung

Weltweit wird die sichere Versorgung mit Trinkwasser zunehmend komplizierter. Mehrere Regionen des mexikanischen Hochlandes leiden bereits heute unter einer deutlichen Kontamination des Grundwassers mit anorganischen (z.B. Arsen und Fluoride) und bakteriellen Verbindungen, welche über den offiziell festgeschriebenen Grenzwerten liegen. Eine der betroffenen Regionen ist die Hochebene *Altiplano Potosino* im Bundesstaat von San Luis Potosí. Die Mehrheit der ländlichen Gemeinden verfügt nicht über die angemessene Technologie zur Grundwasseraufbereitung und damit sind deren Einwohner erhöhten Schadstoffkonzentrationen ausgesetzt, welche eine Vielzahl von Erkrankungen, unter anderem die *Fluorose* auslösen. Bedingt durch einen hohen Grad an Marginalisierung und Armut ist es notwendig, dezentrale und erschwingliche Technologien zur Wasseraufbereitung in Erwägung zu ziehen, welche im kleinen Rahmen (z.B. Haushalte) eingesetzt werden können. Der Schwerpunkt liegt hierbei auf einfacher Herstellung, Bedienung und Wartung der Technologie. Ein vielversprechender Ansatz für die Trinkwasserversorgung auf Haushaltsniveau ist die Technologie der solaren Destillation, welche von den hohen regionalen Solarstrahlungswerten profitieren würde. Es ist bewiesen, dass diese Technologie fast alle Arten von Schadstoffen aus dem Rohwasser entfernen kann. Die einfachste und gleichzeitig robusteste Ausführung ist die sogenannte passive Solardistille nach Gewächshausprinzip, welche einen geringen Wasserstand im Verdunstungsbecken und nur eine (nach Süden ausgerichtete) Glasabdeckung besitzt. Der Nachteil dieser Konstruktionsweise liegt in ihrem geringen Destillatertrag (ca. zwei bis fünf Liter pro Quadratmeter bestrahlter Fläche und Tag). Im Rahmen der vorliegenden Masterarbeit werden sogenannte “passive Energiesteigerungsmaßnahmen” angewendet, um den Ertrag auf ein Maß zu erhöhen, welches für die tägliche Wasserversorgung einer vierköpfigen Familie ausreichend ist (circa acht Liter pro Tag unter ausschließlicher Berücksichtigung der direkt konsumierten Menge). Ein Prototyp der passiven Solardistille wurde gebaut und - basierend auf zwei verschiedenen Konfigurationen - die Parameter Destillatertrag, Energieeffizienz, sowie Konstruktionskosten bestimmt. Eine zusätzliche Analyse der Destillatqualität wurde durchgeführt. Die erste Konfiguration des Prototypen ist durch einen geringen Wasserstand und eine Konstruktion zur Rohwasservorwärmung gekennzeichnet, wohingegen die zweite Konfiguration eine zusätzliche reflektierende Innenwandbeschichtung aufweist. Desweiteren wurde ein Prototyp einer aktiven Solardistille entworfen, welche als zusätzliche Energiequelle einen solaren Luftkollektor besitzt. Durch diese Maßnahme werden höhere Prozeßtemperaturen und damit eine Steigerung der täglichen Destillatmenge erzielt. Der Schwerpunkt im Prozeß der Konstruktion wurde auf die Benutzung von regional verfügbaren, preisgünstigen oder wiederverwerteten Materialien gelegt, um die Materialkosten bei gleichzeitiger hoher Reproduzierbarkeit zu senken. Desweiteren fördert diese Vorgehensweise die autarke Herstellung von Solardistillen in ländlichen Gebieten. Die erhaltenen Meßdaten sind sehr zufriedenstellend, sowohl bezüglich der gegebenen Klimaverhältnisse, als auch der Energieeffizienz und des Destillatertrags. Durchschnittliche tägliche Destil-

laterträge zwischen 4.2 l für die “einfache” Version und 4.7 l für die Version mit reflektierender Innenwandbeschichtung wurden erreicht. Für weitere Untersuchungen wird dennoch die Konstruktion der aktiven Solardistille empfohlen, da diese durch einen höheren Destillatertrag dazu geeignet ist, die benötigte Kapazität für die tägliche Trinkwasserversorgung einer vierköpfigen Familie sicherzustellen. Das Rohwasser konnte durch die Anwendung der Solardistille erfolgreich von sämtlichen Verunreinigungen befreit werden und besitzt nach der Applikation von Marmorsteinchen im Produktwassergefäß die angemessene Qualität zum direkten Konsum. Die ökonomische Rentabilität konnte nicht erreicht werden, was auf die Verwendung von speziellen (kostenintensiven) Materialien für Verdunstungsbecken und Gehäuse zurückzuführen ist.

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CFU	Colony Forming Units
EPSEA	El Paso Solar Energy Organisation
FMDR	Fundación Mexicana para el Desarrollo Rural
MPN	Most Probable Number
NOM	Norma Oficial Mexicana (Official Mexican Standard)
NTU	Nephelometric Turbidity Unit
POE	Point Of Entry
POU	Point Of Use
SAC	Solar Air Collector
SDU	Solar Distillation Unit
UASLP	Universidad Autónoma de San Luis Potosí
TDS	Total Dissolved Solids
WHO	World Health Organization
WI	Winrock International

1. Introduction

The expression “Water Crisis” was accepted by the UN World summit in the year 2002 to describe the situation of the worlds’ water resources. Access to safe drinking water will be more difficult in the future, due to various reasons such as population growth, environmental pollution and climate change.

Particularly in the arid regions of the world, the drinking water needs are mainly covered by the exploitation of deep groundwater aquifers. In Mexico, about 75% of the population’s drinking water originates from groundwater abstraction. Especially in the arid northern states of the country (like San Luis Potosí, Durango, Zacatecas and Chihuahua), significantly elevated levels (above the established limits in the NOM) of arsenic and fluorides in the groundwater have been detected, which can cause diseases like the *fluorosis* in the exposed population (Armienta and Segovia, 2008). Fernández García (2007) additionally determined elevated concentrations of coliform bacteria in many shallow and deep wells (7 of 12 samples) in the “Wirikuta” region in the state of San Luis Potosí.

Up to date, purification technologies in the rural regions of Mexico largely rely on filtering by activated carbon and chlorination, thus being ineffective towards many kinds of non-bacterial contamination. In the rural regions of the Mexican Highlands like the “Altiplano Potosino” region, which have a weak infrastructure in matters of access roads and water distribution networks, as well as a high grade of poverty, hardly any groundwater treatment plants can be found. In bigger municipalities ($\geq$ 500 inhabitants), chlorination as a means of disinfection is applied to the distribution grid, though with varying results in bacterial decontamination of the product water. It is common practice that a person, especially employed for this purpose, is manually dosing the chlorine in the reservoir of potable water. The manual dosage of chlorine, financial bottlenecks in the provisioning of the chemicals and the lack of control of the water quality lead to non-reproducible chlorination results. In mild cases, the applied chlorination does not significantly diminish the bacterial load of the water; in severe cases it leads to its further contamination by overdosage. These facts lead to the dependence of the population on the not adequately treated water. Solutions like passive filtration systems (based on activated carbon) had to be discarded in previous studies, due to the high levels of fluorides in the raw water (4.02 mg/L in the city of San Luis Potosí; WHO limit: 1.5 mg/L) of the region and the resulting low lifespan of the filters (Medellin-Castillo et al., 2007). Reverse Osmosis plants are very scarce in the state of San LuisPotosí and not always capable to remove the high concentrations of fluorides successfully (3.53 mg/L of F^- in the product water in one case), according to Castillo-Gutiérrez (2010). Also arsenic is known to be not completely removable in Reverse Osmosis plants (George et al., 2006). Furthermore it represents high-level technology, which needs high investments into infrastructure and maintenance, qualified personal and special spare parts (problem of saturated or broken membranes).

Due to these facts, it is exigent to find a solution adapted to the economical situation of the Altiplano region, which fulfills the qualitative requirements of drinking water as stated in the NOM. A promising solution towards these requirements are small-scale, decentralized technologies which can be easily adapted to the particularities of the project region.

1.1. Introduction to the study area chosen for project implementation

One of the sites in the federal state of San Luis Potosí which is mostly affected by severe droughts as well as contamination of the groundwater aquifers, is the Altiplano region in the north of the federal state. At some places, drastically elevated values of organic and inorganic contamination were detected (in reference to the NOM for drinking water). Apart from the natural and cultural heritage of the site (pilgrimage area of the "Wixárika" people (or *Huicholes*)), there have been extensive mining activities (mainly for silver and gold) in the area, in some

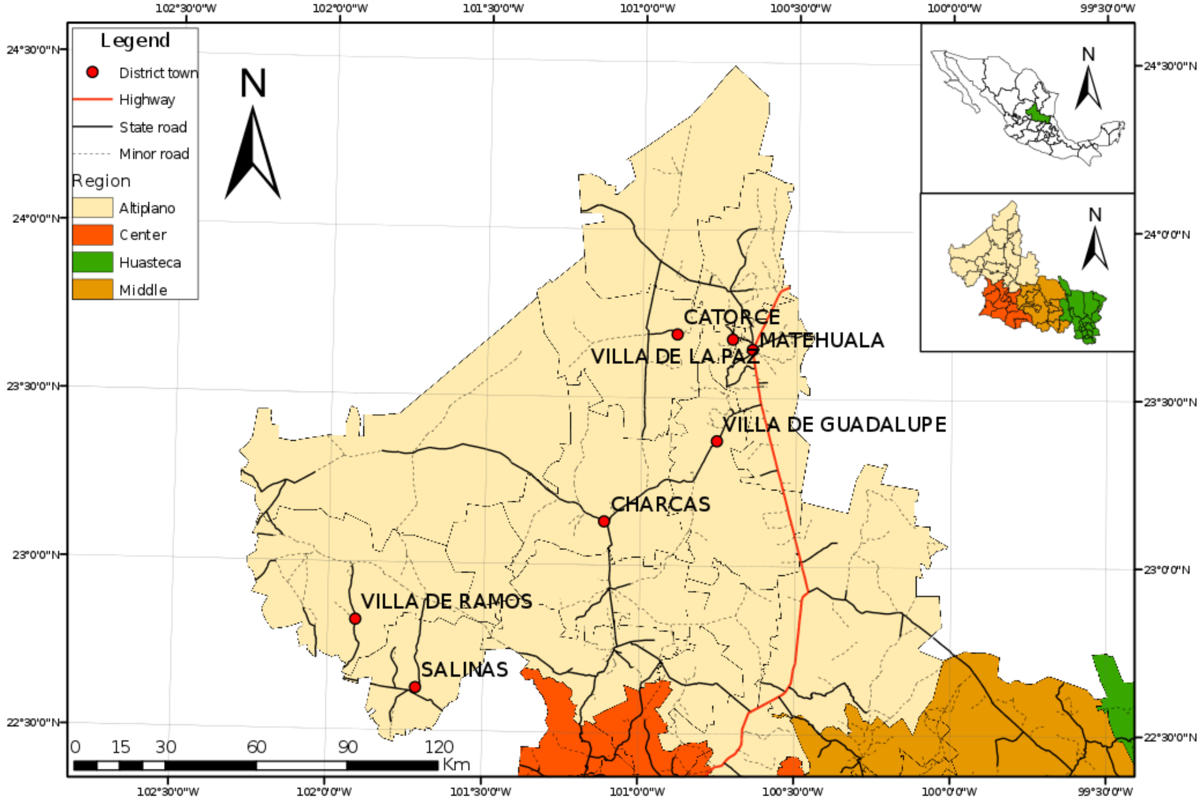


Figure 1.1. Localization of the Altiplano region in the federal state of San Luis Potosí.

parts already since the Spanish conquest of Mexico in the 16th century (e.g. in the municipality of Charcas). The extraction and refining of mineral-rich ores provoked not only a modification of the groundwater flow-patterns, it also led to a deterioration of its quality. Direct influence of mining activities on the levels of arsenic and indirect influence on the levels of fluorides and sulphates in the groundwater is proven. Several point-sources of contamination are added by (former) uncontrolled use of leaching chemicals in the (partly abandoned) mines and toxic residues in the mining dumps (such as mercury, lead, antimony, etc.). This has not only caused a huge damage to the terrestrial and aquatic ecosystems, it also results in severe water scarcity in the city of Matehuala from as long as the beginning of the 20th century. Principal uses of water in the region are domestic use, irrigation (a rather small part) and industrial use in mining (Fernández García, 2007). According to the local authorities, the groundwater system of the region is to be considered as overexploited (De los Santos-Fraga et al., 2008). Both ground- and surface water of the region are affected by varying concentrations of arsenic and fluorides, especially the surface water additionally shows a variable pathogen load, due to effluents from badly- or non-treated domestic sewage water and cattle. Apart from chlorination, which is applied routinely in the bigger municipalities ($\geq$ 500 inhabitants) of the region, the predominant technology of water treatment up to the day, especially in the remote rural parts, is boiling before ingestion. Being an adequate method for bacterial disinfection, it is useless and even dangerous in removing contents of salts, metals and similar contaminants: Boiling concentrates the inorganic (toxic) components in the water, due to its partial evaporation. Because of the weak regional infrastructure, large distances between the municipalities and the predominance of poverty, it is neither common nor feasible for the communities to obtain potable water from tank lorries.

Due to the above-mentioned facts, the risk for arsenic poisoning and diseases like the *fluorosis*, which leads to subsequent teeth and bone damage, exist in the study area (Armienta and Segovia, 2008).

1.2. Motivation

In order to establish a safe water supply for the aforementioned communities, it is necessary and exigent to implement an effective groundwater treatment technology, considering the rural infrastructure (small coverage with electricity grid, no water pipelines and difficult access) as well as social conditions (poverty and marginalization). In favor of the low population density, a decentralized approach towards implementation, which makes use of the high local potential of solar radiation, is promising for a small-scale solution (e.g. a family of up to 4 persons). The fact of poverty demands for a low-cost implementation of the technology, which should have the potential of being self-made. This can be realized using inexpensive, locally available or recycled material for construction. It is very important that the community members are able to identify themselves with the technology, thus being able to construct, maintain and repair their purification units without the need of professional technical assistance. Therefore, the emphasis of the thesis furthermore lies in the attempt to keep the applied technology (as well as materials) as simple and understandable as possible.

1.3. Objective and Justification

The aim of the thesis is to develop a solution for the purification of ground- or surface water, which is capable of liberating it from toxic substances such as heavy metals, dissolved salts, as well as bacteriological contamination. Ideally, such a solution should even be able to purify heavily contaminated water, such as mining- or agricultural effluents. As a base for the development, the following prerequisites are made:

- Dimensioning for the drinking water demand of a small family (three to four persons, i.e. two to five liters per person and day according to Gleick (1996));
- The part of the water which is not ingested (e.g. water for cleaning and other household purposes) is spared;
- The price per unit of water should be as low as possible;
- Adequate water quality for direct ingestion, without the need for further treatment, such as chlorination or boiling;
- Simple and understandable working principle:
  - Maintenance should be possible by local residents;
  - Low running costs and cheap/no expendable parts necessary
- Use of renewable energies/solar radiation for the sake of spatial autonomy and decentralized use

In order to find a solution which is suited best for the circumstances of the project region, several small-scale purification technologies available on the current market are compared in table 1.1. The data applies to POU water treatment technologies, i.e. technologies for household use in small scale (as opposed to the centralized Point Of Entry (POE) water treatment technologies which rely on a working infrastructure and often require huge amounts of energy). Moreover, rural communities in general tend to be unable to finance centralized water supply structures (Peter-Varbanets et al., 2009).

A solution which meets all the proposed requirements and offers adequate water quality at an affordable price, is the technology of solar distillation. Tiwari and Tiwari (2008) and Goosen et al. (2000) emphasize the appropriateness of the technology for regions with high values of solar radiation in conjunction with a high grade of marginalization and lack of potable water, as well as infrastructure (electricity grid and/or water pipelines). Murugavel et al. (2008) states that neither operation nor maintenance of a single-basin Solar Distillation Unit (SDU) needs skilled personnel. Therefore, maintenance and operation costs tend to be very low.

Disadvantages of the so-far implemented solutions are either the use of advanced technology which is difficult to maintain (and therefore fell in disuse, see also chapter 2.1) or the rather low distillate output per unit of area. Therefore, this thesis will try to combine the aspects of “low-cost”, “high-efficiency” and “easy usability” as far as possible in the development and construction of a prototype SDUs, designed for the use in the Mexican Altiplano region. It is planned to investigate two different working principles of solar distillation towards their efficiency and feasibility for the use in the aforementioned region. Namely, these are *Passive Solar Distillation* (chapter 2.3.1) and *Active Solar Distillation* (chapter 2.3.2). Whereas the prototype of the passive SDU will incorporate several so-called “passive energy augmentation techniques”, a new method of energy supply will be tested on the prototype of the active SDU: an air collector made of recycled beverage cans, which is supposed to raise the raw water temperature considerably and therefore accelerates the distillation process. First studies will be made on the prototype of the passive SDU, whose results are taken into consideration for the construction of the second, active SDU prototype. If possible in the given timeframe, a comparison between the two prototypes is to be made, in order to give a recommendation which working principle should be used for further investigation and final implementation in a rural community.

Table 1.1. Overview of POU water treatment technologies.

Technology	Advantages	Disadvantages	Price per m^3 (US$)
Reverse Osmosis (Elfil et al., 2007; Al-Jayyousl and Mohsen, 2001)	• Removal of many organic- and inorganic compounds • Throughput: up to 5 L/h	• Recovery rate 25-37%, rest is effluent water • High initial costs • High maintenance costs (membranes, filters) • High inlet pressure necessary (2-6 bar) or additional pump (electricity costs) • No secure arsenic and pesticide removal (George et al., 2006; Hanson et al., 2004)	15 - 70
Activated carbon filters (Dvorak and Skipton, 2008; Johnson, 2005)	• Removal of organic compounds (which impair taste and odor) and chlorine • Very scalable technology; from pour-through-filters up to water-tank cartridges • Moderately cheap solution • Throughput depends on size of activated carbon - cartridge	• Ineffective towards arsenic and other inorganic contaminants • No removal of viruses and bacteria • No reproducible results (water quality is function of contact time, pore size and amount of carbon in the filter) • Clogging by use of surface water • Danger of bacterial growth in filter when not in continuous use • Pour-through filters very ineffective • Routine replacement necessary	not determinable, due to very variable prices and performance (water quality and quantity)
Clay-Pot filter (van Halem et al., 2009)	• Cheap and local manufacturing (4-8 US$ per unit) • Throughput: 1 - 3 L/h • Removes bacteria	• Total lifespan: 5 years • Effective operation secure for three months • No virus or inorganic compounds removal (arsenic, fluorine) • No use of surface water (clogging) • Frequent maintenance necessary	1.8 - 3
Chlorination (Keenan and Hegemann, 1978)	• Bacteria, virus and metal (Fe, Mn) removal • Cheap technology • Possibility of autonomous use (chlorine pills) • Scalable throughput	• Possible formation of noxious compounds • Precise dosage and quality control necessary • No inorganic compounds removal (arsenic, fluorine)	1 - 10 (Sobsey et al., 2008)
Electric distillation (Derickson et al., 1992)	• Removes 99.5% of water impurities, including arsenic and fluorides • Removes bacteria and viruses • Small and easy-to-handle equipment	• High initial costs (200-1000 US$ per unit) • Need for electricity grid • Continuous running costs (electricity)	77 - 110
Solar distillation (The Schumacher Centre for Technology & Development, 2008; Foster and Eby-Martin, 2001; Tiwari and Tiwari, 2008; Ghoneyem and Íleri, 1997)	• Removes 99.5% of water impurities, including arsenic and fluorides • Removes bacteria and viruses • Autonomous use possible, no need for infrastructure (electricity, water pipes) • Nearly no restrictions in type of raw water (brackish, saline, high amount of TDS possible) • Easy handling, no skilled personnel necessary • Local manufacturing / repairing possible • Very low running- and maintenance costs	• Low water output (2 - 6 L per m^2 and day) • Efficiency dependent on salinity of water, solar radiation and ambient temperature • Relatively high investment costs (from 82 to 650 US$ per m^2 for commercial SDU) • Not recommendable for large-scale use, due to high land use and investment costs	4 - 29 (calculated assuming a yearly production of 1 m^3 of water and a lifespan of 20 years for the SDU)

2. Solar Distillation

The term *Solar Distillation* refers to the evaporation and successive precipitation of raw water, thus purifying it. Basically, there are two principles to be distinguished: direct solar distillation, which is characterized by its immediate use of solar energy to evaporate raw water; and indirect solar distillation, which makes use of more sophisticated energy conversion techniques for raw water heating. Frequently, indirect solar distillation additionally separates the evaporation and condensation processes spatially in order to raise the distillate yield. The basic distinction between the two principles is illustrated in figure 2.1. Although indirect solar distillation in many

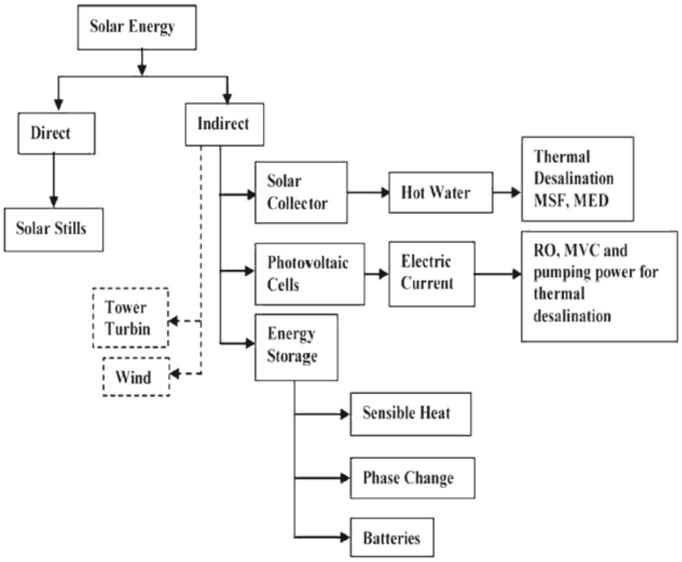


Figure 2.1. Classification of solar distillation systems (Ettouney and Rizzuti, 2007).

cases proves to have a higher distillate output than direct solar distillation, the technology applied is very costly and frequently also shows difficulties in handling and maintenance (due to its high level). Therefore, in this thesis will be made use of the principle of direct solar distillation, due to various reasons, such as low construction costs, simple maintenance, easy reproducibility and the possibility of completely autonomous use - to fulfill the prerequisites for an implementation in rural areas, as mentioned in chapter 1.3.

The technology of direct solar distillation may be seen as a technological implementation of the earth's natural water cycle, i.e. evaporation of water, condensation and precipitation. In analogy to the natural water cycle, the energy source of the process is also the sun. Ideally, the distillation process takes part in a closed, greenhouse-like environment, where the solar radiation gets converted into heat, which is the driving force for the evaporation of raw water.

The most basic type of SDU, also called *Solar Still*, is the single-slope, basin-type still, which is depicted in figure 2.2. In the first step of the distillation process, raw water is heated by the incident solar radiation which passes the transparent (glass) cover. For optimal heat transmission onto the raw water, the basin has a black color. As the raw water reaches temperatures between 50 - 80°C, the evaporation accelerates and water vapor is rising towards the transparent cover (step two). The third step consists in the condensation of the water vapor at the colder cover (temperature difference between 10 and 30°C towards the raw water), its precipitation and

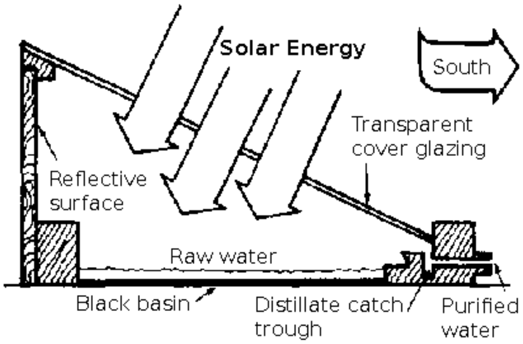


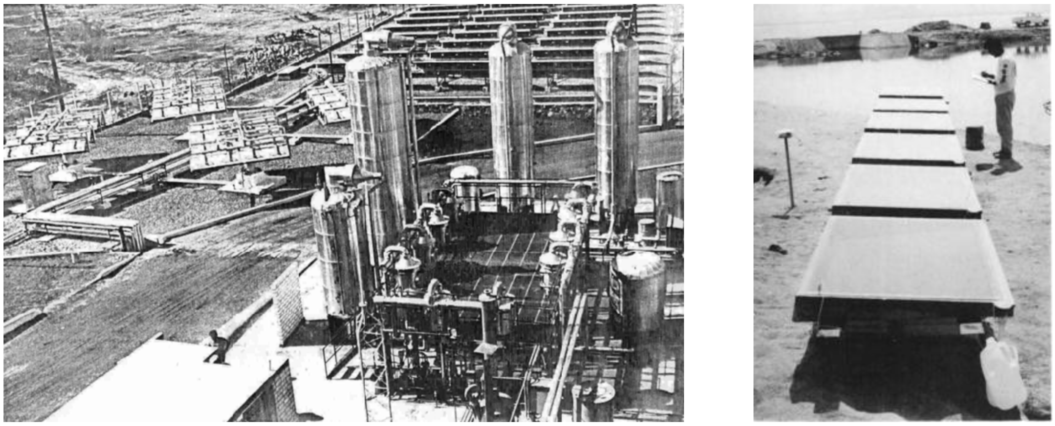
Figure 2.2. Working principle of a single-slope solar still (adapted from McCluney, 1984).

(due to the inclination of the cover) runoff to the catch trough, where it is recollected as purified water. For better process efficiency, several measures can be implemented in the design of the still, one of them is the use of reflective surfaces at the walls of the unit, in order to maximize the input of solar energy. Chapter 2.2 describes this possibility, as well as other measures of efficiency-improvement in more detail.

2.1. Historical Background

The (documented) application of solar distillation with the purpose to purify water reaches back until the 15th century, where it was applied by an unknown Arab alchemist. More precise descriptions are found in the work "Magiae naturalis sive de miraculis rerum naturalium" of the Italian alchemist *Giovanni Battista Della Porta* which was published in 1558, being the first work to contain details on solar distillation with earthenware pots and "water harvesting" from air humidity. The first practical experience with solar distillation was reported by the US-Americans *Wheeler* and *Evans* in the year 1870, which investigated the basic principles and challenges of solar distillation in order to patent the technology. From their work surged basic knowledge about the influence of environmental factors on the process efficiency, as well as constructional challenges (e.g. corrosion). Shortly after, in the year 1872, the first large-scale industrial implementation of *Solar still distillation* was made in a saltpeter mine in Chile, for the supply of workers and cattle with freshwater. The Swedish engineer Charles Wilson constructed a huge array of solar stills (surface area: 4450 m^2), which was capable to provide 22.7 m^3 of purified water per day. The construction consisted of 64 wooden evaporation bays, covered with simple glass sheets. After 40 years of continuous operation, the distillation unit was abandoned, due to the installation of a freshwater pipe. Until the Second World War, there was a rather moderate interest in the technology, but from the 1940s onwards, the US Military started investigations on how to implement autonomous water purification solutions for the use at e.g. open sea. At this time, various designs of SDUs were investigated and the basis for the construction of shallow-basin-, tilted-wick- and multiple-effect-solar stills, as well as humidification-dehumidification greenhouse units was laid (see also sections 2.3.1 and 2.3.2). Research activities were mainly concentrated in the universities of California /Berkeley, New Delhi/India and Melbourne/Australia. Between 1960 and 1970, the first large scale implementations of newly designed SDUs (for seawater) were made, mainly in Greece for the freshwater supply of remote islands (capacity: 2044 to 8640 m^3 per day). Today, hardly any of the aforementioned plants is functional and no new large-scale installations have been done in recent years (Kalogirou, 2009).

In Mexico, the first installation of small-scale SDUs took place between 1972 and 1976. The units had a surface area of 0.8 m^2 and were designed for the purpose of freshwater supply of remote communities. Regardless of the good technical results, the units had a very short lifetime, due to non-acceptance of the technology in the communities. The same fate stroke a Mexican-German joint-venture project called *Sontlán* which was established in 1980 in the federal state of Baja California (see also figure 2.3(a)). Incorporating high-technology multiple-effect and multiple-stage SDUs, the plant was capable of producing 17 m^3 of freshwater per day. Due to the difficult maintenance, costly spare-parts and the need for highly-skilled personnel for plant operation, the project was abandoned only a short time after its inauguration. The first successful project of a medium scale SDU was realized in the federal state of Baja California Sur in the year 1989. With a total surface area of 384 m^2, the SDU produced 1.6 m^3 of freshwater per day (about 4.2 l/m^2). Up to date, the biggest installation of SDUs can be found in the municipality of Puerto Lobos in the federal state of Sonora; the installation is comprised of many shallow-basin stills forming a total surface area of 480 m^2 with a daily production rate of 1.5 m^3 of freshwater. Figure 2.3(b) shows an example of the type of SDUs used in the installation. A remarkable insight regarding the operation of SDUs in Mexico is, that none of the mentioned units stayed



(a) Photo of the *Sontlán* project (Fernández Zayas and Chargoy del Valle, 2005).

(b) Shallow-basin solar stills (Porta et al., 1998).

Figure 2.3. Examples of SDUs in Mexico.

in operation after the period of professional supervision terminated (Porta et al., 1998).

In the federal state of San Luis Potosí, successful implementation of small-scale SDUs is reported from the year 1999, when a joint-venture project of the organizations Fundación Mexicana para el Desarrollo Rural (FMDR) and Winrock International (WI) started to install a total of three shallow-basin solar stills in the cities of San Luis Potosí, Rio Verde and Matehuala. The SDUs were provided to single households in the context of a three-year financing scheme and accompanied by supervision of technicians of the FMDR. The user's experience with the technology is described as throughout positive, with the remark that a previous familiarization with its usage is necessary (Santana and Foster, 2005).

2.2. Basic principles of distillation processes

The term of *Distillation* refers to a combination of two separate processes, namely *Evaporation* and *Condensation*, which in conjunction serve to purify substances. Distillation is always taking place in a closed system (e.g. a box), in order to prevent losses. The product can be either the condensate (in case of a SDU) or the concentrated residue which is not evaporated.

Evaporation is a surface phenomenon of a fluid layer, where molecules with a higher energetic level are leaving the compound and thereby change from the liquid to the gaseous phase (vapor). The higher the fluid temperature, the more molecules are changing their state. In contrast, boiling happens in the entire fluid volume when the vapor pressure exceeds the atmospheric pressure. The process is taking place at a constant temperature (e.g. 100°C at 1013 hPa of atmospheric pressure for water), until the fluid has completely evaporated. In general, the substance which should be distilled has to be heated to at least a certain temperature, in order to raise the process efficiency. Theoretically, evaporation takes place from the melting-point of a substance onwards, until its boiling point. Nevertheless, with more energy available to the process it will take place in a shorter timespan.

The process of condensation can be seen as the counterpart of evaporation: the vapor condenses due to reaching its dew point at a surface bearing a lower temperature than itself. In this process, the vapor releases the quantity of energy acquired by evaporation, cools down and converts into liquid.

Energetic working principles

Figure 2.4 shows a schema of the energetic processes in a solar still-type SDU. In order to estimate the energy input for a distillation process, it is useful to split the process into two parts (which happen simultaneously):

1. Heating up the raw fluid
2. Transformation from the liquid to the gaseous phase

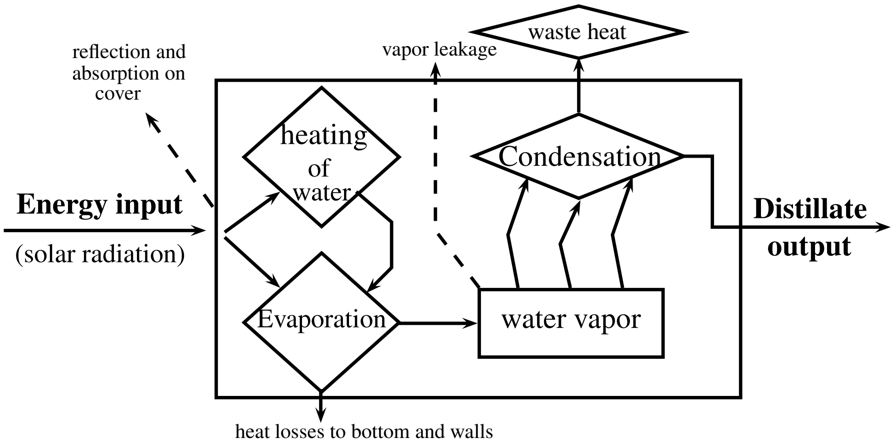


Figure 2.4. Energetic working principle of a single-basin solar still.

Practically, most distillation processes have a working temperature range between 30°C and 90°C, to which the fluid has to be heated in a first step (assuming that it does not already have a sufficient temperature). Therefore, the quantity of energy for heating up the fluid to a suitable temperature has to be calculated in a first step:

Heating energy

$$Q_H = m * c * \Delta T \tag{2.1}$$

Where Q_H is the necessary heating energy in [kJ], m the mass of the fluid in [kg], c the specific heat capacity of the fluid in [kJ/kg*K] and ΔT the temperature difference in [K].
For example the necessary energy for heating up one kilogram of water from an ambient temperature of 20°C to 50°C (this is the approximate temperature in which many passive SDUs work), would be calculated with:

$$Q_H = 1[kg] * 4.19 \left[\frac{kJ}{kg * K} \right] * 30[K]$$

where 4.19 kJ/kg*K is the specific heat capacity of water.

$$Q_H = 124.2[kJ]$$

The result of 124.2 kJ is also known as the quantity of "sensible heat" which the water contains.

Energy necessary for vaporization

In order to convert water molecules from the liquid to the gaseous phase, the quantity of heat ΔH_{vap} which is called **enthalpy of vaporisation**, is necessary. The enthalpy of vaporisation is defined as the amount of energy needed to transform a quantity of substance from the liquid to the gaseous phase at a given (constant) temperature and ambient pressure. For example, the value for water would be 2257 kJ/kg at 100°C and an ambient pressure of 1013 hPa. Table C.1 on page 131 contains the values of the enthalpy of vaporisation for the temperature range of 0°C to 100°C.
In order to calculate the energy required by the process, the dimension **heat of evaporation** is introduced:

$$Q_{vap} = m * \Delta H_{vap} \tag{2.2}$$

This form of energy is also denominated as “latent heat”, because it is used in the process of phase change.

Depending on the temperature to which the fluid was heated in the first step, the (according) heat of evaporation has to be summed to the heating energy Q_H, in order to determine the total energy need Q_{tot} in [kJ] for the evaporation process.

$$Q_{tot} = Q_H + Q_{vap}$$

or substituting eq. 2.1

$$Q_{tot} = m * (c * \Delta T + \Delta H_{vap}) \tag{2.3}$$

If no constant energy input is given, the fluid would cool down in the process of evaporation, because Q_{vap} is taken from the sensible heat of the fluid mass. Continuing the example from the anterior section, the total energy necessary to evaporate one kilogram of water which has been heated from 20°C to 50°C would be:

$$Q_{tot} = 1[kg] * (4.19 \left[\frac{kJ}{kg * K}\right] * 30[K] + 2382.7 \left[\frac{kJ}{kg}\right])$$

$$Q_{tot} = 2508.4[kJ]$$

It has to mentioned that this amount of energy is approximated, due to the fact, that the amount of latent heat in the temperature range from 20 to 50°C was neglected (theoretically it has to be considered, due to parallelism of the two processes). Doing so, results in a marginal error of approximately 3%.

Condensation

Assuming that there are no (or negligible) losses in the (closed) system, the majority of the energy of evaporation is released again in the process of condensation. This amount of energy is composed by the heat of evaporation and a part of sensible heat which is surging from the temperature loss of the vapor at the condensing surface. To calculate the release of energy in the condensation process the dimension Q_{rc} is introduced:

$$Q_{rc} = m * c * (T_f - T_{surf}) \tag{2.4}$$

with T_f being the temperature at which the fluid evaporates and T_{surf} the temperature of the condensing surface. The sum of energy released in the condensation process is given by:

$$Q_{cond} = Q_{vap} + Q_{rc} \tag{2.5}$$

It is important to assure a good heat removal from the condensing surface, in order to keep an acceptable process efficiency. Furthermore, a big difference between the temperature of evaporation and the temperature of the condensing surface promotes a high efficiency of the entire process. Continuing the given example, an energy of

$$Q_{cond} = 2382.7[kJ] + (1[kg] * 4.19 \left[\frac{kJ}{kg * K}\right] * (50 - 30[K])) = 2466.5[kJ]$$

will be released in the condensing process, assuming that the condensing cover has a temperature of 30°C (which is likely in the case of passive SDUs).

Energy losses in SDUs

Putting the principle of distillation into practice in form of a SDU, various losses in the distillation process are inevitable and have to be considered in its implementation. Not only that the evaporation process itself will only work with a limited efficiency, which means re-condensation of water vapor before it reaches the condensing surface; also the condensation process will lose efficiency due to the practical inability of the condensing cover to immediately discharge the occurring heat. Further losses are the following (percentage values provided by Quaschning, 2005):

- Vapor leakage due to not entirely sealed housing (Murugavel et al., 2008);
- Conductive heat losses to the bottom and/or the side walls due to not completely insulatable housing - approx. 3%;
- Distillate loss due to backdrop into the evaporation basin (caused by dirty cover or too small cover inclination);
- Absorption (approx. 2%) and reflection (approx. 8%) of incident sunlight by the cover glass;
- Reflection of sunlight by water surface and basin - approx. 8%;
- Heat losses by convection (approx. 13%) and radiation (approx. 6%) at the water surface

Due to these systematic and unavoidable losses, the overall energy efficiency of a passive SDU is likely not to reach values above 60%. The overall efficiency of a SDU is also greatly influenced by its design; section 2.2 shows various considerations in order to optimize its construction and therefore reach higher distillate outputs.

Efficiency of SDUs

In general terms, the overall energetic efficiency of a solar still can be roughly calculated by the following equation:

$$\eta_{SDU} = \frac{\Delta H_{vap} * m_{D,d}}{Q_{sol,d}} \tag{2.6}$$

With $m_{D,d}$ being the mass of daily distillate production and $Q_{sol,d}$ the sum of daily solar radiation on the inclined surface of the solar still (adapted from McCracken and Gordes, 1985). For more detailed information on the efficiency of different implementations of SDU, see sections 2.3.1 and 2.3.2.

The preliminary calculation of the distillate output proves to be quite difficult. Present thermodynamical models show either deficiencies regarding the geometrical design of the unit or are only valid for a specific temperature range (e.g. until 50°C or above 70°C). Also the material of the condensing cover and its properties, as well as the influence of wind speed on heat removal (wind loss coefficient) impose uncertainties (Shawaqfeh and Farid, 1995). In conclusion, this demands for advanced mathematical and thermodynamical models and simulations, which can not be treated in the scope of this thesis. Tiwari and Tiwari (2008) provide the base for analytical, thermodynamic approaches towards the distillate yield of a SDU.

Capability of substance removal

Generally, evaporation leaves behind all the substances of a fluid mixture, which have a higher boiling point than the main fluid. For the case of solar distillation, the following substances can efficiently be removed (residues in the distilled water $\leq 0.05\%$, (Hanson et al., 2004; Foster and Eby-Martin, 2001)):

- Arsenic, fluorides and heavy metals
- Hardness (calcium, magnesium and other mineral compounds)

- Molybdenum and selenium
- Nitrates and chlorides
- Manganese and ammonia
- Dissolved solids

Bacteria and viruses could even be removed with an efficiency of 99.9%, if cross contamination with the raw water source is avoided. Pesticides can only be removed partially, depending on their volatility. Examinations conducted by Hanson et al. (2004) showed that volatile organic compounds could not be removed very efficiently, but stayed in the permissible limits for drinking water. Nevertheless, if the raw water is contaminated by such substances, it is recommended to make a careful analysis in advance.

Substances which can not be removed include highly volatile compounds, such as petrol and alcoholic compounds. In such cases, it is recommended to use an activated carbon pre-filter (Hanson et al., 2004).

Influence of environmental conditions on the process of solar distillation

The following factors have a positive impact on the efficiency of shallow-basin solar stills (Murugavel et al., 2008; Tiwari and Tiwari, 2008):

- Sunlight with a high fraction of direct radiation (important for the heating process);
- High ambient temperature (beneficial for the evaporation process);
- Moderate to high wind speed (cooling of condensation cover);
- Raw water with a low to moderate salinity (improves evaporation)

Tiwari and Tiwari (2008) also state that contents of fluorides, arsenic and iron in the raw water hardly affect the evaporation rate of a solar still, in contrast to sea water which is more energy-intense to evaporate, due to its high content of dissolved salts.

A factor with potential influence on the distillation process could also be the geological height of the location of the SDU. The variation in atmospheric pressure (between e.g. sea level and very elevated terrain) has a direct influence on the evaporation rate and the boiling point of water. Up to date, there seems to be no scientific article which investigated this phenomenon. Therefore it is also not known to which extent there could be a measurable influence on either the process efficiency or distillate output.

Parameters for optimization of SDUs

Apart from the climatological parameters, there are several considerations in the design of a SDU in order to minimize energy losses and consequently to maximize the distillate output. These measures in general apply to all forms of basin-type solar stills (which is the design used for the prototypes investigated in this thesis) and should be followed to the greatest extent possible in order to reach satisfactory results. Starting with the properties of the glazing (condensing cover), the recommendable measures are the following:

Condensing cover

Usage of highly transparent, low-reflection glazing in order to minimize the energy entrance losses (see also section 2.2). An ideal material for this is glass, as opposed to plastic covers which degrade with constant ultraviolet radiation and heat from inside and outside the still, which subsequently leads to a higher opacity and therefore to high energy losses. Furthermore, glass shows a superior wettability compared to plastic materials, which is important for a satisfactory condensation of the water vapor and its runoff. The life expectancy of (ordinary) glass is expected to be about 50 years (McCracken and Gordes, 1985).

Therefore, on the short-term perspective, glass may impose a higher initial cost but proves to be a reliable and easy-to-maintain material (Murugavel et al., 2008). The thickness should lie in between three and five millimeters, as a compromise between stability and the possibility of discharge of heat to the atmosphere, which is arising from the condensation process (Ghoneyem and Íleri, 1997). Furthermore, a low glass thickness leads to a minimized absorption of solar radiation in the glass itself, thus lowering its warming-up. Tiwari and Tiwari (2005) state very satisfactory results of distillation efficiency using a glass cover of four millimeters thickness. According to Singh and Tiwari (2004) as well as other authors, the inclination of the condensing cover should be equal to the latitude of the project location, in order to optimize the distillate output throughout the year. Practically, the still would work effectively with lower values of inclination in summer (starting from about 10°) and higher values for the winter period (up to 60°), due to the change of the sun's elevation in the course of the year (Tiwari et al., 1994). Another important factor is the distance between the evaporation basin and the condensing cover: It should be as small as possible (in the magnitude of a few centimeters), according to McCracken and Gordes (1985) for guaranteeing a high distillate yield. Practically, this is difficult to handle for basin-type stills, due to the aforementioned assumption that the condensing cover should have the same inclination as the latitude of the project site. Tilted wick stills and stepped stills are advantageous concerning this aspect (see also section 2.3.1).

Enclosure of the SDU

An ideal enclosure of a SDU should resist environmental forces like strong wind and rain. It furthermore should form a hermetical enclosure for the distillation basin, thus being resistant to degradation by aforementioned rain, as well as elevated values of ultraviolet radiation. For the sake of minimizing heat losses from its inside to the environment, it should have a low thermal conductivity or optionally be well isolated.

Materials like plastic or fiberglass are inadequate, because they tend to deteriorate and/or emit potentially harmful substances, especially in the upper temperature range of 60 to 80°C in connection with the high air humidity inside the still; thus having a negative impact on the distillate quality. A construction of metal seems to be a technically viable option, but imposes high costs, especially in relation to manufacturing, handling and impregnation against humidity. Furthermore a rather huge layer of isolation material has to be applied inside the still, due to the high thermal conductivity of metal, which leads to further costs. A combination of metal on the inside of the still and other materials like wood or plastic on the outside could be a compromise in order to lower the construction costs. Nevertheless, the different expansion coefficient of a compound construction metal/wood could be problematic due to the extreme variation of ambient temperatures in the project region (see table 3.1 in section 3.1).

Constructions of concrete are economically viable, but also impose difficulties in building and maintenance. In addition they tend to deteriorate over time, due to weathering of the concrete. Nevertheless, metal-reinforced concrete may be an adequate construction material for larger installations of solar stills on ground level. Wood may be seen as an economically and ecologically feasible option, but a good impregnation has to be considered in order to shield it from deterioration or warping. An option could be the use of high-quality hardwood, such as cypress (McCracken and Gordes, 1985) or for the state of San Luis Potosí *mesquite wood* (see also section 3.2).

Isolation

In order to keep the temperatures in the evaporation basin as high as possible throughout the day, the basin needs to be isolated against the bottom of the solar still. Additional isolation of the side walls contributes to minimize the energy losses in the entire system. Commonly used material for this purpose is polystyrene foam or polyurethane (McCracken and Gordes, 1985), but the use of glass- or rock wool is also possible (Badran, 2007). Another option is to use aluminum foil on the inner rear wall (and optionally on the vertical side walls) of the distiller. It fulfills two important functions: 1. Improved thermal isolation of the distillation chamber and 2. Redirection of incident solar radiation towards the evaporation basin. By this measure, the overall productivity of a passive solar still can be raised by 20 to 30% (Al-Hayek and Badran, 2004; Abdallah et al., 2008).

Evaporation basin

For the design of the evaporation basin, it should be considered that it should withstand the potential aggressivity of the raw water (e.g. highly corrosive mixtures of dissolved salts) in conjunction with high operating temperatures (until 80°C). McCracken and Gordes (1985) recommend aluminum coated with silicone rubber as an adequate material for the basin and emphasize that most materials (including copper, galvanized steel, plastics and fiberglass) only last between few months and a few years. The basin should warm up as much and as fast as possible by the solar radiation, therefore it is important to coat or paint it with a black material or color which can withstand constant contact with water as well as high temperatures.

Water level

The raw water level in the still plays a very important role in distillation efficiency: The lower it is, the faster the water warms up and starts to evaporate. On the other hand, small changes in solar radiation already affect the distillation rate. An increase in water depth elevates the heat capacity of the water and therefore provides a more uniform process of distillation which is prolonged even after sunset, but generally operates at much lower temperature levels (Murugavel et al., 2008) and energy efficiencies (approximately 25 to 35%). These so-called “deep-basin” solar stills (water level: 10 to 50 cm) are recommendable for larger installations, also due to easier maintenance. Due to the commonly lower water level (usually one to three centimeters) in shallow-basin stills, the evaporation takes place faster and at higher temperature levels, resulting in a superior energy efficiency and a higher distillate output. Actually, it is recommendable to keep the water level as low as possible in these stills (Sampathkumar et al., 2010) - see also figure 2.5.

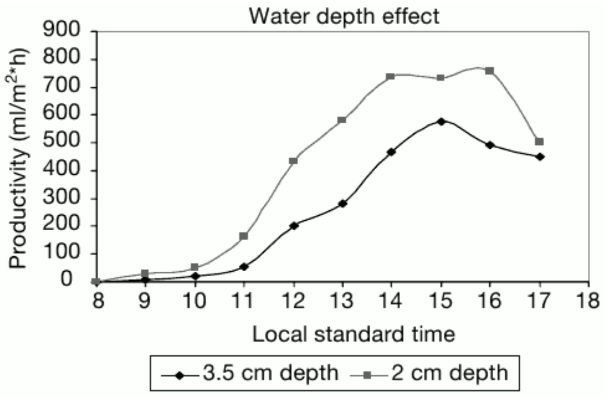


Figure 2.5. Influence of raw water depth on the productivity of a SDU (Badran, 2007).

Raw water temperature

Concerning the temperature of the raw water, pre-heating is very recommendable in order to augment the evaporation rate. Pre-heated raw water can immediately be evaporated and does not need to be warmed up in the distillation basin. This can be done either by using waste heat from other processes or simply by exposing the raw water to solar heat before it gets fed into the distiller. While active systems (see section 2.3.2) frequently use a collector coupled to the solar still, passive systems can benefit from pre-heating the water in the (black-painted) storage tank which is exposed to sunlight. Raw water temperatures of over 80°C avoid the formation of algae (McCracken and Gordes, 1985), which is impairing the absorption of solar radiation, and at the same moment raise the distillate output about 50% compared to the temperature range of 30 to 50°C (Schwarzer, 1995).

2.3. Technological implementation of solar distillation

There are several different ways on how to implement the technological working principle of solar distillation. Especially in the Second World War and in the epoch of the 1970s (in times of the global oil crisis), there have surged many innovative still designs in order to maximize the yield. Recent innovations in material science and computational models contributed to the advance of the technology.

The selection of the technologies presented in the following paragraphs is based on the possibility of stand-alone-use of the units, this means that they are not part of a bigger solar distillation system. First of all, there is a distinction between passive and active SDUs, which is based on the form of energy supply of the units. While passive solar distillation is using exclusively the incident solar radiation on the condensing cover and evaporation basin as an energy supply for the distillation process, active solar distillation makes use of additional heat sources, such as solar collectors - thus incrementing the energy amount available to the system and therefore at the same time the distillate output. Figure 2.6 shows the most common forms of implementation of passive and active solar stills, which will also be discussed in the following sections.

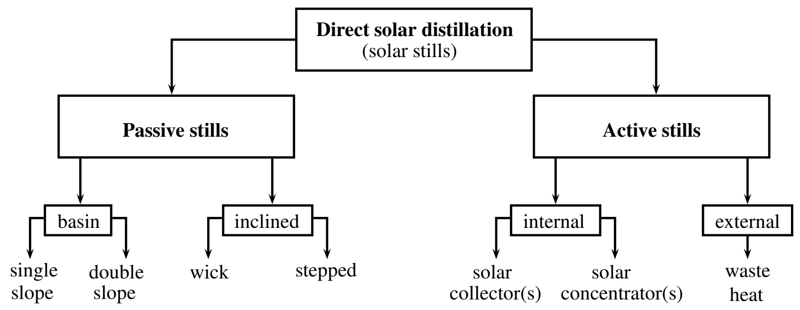


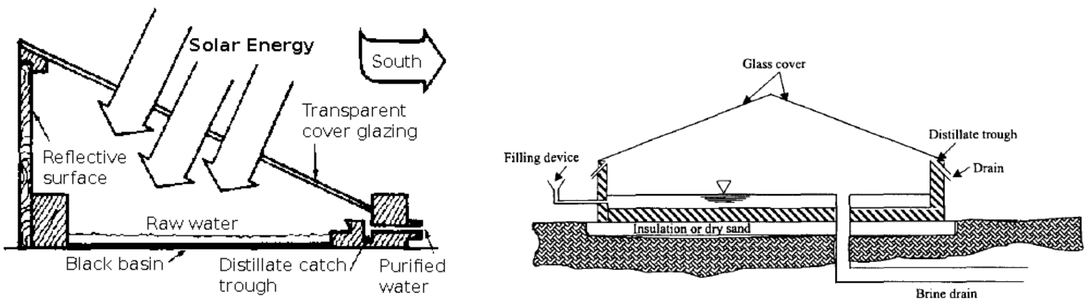
Figure 2.6. Overview of solar distillation systems (adapted from Goosen et al., 2000; Tiwari and Tiwari, 2008).

2.3.1. Passive Distillation

The most simple form of a passive still is the single-slope, basin-type solar still, as shown in figure 2.7(a). This design combines easy manufacturing with low material costs (use of local or recycled material possible); the disadvantage is its low distillate output of two to six liters per day and square meter - depending on the location and applied energy-augmentation measures (as discussed in section 2.2). This design is viable for locations with a latitude greater than 20°; for locations below this latitude, it is recommendable to use the design of the double-slope, single-basin solar still, as depicted in figure 2.7(b), due to the higher solar elevation angles (Murugavel et al., 2008). This type of solar still only has slightly higher material costs, due to the use of a bigger number of glass sheets. For practical reasons (water supply for entire communities), this type of still frequently is constructed as a deep-basin still on ground level with water depths between 10 and 50 centimeters, whereas the single-slope still mostly serves as purification unit for small-scale domestic purposes and has a water depth of only a few centimeters.

The overall energy efficiencies (see also 2.2) of the two types of solar stills vary between 25 and 45% for commonly built models (The Schumacher Centre for Technology & Development, 2008; McCracken and Gordes, 1985), with the single-slope still generally having a 10% higher efficiency than the double-slope still (Al-Hayek and Badran, 2004). In particular cases, efficiencies of up to 60% have been reached.

Commonly, the evaporation process takes place in a temperature range from 20 to 50°C (Sampathkumar et al., 2010), depending on climatic and design factors, which are mentioned in the sections 2.2 and 2.2. An approach to raise the efficiency of solar stills is to minimize the space between evaporation basin and condensing cover. What seems difficult to do in basin-type stills - due to the angular adjustment of the condensation cover - can be done by so-called “inclined passive stills” which let the raw water pass over an inclined surface (ideally) parallel to the condensing cover. Most frequently used is the tilted-wick still (figure 2.8(a)), where the water runs

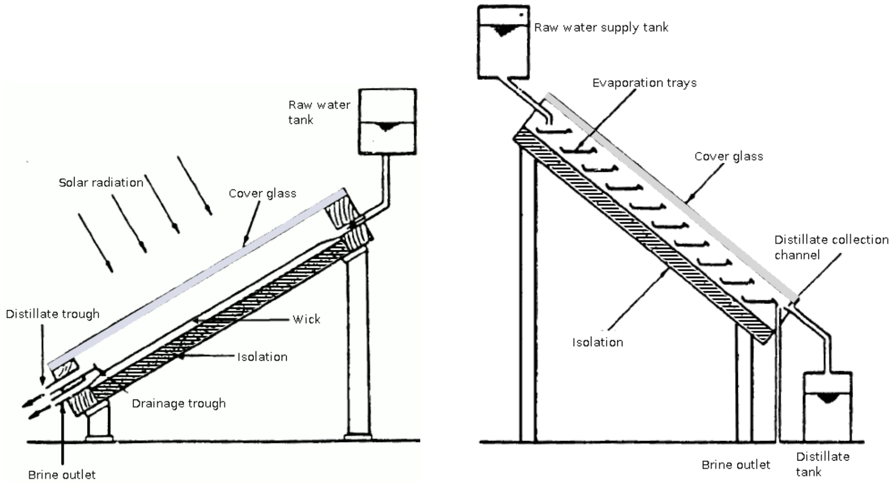


(a) Single-slope, basin-type solar still (adapted from McCluney, 1984).

(b) Double-slope, basin-type solar still (Goosen et al., 2000).

Figure 2.7. Simple solar still designs for passive distillation.

over a dark cloth or is absorbed to the latter by capillary effect. In comparison to the single basin still, the distillate production augments by 29.6%, according to Velmurugan et al. (2008). Apart from the acceptable distillate yield, the construction costs are comparable to those of a single-basin solar still. The mayor drawback of this technology is the fast aging of the used cloth in the process, caused by the strong insolation as well as mineralization of salts contained in the raw water. Therefore it has to be changed and/or cleaned frequently, which is another cost factor. Depending on the working principle, an additional pump may be needed to guarantee a constant flow rate and homogeneous wetting of the cloth. A pump can also be necessary to redirect the effluent brine onto the cloth. In order to overcome the difficulties which imposes the use of a cloth, another similar design has been developed: The stepped-basin solar still, which is depicted in figure 2.8(b). This still consists of several small trays which are connected in form of a stair. A thin layer of water is constantly flowing over them, thus evaporating rapidly. The distillate production of the stepped-basin solar still is estimated to be about 80% higher than the single-basin solar still (Abdallah et al., 2008). Disadvantages are the elevated material costs and a more complicated assembly and maintenance. This still also generates a constant brine output which has to be recycled (pump) or disposed of (the latter lowering the overall efficiency considerably).



(a) Tilted-wick still. (b) Stepped-basin still.

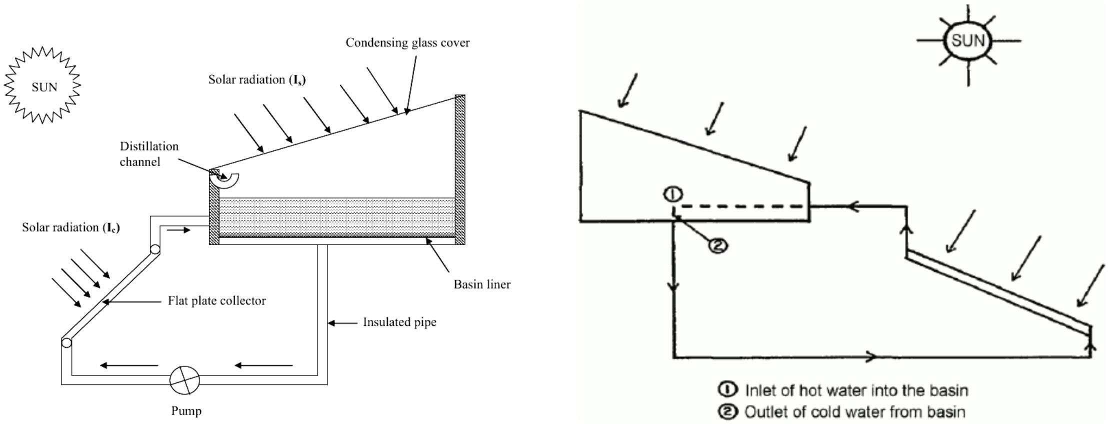
Figure 2.8. Advanced solar still designs for passive distillation (adapted from McCracken and Gordes, 1985).

2.3.2. Active Distillation

As mentioned before, the process of active solar distillation obtains additional energy from other sources, the most common one being an additional solar (water) collector, connected to the evaporation basin. The usage of pre-heated raw water raises the evaporation rate and therefore also the overall distillate output by approximately 35 to 50%, compared to a single-basin solar still (Yadav, 1991; Ettouney and Rizzuti, 2007). Evaporation temperatures are higher than in passive distillation, about 70 to 80°C (Sampathkumar et al., 2010). Generally, there are two working principles of the additional hot water collectors:

1. Thermosiphon mode: The water circulates from the evaporation basin to the collector and vice versa by force of gravitation and gradients in water density, due to the temperature difference between hot and cold water.

2. Forced circulation mode: An additional pump is connected between evaporation basin and collector, thus guaranteeing a constant flow rate and faster raw water warming.

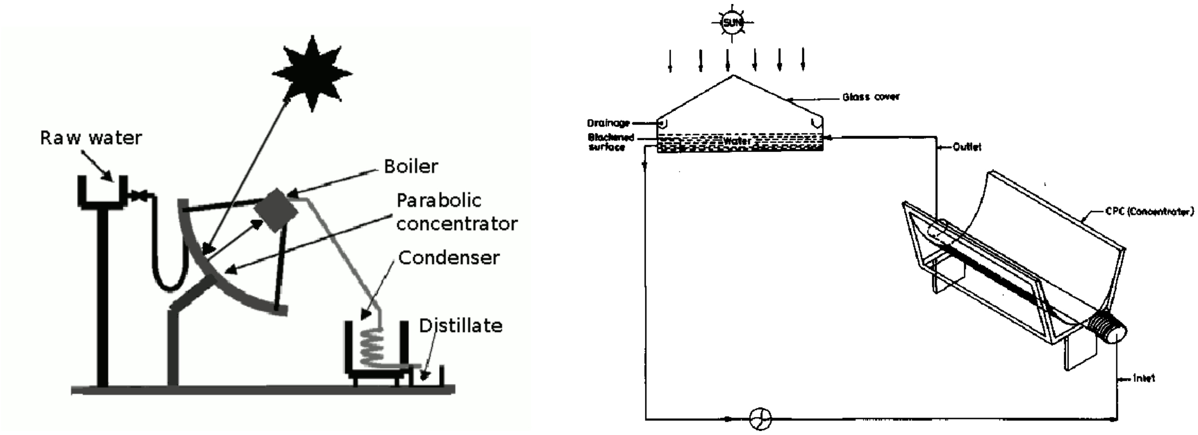


(a) Forced-circulation mode (Tiwari et al., 2009).

(b) Thermosiphon mode (adapted from Lawrence and Tiwari, 1990).

Figure 2.9. Active distillation systems coupled with flat-plate water collector.

Whereas SDUs operating in thermosiphon mode (see 2.9(b)) show a smaller increase in distillate yield compared to forced-circulation mode (35% augmentation in comparison to passive systems - due to the slow transport processes of the heated water), they have the advantage of not needing any additional energy and therefore are very convenient for autonomous installations. The raise of 50% in distillate output of the systems in forced-circulation-mode (see figure 2.9(a)) is accompanied by the installation of an additional pump, which causes additional costs and operational expenses. For the sake of a higher process efficiency, the water level generally is kept low - between one and five centimeters approximately. Despite of the higher efficiencies, the use of solar water collectors for the provision of additional process heat is a cost factor and leads to further system complexity and more regular maintenance work, especially when raw water with a high salinity (corrosiveness) or high amount of TDS (danger of tube blockage) is used. Another approach is to install a concentrator which either heats up the evaporation basin directly (as in figure 2.10(a)) or via an additional circuit of hot water (as in figure 2.10(b)). The gain in distillate output for the latter is described as nearly twice as much as for passive SDUs by Sinha and Tiwari (1992) - about 8.5 liters per day and square meter. Systems using a parabolic



(a) System with (direct) parabolic solar concentrator (adapted from Chaouchi et al., 2007).

(b) System with cylindrical parabolic concentrator (Sinha and Tiwari, 1992).

Figure 2.10. Use of concentrators for active distillation

concentrator are still in their early phase of development and rather adequate for bigger installations. As for those systems, the production and maintenance costs, as well as the complexity of the system may be seen as very elevated; for this reason it is recommendable to integrate them into a bigger water supply system, rather than use them for an autonomous solution. More economical would be active SDU which use waste heat from other (industrial) processes. The distillate costs may be very low, due to an abundance of heat to the process, which would be otherwise dissipated. For water supply systems close to industrial areas, such a solution seems to be viable. The technical integration of such a SDU into an existing (cooling) system may cause the biggest part of the initial costs, not to mention the amount of control- and regulation systems to assure the effective functioning of the coupling.

2.4. Cost estimation

The approximate cost per volume unit of water produced by SDUs is shown in table 1.1 in the chapter 1.3. Calculating the cost of the distilled water is a very difficult task, due to various reasons. First of all, the material costs vary from place to place, so do the costs for construction in all its facets - territory prices, workers' salaries, costs for tools, auxiliary means, etc.. Apart from those rather obvious costs, there exist additional expenses, which are rather difficult to quantify, such as maintenance and reparation costs. The final water price is calculated as a function of the total lifespan of the SDU, which in most cases is estimated to be either 10, 15 or even 20 years. There is no project known to the author of this text, which can present a coherent cost calculation over the complete and real lifespan of a solar distillation project. Furthermore, depending on the projects' circumstances, various costs sometimes are estimated to be zero, such as the territory costs or salary for construction workers. At last, the used technology and climatological factors, as well as the raw water salinity play an important role for the distillate output and therefore the overall price.

Due to the existence of various methods of cost estimation, it is not possible to determine a universal, comparable price per technology. Table 2.1 gives a short overview of the estimated costs for some of the distillation technologies presented in the previous sections. All data apart from Dwivedi and Tiwari (2008) and Santana and Foster (2005) was elaborated by Kabeel et al. (2010) and is based on a method by Fath et al. (2003)[1]. Concerning the initial investment costs of a SDU, literature provides various examples, from which an approximate price span can be deduced. Santana and Foster (2005) give a price of 450 to 650 US$ per commercial, pre-fabricated unit of a single-slope solar still, while Khanna et al. (2008) calculated investment costs of approximately 222 US$ for a community-made still.

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[1] Note: Apparently Dwivedi and Tiwari (2008) as well as Santana and Foster (2005) used other methods for cost calculation and therefore came to a much lower water price per liter.

Table 2.1. Water prices for selected solar distillation technologies.

Technology	**Country**	**Water price (US$/L)**	**Author**
Single-slope	Egypt	0.035	Fath et al. (2003)
Single-slope	India	0.007	Dwivedi and Tiwari (2008)
Single-slope	Pakistan	0.063	Samee et al. (2007)
Single-slope	Mexico	0.028	Santana and Foster (2005)
Double-slope	India	0.006	Dwivedi and Tiwari (2008)
Active single-slope with flat plate solar collector	Jordan	0.115	Badran and Al-Tahaineh (2005)
Active single-slope with parabolic trough collector	Egypt	0.058	Abdel-Rehim and Lasheen (2007)
Tilted-wick	India	0.065	Velmurugan et al. (2008)

3. Project implementation

In order to find an adequate design solution of a SDU for the use in the project region, investigations on a prototype of passive, single-slope, basin-type still are made. An implementation of active solar distillation in a second prototype is planned. As mentioned before, the focus will be kept on the use of locally available and inexpensive material, as well as taking into account the measures of efficiency augmentation mentioned in the previous chapter. The design of a single-slope, basin-type solar still has the following advantages:

- Low material and construction costs
- Simple working principle and robustness
- Minimum maintenance and high reliability
- Use of nearly any type of raw water possible (even sewage or water with high TDS)
- No expendable parts (like pre-filters or wicks)
- High reproducibility
- Adequate quality of distillate output for human consumption (according to Coutiño, 2000)
- The single-slope design is adequate for latitudes bigger than 20°(Murugavel et al., 2008)

- Possibility of completely autonomous use without the need for additional power sources (electricity or fuel)

The design of the active distillation prototype will incorporate the same geometry as the passive one, due to reasons of comparability; the difference consists in the application of an additional energy augmentation technique. Whereas the effect of constructive (passive) energy augmentation techniques will be examined in the first prototype, the second prototype is planned to investigate the effect of an additional solar collector on the distillate yield. The concrete energy augmentation measures incorporated in the design of the SDUs are presented in section 3.2 and in the corresponding subsections (3.3.1 for passive distillation and 3.4.1 for active distillation). Ideally, the two prototypes should be compared in a final performance analysis, where they will be observed simultaneously. Due to the short period of time available for field studies, it is not certain yet if it can be performed. The investigation of several passive energy augmentation techniques and their effect on the distillate yield will be made in the first prototype, before constructing the second (active) SDU. This procedure is necessary to find out, which measures of passive energy augmentation can be effectively transferred onto the active system.

In order to get an impression of the influence of the climatological parameters on the distillate yield, it is planned to continuously measure the following parameters:

- Daily amount of solar radiation on the inclined plane (according to the inclination of the cover of the unit)

- Wind speed in the height of the distillation unit

- Ambient temperature

Chapter 4.1 describes the variables which are measured directly in the units.

3.1. Project parameters for the chosen region

In order to make a rough calculation for the expected efficiency and distillate output of the prototype units, some climatological data for the chosen region is necessary. One of the cities in the project region which counts with weather statistics and a meteorological station, is Charcas (SLP). The dataset provides maximum, minimum and mean temperature values for the timespan 1971-2000 (see table 3.1) and was obtained from the National Mexican Weather Service (Servicio Meteorológico Nacional, 2011). Additional data is provided by the calculation tool for renewable energy systems *RetScreen*® - see table 3.2. The inclination value of 23° in table 3.2 surges from the fact that maximum solar radiation is received throughout the year, if the cover inclination of a SDU is equal to the latitude of its designated location (see also chapter 2.2). Charcas has the geological coordinates of 23°08'00" latitude, 101°07'00" W longitude and a geological height of 2,057 meters above sea level. With the mean daily insolation on the inclined surface being the single most important parameter for the installation of a SDU, several other parameters are of potential influence on the distillation process: ambient temperature, wind speed, air humidity (for a posterior evaporative water cooling system) and atmospheric pressure (influence on the boiling point of water). The ground temperature is of marginal interest, but

Table 3.1. Long-term temperature values for Charcas (SLP).

Month	**Mean temperature [°C]**	**Mean minimum temperature [°C]**	**Absolute minimum temperature [°C]**	**Mean maximum temperature [°C]**	**Absolute maximum temperature [°C]**
January	10.7	3.2	0.4	18.2	23.2
February	11.7	4.0	1.5	19.4	25.7
March	14.3	5.9	1.9	22.7	28.7
April	16.1	8.1	4.6	24.1	31.4
May	18.3	10.5	7.0	26.0	34.0
June	18.1	11.0	8.5	25.1	32.4
July	17.3	10.7	8.2	24.0	29.6
August	17.6	10.6	8.3	24.6	30.0
September	16.8	10.4	7.6	23.3	29.4
October	14.7	7.9	3.8	21.6	25.8
November	12.7	5.5	2.4	19.9	24.3
December	11.6	4.4	1.7	18.8	24.6
Annually	15.0	7.7	-	22.3	-

Table 3.2. Climatologic mean values for Charcas (SLP).

Month	**Relative air humidity**	**Mean daily solar radiation-horizontal [kWh/m^{2}d]**	**Mean daily solar radiation-23° inclination [kWh/m^{2}d]**	**Mean atmospheric pressure [kPa]**	**Mean wind speed [m/s]**	**Mean ground temperature [°C]**
January	57.8%	4.42	5.61	81.2	4.3	12.9
February	50.0%	5.34	6.32	81.1	4.3	15.5
March	40.0%	6.49	7.03	81.0	4.5	19.0
April	39.9%	6.80	6.71	81.0	4.3	22.9
May	48.6%	7.02	6.49	81.0	3.8	24.7
June	64.9%	6.78	6.10	81.1	3.3	23.8
July	69.9%	6.48	5.92	81.2	3.3	22.3
August	68.5%	6.26	6.02	81.2	3.2	22.7
September	72.0%	5.51	5.69	81.2	3.4	20.9
October	69.9%	5.30	6.04	81.2	3.5	18.7
November	64.9%	4.90	6.10	81.2	4.0	15.5
December	60.6%	4.24	5.52	81.2	4.1	13.2
Annually	59.0%	5.80	6.13	81.1	3.8	19.3

nevertheless may have a slight impact on the air temperature near ground level (where the SDU might be installed). In the period of summer (from April to August), the air temperature near ground level can facilitate a faster initiation of the distillation process, due to the heat stored in the soil. Especially for the solar air collector of the active SDU, which has contact with the ground, this can be of importance for the heating rate of the input air.

3.1.1. Yield estimation

According to the daily radiation values of table 3.2, an estimation of the distillate output of a passive single-basin solar still is made in table 3.3. Therefore it is necessary to assume an overall energy efficiency, which usually varies between 25 and 45%, according to the literature (see section 2.3.1). Following further assumptions are made:

- Aperture area of the unit: 1 m^2
- Energy efficiencies of 30, 35, 40, 45 and 50% (this includes energy losses and energy to heat up the raw water)

- Evaporation process takes place at a temperature of 50°C (according to Sampathkumar et al., 2010)

Equation 2.6 from section 2.2 can be used for the rough estimation of the distillate output, if it is transposed to the daily distillate mass $m_{D,d}$ as result:

$$m_{D,d} = \frac{Q_{sol,d} * \eta_{SDU}}{\Delta H_{vap}} \tag{3.1}$$

It is necessary to apply the unit conversion of $Q_{sol,d}$ from [kWh] to [kJ] in order to solve the equation.

$$1[kWh] = 3600[kJ] \tag{3.2}$$

The enthalpy of vaporization ΔH_{vap} has a value of 2382.7 kJ/kg at an evaporation temperature of 50°C. As shown in table 3.3, the maximum distillate output for the passive single-basin still will be reached for the month of March (light gray row), with estimated distillate volumes of 2.66 to 5.31 liters per square meter, depending on the assumed energy efficiency. Minimum distillate

Table 3.3. Distillate output in function of energy efficiency.

Month	**Mean daily solar radiation - 23° inclination [kWh/m^{2}d]**	**Average daily distillate yield [L] for η_{SDU} =**					
		25%	30%	35%	40%	45%	50%
January	5.61	2.12	2.54	2.97	3.39	3.81	4.24
February	6.32	2.39	2.86	3.34	3.82	4.29	4.77
March	7.03	2.66	3.19	3.72	4.25	4.78	5.31
April	6.71	2.54	3.04	3.55	4.06	4.56	5.07
May	6.49	2.45	2.94	3.43	3.92	4.41	4.90
June	6.10	2.30	2.76	3.22	3.68	4.14	4.60
July	5.92	2.23	2.68	3.13	3.58	4.02	4.47
August	6.02	2.27	2.73	3.18	3.64	4.09	4.54
September	5.69	2.15	2.58	3.01	3.44	3.87	4.30
October	6.04	2.28	2.74	3.19	3.65	4.10	4.56
November	6.10	2.30	2.76	3.22	3.68	4.14	4.61
December	5.52	2.09	2.50	2.92	3.34	3.75	4.17
Annually	6.13	2.31	2.78	3.24	3.70	4.17	4.63

output is estimated for the month of December, with values ranging from 2.09 to 4.17 liters per square meter (dark gray row).

It is obvious that measures have to be taken in order to raise the overall efficiency of the distillation process and so to improve the distillate output. At least eight to ten liters per day and square meter would be needed to satisfy the drinking water needs of a small family of four persons.

3.1.2. Raw water quality in the Altiplano region

Fernández García (2007) determined various parameters of water quality in the project region. It is notable that in various samples elevated concentrations of coliform bacteria and metals were found (compared to the official Mexican drinking water standards). In general, the water can be characterized as having a medium to high salinity, with different concentrations depending on the site. For aluminum and lead, elevated values were detected in most of the sites (at least 6 of 12 samples). The same applies to fecal and non-fecal coliform bacteria (7 of 12 samples). In two cases, the permissible limits for arsenic, fluoride and cyanide were exceeded.

In order to make a statement towards the raw water quality of a certain locality of the Altiplano region and the possibility of contaminant removal by means of solar distillation, a raw water sample was obtained from the municipality of *Vigas* near Matehuala. The researched parameters are the following:

- Total coliform organisms and total fecal coliform organisms
- Color, smell and taste
- Turbidity
- Chloride
- Copper

- Hardness ($CaCO_3$)
- Fluorides
- Nitrates and nitrites
- Lead
- pH and conductivity

A comparison between raw water quality and distillate quality in reference to the mentioned parameters is made. The results are described in chapter 4.2.4.

3.2. Prototype design and considerations in construction

For providing an adequate solution concerning product water quality and quantity as well as construction- and installation costs, the working principle of the shallow-basin, single-slope solar still is chosen (see also chapter 3). It is planned to incorporate various techniques of energy augmentation in order to reach a satisfactory yield gain (according to the assumptions made in the sections 1.3 and 3.1.1). The following sections describe considerations which are made for the prototype of the passive SDU and which are planned to be transferred also onto the second, active SDU prototype in case of its realization (see chapter 3.4).

3.2.1. Elevated platform for the SDU

An optimum place for installing a SDU would provide unshaded solar radiation throughout the day, as well as exposure to wind, in order to cool down the condensing cover for better removal of the emerging latent heat of condensation. The initial thought of putting the SDU onto a rooftop had to be discarded due to the properties of many of the local buildings (metal sheet roof of low stability). As an alternative, a kind af table or stand will be built to provide a slightly elevated height for the SDU. This has the advantage that small obstacles like fences or walls will not obstruct the solar radiation by casting a shade. By this mean, also the exposure to wind is elevated, as normally the rugosity of the surrounding objects slows down the wind velocity to nearly zero at ground level.

The projected height of the stand is one meter above ground level - as a compromise between yield gain and passable accessibility of the SDU. A vital detail are legs with adjustable height, in order to balance case and evaporation basin, as well as to correct small unevennesses of the ground. Usable materials are either reinforced and impregnated wood from recycled pallets or metal/iron, preferably from a local scrapyard in order to lower the costs. The stand for the prototype of the passive SDU was made of recycled parts of steel profile which were taken from a discarded experimental set-up of the faculty of chemistry of the Universidad Autónoma de San Luis Potosí (UASLP). An additional level was incorporated in the height of approximately 30 cm above ground, in order to prepare a space for the distillate collection vessel and the measuring equipment.

3.2.2. Case of the SDU

As mentioned in section 2.2, wood may be an adequate material for the construction of the SDUs' case, especially if it is adequately impregnated and of a high quality. Experiments with commercially available plywood failed, due to its tendency to warp and rot (Crane and Kinzer, 2006). It is preferable to use wood of local origin, due to the high availability and potentially lower costs. The available options for the state of San Luis Potosí seem to be local mesquite wood, swamp cypress ("sabino") wood brought from the *Huasteca* region or pine wood (which is available throughout the entire country). According to Weldon (1986), mesquite wood seems to be the best technical option, due to its hardness, dimensional stability (no warping) and durability (resistance against insects and fungi). Arguments against its use are the high price, difficult processing (special tools necessary) and the provision of only small sections, due to the size of the plant. An economically more feasible option is the use of swamp cypress wood, which also has favorable mechanical properties (low coefficient of shrinking and warping) and is much easier to work with than mesquite wood. Rich (2011) mentions water pipes, vats and construction material as its common uses. For this reason, the case of the prototype unit for passive solar distillation was fabricated using swamp cypress wood with a thickness of 2.5 cm. Even though this wood is known for its durability in wet environments, it is not yet known which effect the long-term exposure to hot water vapor causes in the material. Olsson et al. (2001) mention that commercially available wood sealants often contain a mixture of noxious substances such as copper, chromium and arsenic. For avoiding any possible contamination of the distillate, it is vital to use non-toxic or food-grade material for sealing. Schneider (1980) describes linseed oil as an adequate wood sealant, which is raising the dimensional stability and lowering the absorption of water considerably. In spite of creating an impermeable film on the surface of the wood, linseed oil is filling up cavities and cracks in the wood structure, which result mainly from the drying process (Olsson et al., 2001), thus raising the resistance of the entire wood structure against warping, rotting and decay. Another reason in favor of its use is the low price and the availability in the state of San Luis Potosí.

On account of this, the case was treated with linseed oil before its final use. Four layers of oil were applied to the entire wooden surface of the case (inside and outside), with each layer given sufficient time to permeate into the wood and dry.

It has to be mentioned that the case for the passive SDU was fabricated of not sufficiently dried wood in a local workshop and therefore required additional stabilization and rectification afterwards. Despite all efforts, the bottom of the case stayed in a slightly warped form, also due to its large surface area.

3.2.3. Isolation

Considering that the thickness of the used wood provides a sufficient basic isolation for the evaporation process, there is less isolation necessary inside the still. According to McCracken and Gordes (1985) it is not necessary to incorporate much isolation in regions with high solar radiation values. Nevertheless, it is recommendable to apply some additional isolation below the distillation basin, in order to assure a high operating temperature.

After preliminary experiments with loose glass wool recycled from hot-water tubes failed due to the difficulty of forming a homogeneous layer, a mixture of tezontle stones with marble was used. The advantage of this combination of stones is the possibility of leveling smaller height differences, which were caused by the warped wood in the first place. Furthermore, the porous structure of tezontle is advantageous in retaining and storing heat from the evaporation basin. It is convenient to use these stones as they are local material at a very accessible price. Even though prefabricated glass- or mineral wool boards would have been the better choice for the bottom isolation, the availability of such material is very low and the cost may be seen as very elevated for the region of San Luis Potosí.

Regarding the isolation of the side walls of the case, recycled polystyrene material, commonly known as *Unicel* can be used. This material is very economic and known for its robustness. It does not degrade if the temperatures keep below 70°C. In order to form an effective isolation layer, thicknesses of at least two centimeters are necessary. For the moment, this material is not incorporated into the prototype units, due to the use of reflective wall coating, which also has an isolating effect (see chapter 2.2).

3.2.4. Condensing Cover

According to section 2.2, ordinary window glass with a thickness of 4 mm is chosen as condensing cover. This is a compromise between efficiency and price, as special low-absorption and low-reflectance glazing would imply a higher cost and a low local availability.

3.2.5. Enhanced distillation basin

McCracken and Gordes (1985) analyzed various materials for the use as distillation basin, of which only a few show a high durability. One of these few materials is aluminum, due to having an already pre-oxidized surface making it resistant against corrosion from aggressive compounds in the raw water. Based on this assumption, the evaporation basin is fabricated from an aluminum sheet of 3 mm thickness, as a compromise between cost and dimensional stability. Whereas the basin area has the dimensions of 145×70 cm, the border height is only 1 cm, due to the low water level in the basin (between 4 and 7 mm). The water level was chosen in conformity to the literature, which affirms a linear dependence between water level and evaporation rate: up to date solar stills were investigated with a minimum water height of one centimeter, thus giving the best evaporation rates. Concluding, adjusting the water level to the lowest possible height (which still is handleable without the basin partially drying out) would imply an improved evaporation rate.

The basin is painted black with matte finish in order to reach a high absorption- and a low reflection coefficient. Before the application of the black spray paint, the aluminum was prepared with a layer of special primer, in order to improve the adhesion of the spray paint to the basin surface.

A water inlet of bronze was attached to the basin from the bottom, for installing the raw-water inlet. Precautions were taken to avoid the contact between the bronze and aluminum surfaces in order to avoid electrochemical corrosion between the two phases in the aqueous environment. This was realized by applying a special two-component adhesive between the surfaces and in the drilling hole.

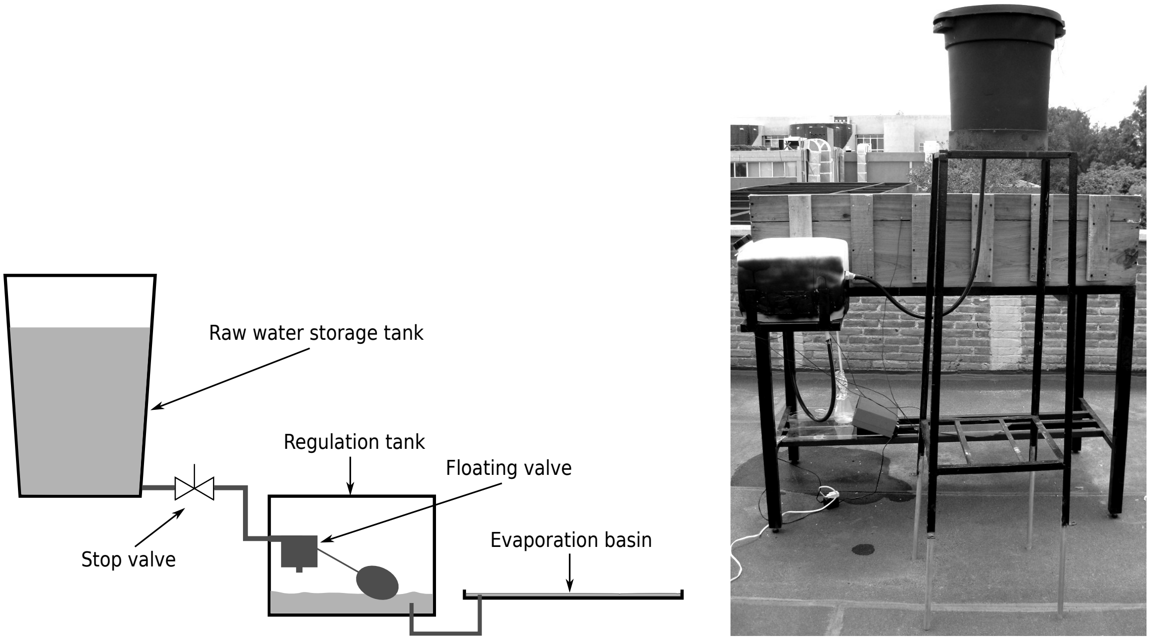
3.2.6. Raw water dosage system

One of the inconveniences of many up-do-date solar still constructions is the fact, that the filling process of the evaporation basin has to be made manually, e.g. by removing the condensation cover of the still. Not only does this impose a further source for cross-contamination between the raw water and the distillate, it also leads to an inhomogeneous behavior of evaporation due to the fact, that a great quantity of raw water has to be heated (ideally) in the morning, which will gradually become lesser in the later hours of the day. Therefore, the actual distillation process starts later in the day, because the first hours are mainly spent on warming up the raw water. In case that the supplied water quantity was not sufficient, the evaporation basin can (partially) dry out over the day and salts contained in the raw water are forming crusts, which are difficult to remove.

An automatic raw water dosage system can eliminate all those problems at the same time, by providing a constant water level in the evaporation basin. It contributes to a uniform, high evaporation rate and avoids desiccation of the basin. The raw water dosage system applied to both of the prototype units consists of three important parts:

- Black-painted 40 L raw water storage tank (additional energy input)
- Regulation tank with floating valve
- Connection to the evaporation basin (assuring equal water heights in basin and regulation tank)

In order to reach a sufficient water pressure for operation of the floating valve in the regulation tank as well as to assure unshaded solar radiation, the raw water tank is put on a separate stand behind the SDU which has a height of 160 cm. The amount of water contained in the regulation tank is about eight to ten liters. Figure 3.1 shows the working principle of the proposed system and its practical realization. All parts of the system are commercially available items; the con-



(a) Schematic drawing. (b) Implementation (rear view).

Figure 3.1. Raw water dosage system.

nections between the tanks and the evaporation basin are made of a flexible hose with a half inch of inner diameter. The floating valve in the regulation tank is a common item, which is normally used in domestic water storage tanks. As a floating lever, a tightly sealed, black painted plastic bottle was used (see figure 3.2).

3.2.7. Distillate trough

Choosing an appropriate material for the distillate trough is one of the most difficult tasks, because it should not influence the taste of the condensed water. Stainless steel would be a good choice, but is difficult to access in the form of a tube. PVC pipes are not adequate, because they emit noxious substances and are prone to aging by the solar radiation and high humidity. The chosen material for the distillate trough is reinforced aluminum foil which is commonly

Figure 3.2. Leveling mechanism inside the regulation tank.

available for handicraft purposes. Aluminum is supposed to be inert towards water and most aqueous compounds, for which it is commonly used in the packaging of food and beverages. In order to form a channel, the aluminum foil is bent with the help of a metal bar and afterwards molded to the case of the SDU, which has a small clearance in the front wall for this purpose (see figure 3.5). The channel has a slope of about 1° over the entire length of the case (approximately 150 cm), so that the water can easily run off to the drainage pipe, which is placed in the right front corner of the bottom. To avoid distillate spillage, the drainage pipe is equipped with a funnel (see figure 3.3). Discharging the distillate at the bottom of the SDU has the advantage of avoiding

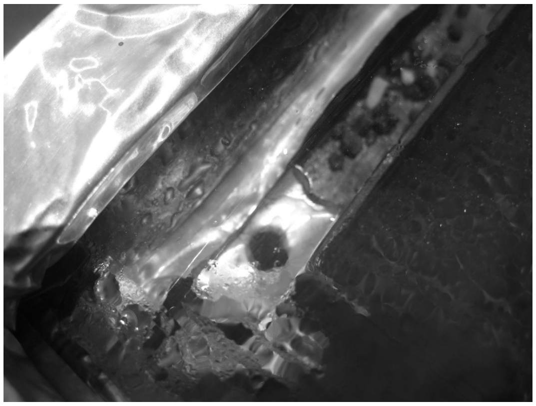


Figure 3.3. Top view of distillate trough and drainage pipe with funnel.

vapor leaks at the side walls, where the distillate trough commonly is led through. Furthermore the drainage pipe is not exposed to direct solar radiation, thus avoiding unnecessary warming of the distillate. Aluminum tubing is used for the drainage pipe, due to the above-mentioned reasons.

3.2.8. Evaporative cooling system for the distillate (*Zeer pot*)

It is crucial to avoid a re-contamination of the distilled water in the collecting vessel. Most domestic distillation systems simply use a plastic bottle to recollect the distillate. Hereby the problem may be seen in a potential contamination by algae growth and dissolution of plastic compounds into the water, which can cause a bad taste and may have negative long-term health effects. Due to the warming of the collection vessel by solar radiation (in connection with a not completely cleaned bottle), growth of microorganisms can occur, thus imposing a health hazard. The solution to this problem could be the use of a non-transparent material for the vessel which can easily be cleaned and - if possible - cooled.

Such a solution can be found in evaporative cooling, which is implemented by the so-called "pot-in-pot" principle or *Zeer pot*, where two clay pots are put into another, separated by a thin layer of sand or other porous material, which is constantly wetted (see figure 3.4). The inner

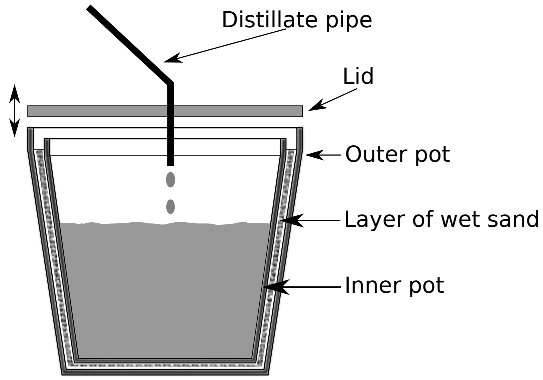


Figure 3.4. Pot-in-pot evaporative cooler.

clay pot contains the product, in this case the distillate. Due to the slow evaporation of the water from the intermediate sand layer through the wall of the outer pot, the inner pot is cooled. Aimiuwu (2008) states that it is possible to cool water inside the system by 15°C below the ambient temperature, under favorable ambient conditions, such as low air humidity, sufficient air circulation and high temperatures on the outside. Ogutu et al. (2001) state that a significant reduction in pathogens can be reached by using a clay vessel instead of a plastic vessel for water storage. Another positive aspect of using clay pots for distillate storage is the partial re-mineralization of the water. McCracken and Gordes (1985) state that another good way of mineralizing the distillate is to put some chips of limestone or marble in the collection vessel. Nevertheless, the pot-in-pot evaporative cooling system is to be seen as an additional device for the prototype implementation and not subject to detailed investigations. More information towards its mode of operation is provided by Mittal et al. (2006).

3.3. Prototype of the passive SDU

According to the specifications given in the antecedent section, the prototype of the passive SDU is built with the following specifications:

- Platform for the case made of recycled metal profiles with a height of 1 m
- Evaporation basin of 3 mm aluminum sheet with 145 × 70 cm basin area and a border height of 1 cm
- Case made of swamp cypress wood of 2.5 cm thickness, impregnated with four layers of linseed oil on the inside and outside. Inside measures are 150 × 75 cm, with a front wall height of 6 cm and a rear wall height of 38 cm (according to a cover inclination of 23°)
- Condensing cover made from 4 mm window glass with the measures 152 × 82 cm (active area: 150 × 80 cm)
- Connections between wood glued and screwed, without the use of silicone [1]
- Application of a 2 cm-layer of tezontle and marble stones for isolation of the evaporation basin and as heat storage element (see figure 3.5)
- Distillate collection trough of aluminum foil; additional isolation of the cover slots made of the same foil (see figure 3.7) to ensure safe enclosure of the glass in the slot and to prevent vapor leakage
- Removable section of the rear wall for inserting the cover glass into the slots

A schematic drawing of the components, as well as important measures are shown in figure 3.5. Figure 3.6 shows a schematic drawing of the entire passive SDU. The water level is kept at a

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[1] Silicone sealing agent is prone to either grow mildew in humid environments over large timespans or to contain fungicides (like Tri-Butyl-Tin) which are known to be highly toxic to the human organism.

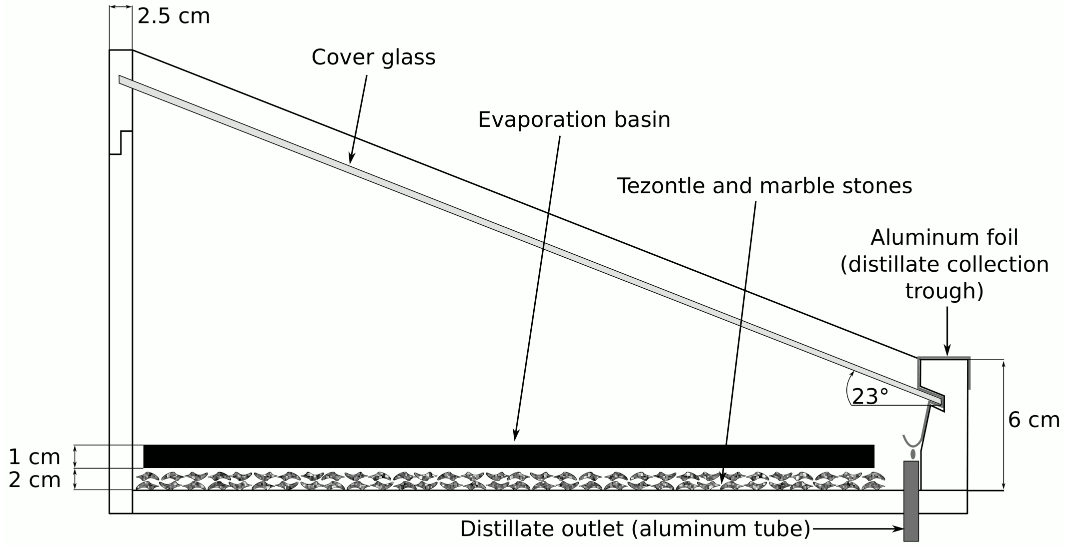


Figure 3.5. Side view of the passive prototype SDU.

constant height of five to six millimeters by the raw-water dosage system in order to ensure a homogeneous water heating and a constant evaporation rate. Care was taken to avoid contact between the evaporation basin and the walls, in order to eliminate heat losses by conduction.

3.3.1. Passive energy augmentation techniques

In order to optimize the distillate yield, various techniques were implemented in the design of the passive SDU:

- Optimized condensing cover inclination of 23° (equal to latitude of the project region) for optimal distillate yield throughout the year
- Very low water level in the evaporation basin (below 1 cm)
- Raw-water pre-heating in the storage tank
- Minimum possible distance between evaporation basin and condensing cover in the front part of the unit

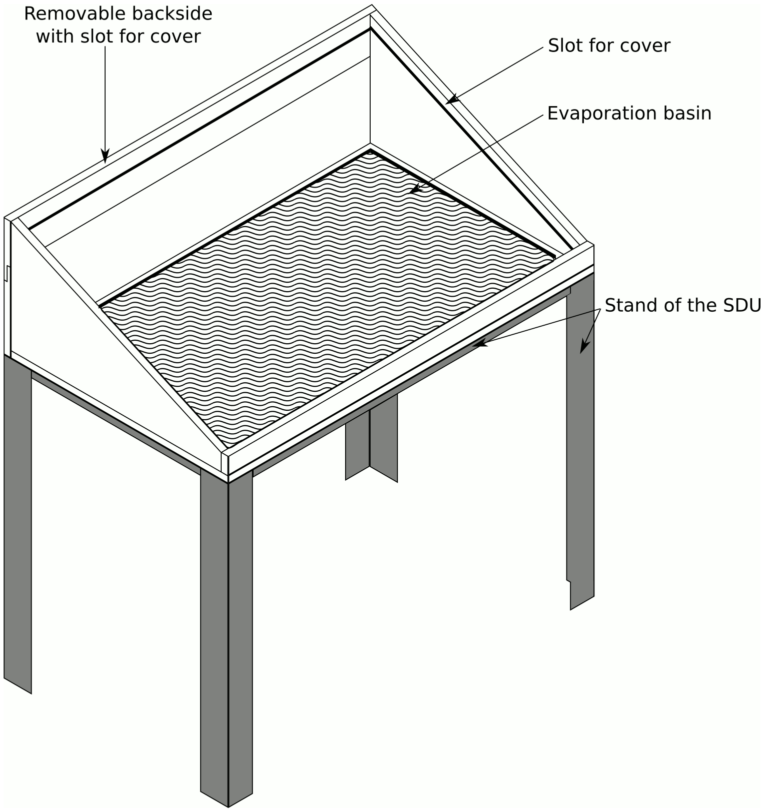


Figure 3.6. Model of the passive SDU.

- Optional reflective side- and rear walls with additional distillate troughs and cooling by ambient air

Additional reflection- and condensing surface

The option of equipping the side- and rear walls of the unit with additional aluminum foil deserves special attention, due to a double effect on the evaporation- and condensation rate: whereas the foil in the first place serves as a mirror to redirect solar radiation which is not directly incident on the evaporation basin back into it (and so rises the evaporation rate), the second function is the provision of additional condensing surface. Normally the water vapor condenses only at the glass cover, which is supposedly the coldest place of the distillation unit.

Figure 3.7. Aluminum enclosure in the cover slots, rock isolation and distillate drainage pipe with funnel (distillate trough removed).

By the provision of additional condensing surfaces, a much higher quantity of water vapor could be reclaimed as water. This opportunity is given by the installation of additional aluminum foil at the side- and rear walls, which is not only fixed at the walls, but extended to the outside of the distiller by molding it into the slots bearing the cover glass, and passing it through them (similar to the installation of the distillate trough, see figure 3.5). Not only will the aluminum foil act as a heat sink for the water vapor, it also helps cooling down the condensing cover to a small extent. Up to date, this combined energy augmentation technique has not been described or investigated yet. Kumar and Bai (2008) mention the possibility of cooling the side walls of a SDU actively by installing a water circulation system with aluminum tubing, which is soldered to the side walls. In analogy, the reflective side walls in this experiment will be air-cooled, which is cheaper as well as less complex and error-prone as the mentioned water-cooled system. Figure 3.8 shows an illustration of the gain in condensing surface which an installation of aluminum foil reflectors would have. The additional condensing surface would be 0.63 m^2, which is a bit more than half of the area of the condensing cover. Theoretically, this could imply a distillate gain of up to 50%, compared to the yield which results in using only the glass cover as condensing area. In

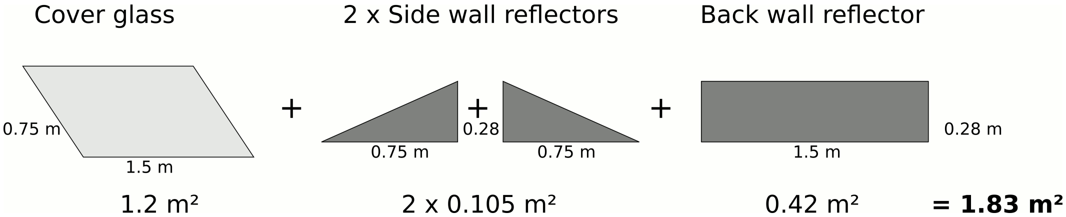
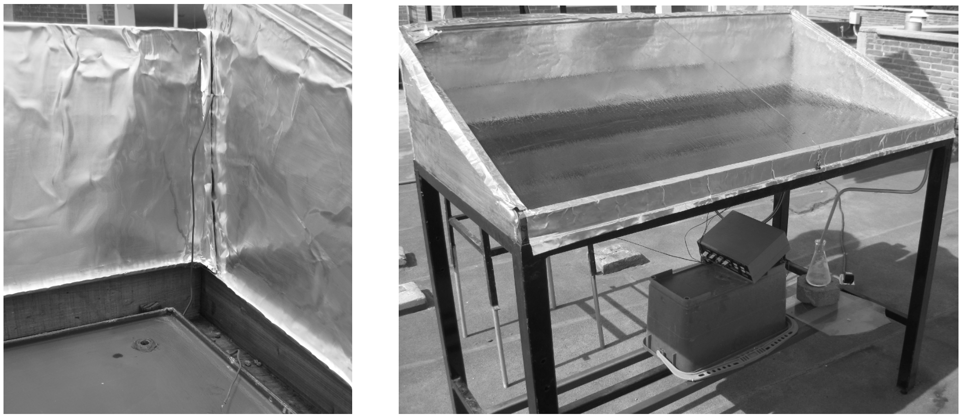


Figure 3.8. Schematic view of the condensing surface areas.

addition to this (direct) yield gain, also the raise in efficiency by installation of the reflective surfaces has to be considered. Al-Hayek and Badran (2004) and Abdallah et al. (2008) describe a yield gain of 20 to 30% for this measure, so that the overall yield gain could be up to 80% in the ideal case, compared with the distillate output of a simple solar still. Figure 3.9 shows the arrangement of the aluminum foil in the SDU prototype.



(a) Right corner of the rear wall with temperature sensor.

(b) Front view of the prototype during operation .

Figure 3.9. Prototype SDU with reflective side- and rear walls.

3.3.2. Cost analysis

The following table 3.4 shows the materials used in the construction of the passive SDU and their respective costs. In the case of materials, where it was not possible to determine a specific price, an estimation is made (e.g. the stand for the SDU which was made entirely of recycled metal parts). The total price of 5,909 MXN, which equals approximately 500 US$ at the time of August 2011, is to be seen as a maximum price for the SDU prototype. It has to be mentioned that mainly the cost of the wooden case is subject to price variations and that the paid amount is representing the upper level of the price range.

Table 3.4. Material costs for the passive prototype SDU.

Quantity	**Item**	**Cost in MXN**
1	Wooden case (enclosure)	2352
1	Aluminum basin	1800
1	Stand of the SDU	500
1	Stand for the raw water container	100
1	Glass cover 152 × 82 cm	245
1	Aluminum foil, 200 × 60 cm length	104
1	Aluminum primer spray paint	74
2	Cans of black spray paint - matte	70
1	40 L - tank for raw water storage	134
1	20 L - tank for raw water leveling	80
1	Floating valve	178
2	1 m - pieces of flexible hose for raw water feeding	12
1	Spigot (stop valve) for the raw water storage container	52
1	1-L Bottle of linseed oil	75
1	Bronze connector for raw water inlet to basin	38
2	Clay pots for evaporative cooling	50
1	Various installation material for raw-water connections	25
1	Wood screws for rear side cover	20
Total		**5909**

As mentioned in chapter 1.3, the operation- and maintenance costs are very low, so that the initial construction costs account for approximately 99% of the entire costs throughout the lifetime of a solar still. Considering that there are no additional costs for the land where the SDU is installed (which will most probable be the terrain corresponding to the persons who use the SDU), as well as no contracted workers are employed (the SDU can easily be assembled without special tools or -knowledge), the total cost for the SDU is equal to the material costs. Nevertheless, due to the prevailing poverty and marginalization in the Altiplano Region it is unlikely, that the material costs can be financed at one time. Considering the minimum wage for the region, an unskilled worker is likely not to earn more than 1,361 MXN per month. This calculation is based on the regional daily minimum wage of 56.70 MXN, provided by Gobierno Federal (2011), which was multiplied with 24 days (assuming six work days per week). In order to calculate the theoretical timespan, in which the SDU can be paid, it is assumed that an amount of 10% of the monthly income can be spent for the purchase of construction material for the unit, which would equal 136 MXN. By dividing the total unit costs of 5,909 MXN by 136 MXN, the time for refinancing the construction of the SDU would be 43 months (about 3.5 years).

Another calculation approach is based on the yearly distillate yield and the costs for bottled water. Based on an assumed energy efficiency of the SDU of 45% (which is realistic, as will be proved in chapter 4.2.3), a yearly fresh water output of 1519.2 L is expected. This result bases on the average values of distillate output from table 3.3 which were multiplied by the number of corresponding days of every month and afterwards summed up. Commonly available bottled water, which is shipped in 20 L-bottles (*Garrafón*), costs about 20 MXN per unit. To achieve the yearly distillate output of the SDU, it would be necessary to purchase 76 *Garrafones* with a total cost of 1,520 MXN or 128.8 US$. For the case that the *Garrafón* is refilled for a cost of 12 MXN each time (which is common practice in the city of San Luis Potosí), the bottled water would cause a cost of 912 MXN (77.3 US$). Taking this fact into account, the construction costs of the SDU would amortize in approximately 3 years and 10 months (if the bottled water accounts with 1,520 MXN per year) or 6 and a half years (if the bottled water is obtained as refill) if the bottled water is replaced with the water produced by the SDU. Concerning the water price per L, the SDU would produce water for a price of $\frac{5909}{1519.2}\frac{MXN}{L} = 3.89\frac{MXN}{L}$ (0.3 US$/L), whereas bottled water in *Garrafones* costs between 0.6 and 1 MXN per liter (0.05 to 0.09 US$).

These calculations show that the economic feasibility of the SDU prototype with the current construction costs is not given. For competing with the price of bottled water in the course of the first year of the installation, the construction costs have to be lowered about at least four times to about 1,500 MXN per unit, instead of 5,909 MXN. This decrease in construction costs is seen as possible, if other materials than hardwood for the case and aluminum for the evaporation basin are used. A possible solution would be the construction of brick stones and black tiles.

3.4. Prototype of the active SDU

For reasons of comparability, the second prototype has the same geometrical dimensions as the first one. The only difference is the addition of a Solar Air Collector (SAC) in order to incorporate an auxiliary energy input for the evaporation process. With an additional surface area of 1.7 m^2 (see also 3.4.1), the SAC can theoretically provide about 70% more thermal energy to the evaporation process in comparison to the amount of energy which surges from the solar radiation caught by the aperture area of the distiller itself (assuming the same energy conversion efficiency - about 45% - see also section 2.2). By this measure, the water temperature in the evaporation basin is expected to rise above 80°C thus increasing the distillate yield considerably (as described by Schwarzer (1995)). In combination with the reflective wall coating and additional distillate troughs, a total amount of daily distillate yield between eight and ten liters is to be expected for the SDU. This would be a satisfactory amount for the drinking water needs for a small family of three to four persons, according to Gleick (1996).

Concerning the incorporation of an additional solar collector, Ettouney and Rizzuti (2007) describe the additional distillate yield gain with 50% compared to a unit without solar collector. Nevertheless, up to date only solar water collectors have been used to augment the water temperature in the evaporation basin, therefore the rate of efficiency augmentation only considers this type of collectors. Additional heating of SDUs by means of SACs has never before been considered. The advantages of a SAC compared with a solar water collector are the following:

- Low investment costs due to the use of few and simple material (use of local material such as wood and [recycled] metal sheets possible)
- Robust construction with nearly no susceptibility for failing (neither pump, nor valves necessary)
- Faster response time and higher temperature levels due to the lower heat capacity of air compared to water
- Nearly no maintenance necessary
- Simple and reproducible working principle (maintenance possible by locals)
- No danger of tube blockage, corrosion, freezing or boiling of the heat transport medium

The only disadvantages may be seen in the low efficiency due to the low heat capacity of air (approx. 1 kJ/kg*K compared to 4.19 kJ/kg*K of water) and losses in heat transmission to the basin, due to the separation of the heating- from the evaporation system.

The SAC will be installed at the front side of the SDU facing south, with an inclination of approximately 45°. This provides additional energy for the evaporation process especially in the winter months with low solar altitude. Furthermore, the inclination angle has the advantage of providing an optimum natural airflow in the collector (Zhai et al., 2005) which guarantees a constantly high mass flow. In order to install the additional SAC, the base of the SDU's case is redesigned for the installation of an air duct which terminates below the evaporation basin. For the purpose of maximizing the contact area between hot air and basin surface, only the outer edges of the wooden base are left, in order to sustain the basin mechanically. By doing this, also the stone isolation is omitted in its majority (only a small margin will be applied at the edges). Additionally, the possibility of putting a certain quantity of stones into the air channel in order to store energy will be investigated. Figure 3.10 shows a side view of the modified active SDU with additional air channel.

3.4.1. Design of the additional SAC

SACs are commonly used for food drying or space heating in the temperature range from 20 to 60°C. Nevertheless, it is possible to design them for higher temperature ranges in order to use them for the provision of process heat (up to 80 - 100°C). The simple type of SAC consists of an isolated box which has an air inlet at its bottom, an absorber made of metal sheet and an outlet for the hot air. Depending on the construction, the air can either flow below or above the absorber to heat up. Thermal efficiencies vary between 30 and 45% (Ramani et al., 2010). An advanced design consists in the implementation of a double-flow working principle: the air enters the collector on the same side of the unit where it leaves, thus flowing below or above the absorber in a first step, in order to pre-heat. In the second step, the air temperature raises by direct contact with the heated absorber. The gain in thermal efficiency is described as 20 to 35% in comparison to single-pass SACs (Ramani et al., 2010). Alvarez et al. (2004) describe a double-pass SAC entirely made of recycled aluminum cans, having thermal efficiencies of approximately 70% at a temperature range of 30 to 45°C. In order to provide an effective additional heating for the evaporation basin of the SDU, the temperature of the hot air should at least be in the range of 60 to 80°C. For achieving this temperature level, an intent is made to combine the advantages of the "traditional" flat-plate absorber with the benefits of absorbers made of recycled aluminum cans. Whereas the flat-plate absorber provides an optimal surface for the absorption of solar radiation, the air is likely to develop a stationary laminar flow, which is avoiding the mixture of air layers with different temperatures and thus lowering the energy uptake of the air mass. The construction of aluminum cans is advantageous concerning turbulent air flow (in the cans) and energy uptake, but exposes only a small fraction of surface area directly to solar radiation due to the circular shape of the cans. This results in a smaller energy conversion factor and therefore in an incomplete heating of the available air mass.

Keeping in mind the cost-efficiency-relation, a SAC which can be built from black-painted, recycled aluminum cans (beverage cans) and recycled wood from transport pallets is designed. In order to investigate the optimum working conditions, the SAC can be used either in circulation mode which makes use of the gravitational buoyancy forces of the air or with an optional ambient air input on the bottom (hatch) in order to raise the air speed. The system works entirely by natural airflow and has no additional devices (fans).

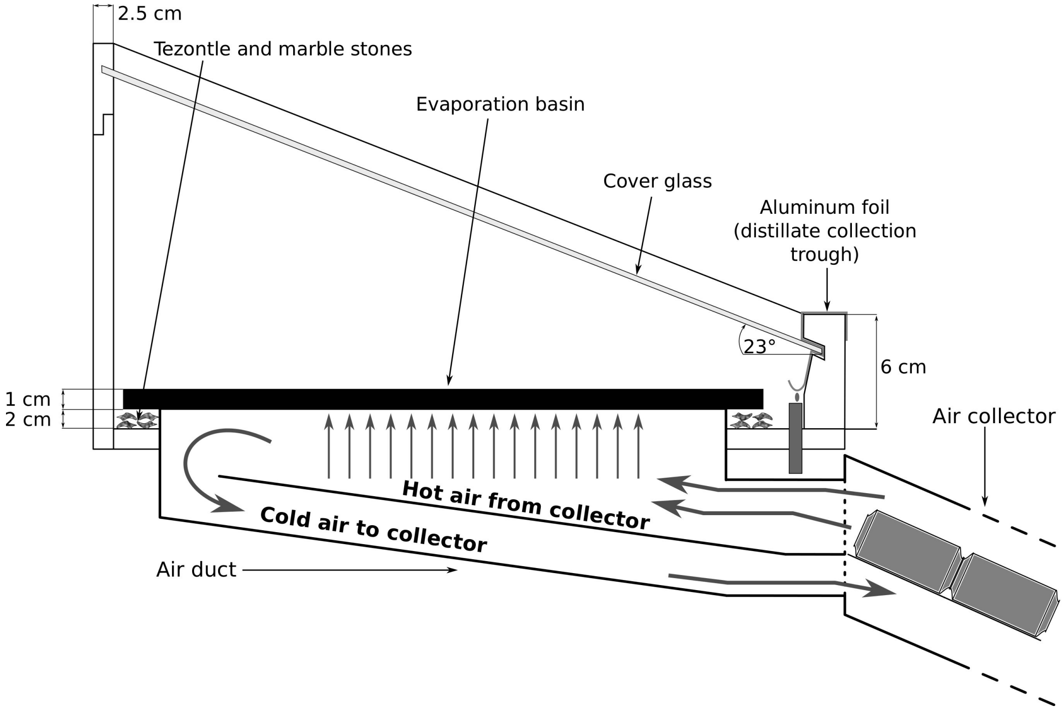


Figure 3.10. Side view of the SDU with air duct of the SAC.

Figure 3.10 shows the installation of the SAC at the SDU, as well as the air in- and outlet; figure 3.11 shows a schematic cross section of the proposed SAC with an absorber incorporating tubular and flat elements (metal sheets made of uncoiled beverage cans). The cold air is fed from the upper side of the collector (see figure 3.12), flowing below the rows of cans and sheets, thus heating up slowly. At the bottom side of the collector it turns towards the upside of the absorber, being diverted and heated directly either inside the columns of cans or above the cans and metal sheets. The beverage cans fulfill various functions: while providing an augmentation of active

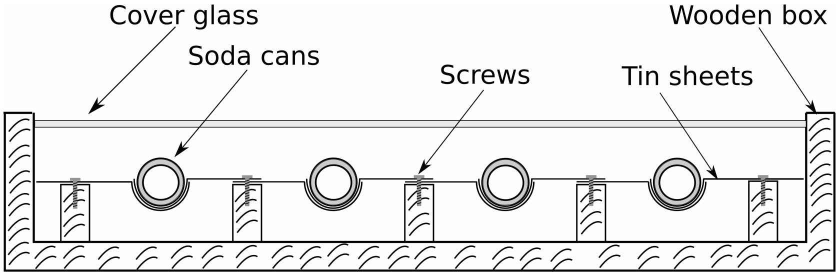


Figure 3.11. Schematic front view of the SAC.

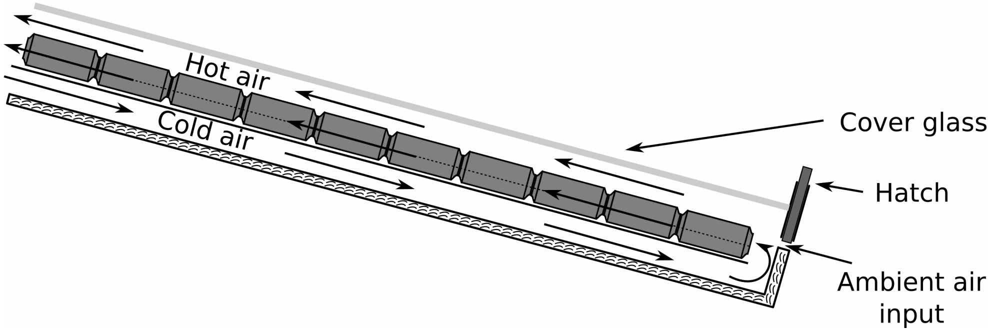


Figure 3.12. Air flow in the SAC.

heating area (due to their enclosed volume), they also help to raise the rate of air flow (chimney effect) and to lower the convective energy losses towards the cover glass (due to the heating of a considerable amount of air inside the cans). Figure 3.13 shows the proposed arrangement of the absorber, consisting of 80 beverage cans and approximately 160 metal sheets made of uncoiled cans. The approximate (inner) dimensions of the SAC are 130×130 cm, which is an active surface area of nearly 1.7 m^2.

Considering the box of the SAC, incorporation of additional isolation material would be counterproductive, first of all because the box itself is made of wood (thickness > 2 cm) which already is an isolating material, and secondly, it is necessary for the air to cool down on the rear side in order to return to the bottom side by density differences. For practical implementation, it might be necessary to incorporate an additional horizontal layer of metal or wood below the rows of cans and metal sheets to avoid excessive heating of the returning air in the bottom part

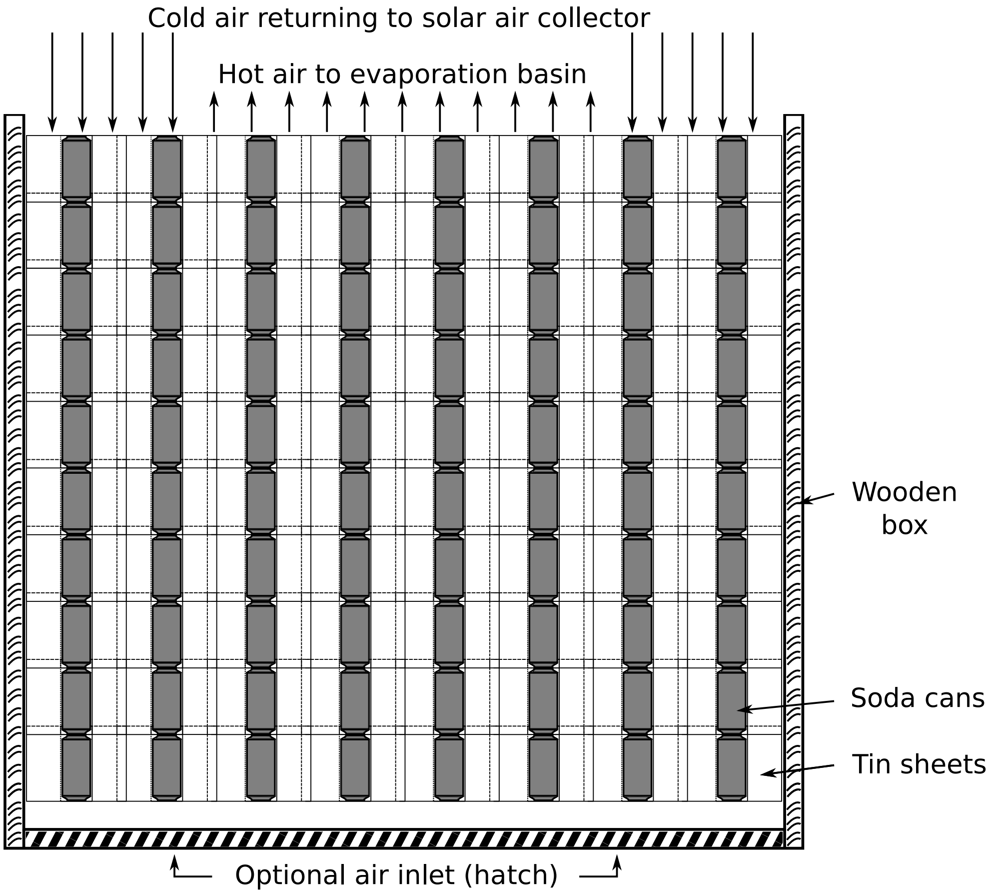


Figure 3.13. Top view of the proposed SAC.

of the SAC, which would provoke a stall and backflow of the air towards the distiller.

For the cover glass, ordinary window glazing can be used, as a compromise between stability and transmissivity of solar radiation. In contrast to the condensing cover of the SDU, a thickness of at least 5 mm is recommended in order to provide a shielding effect on the contained hot air.

4. Performance of the proposed Solar Distillation Unit

This chapter is dedicated to provide an analysis of the productivity and efficiency of the proposed SDUs. At the time of concluding the thesis, just one of the two proposed units could be completed, which is the design of the passive SDU. Due to various unexpected complications in the completion of the first prototype and due to the short period of time available for practical thesis work, it was not possible to terminate the prototype of the active SDU. Complications mainly surged from a delay (six weeks) in the assembly of the wooden enclosure of the first unit, which was made by an external workshop, and the manifold problems arising in the rectification of the latter due to its composition of not properly dried wood (e.g. the front wall had to be removed completely due to excessive warping and to be replaced by a piece of pine wood). Further delay arouse from the complicated process of determining a suitable locally available and inexpensive isolation material for the bottom of the evaporation basin, after preliminary experiments with recycled glass wool had to be discarded due to the impossibility of forming a homogeneous layer which sustains and at the same moment levels the basin against the warped bottom of the enclosure.

Due the above mentioned reasons, the evaluation will investigate the performance of the passive SDU prototype in the presence and absence of reflective side- and rear wall coating, with a focus on distillate yield and energy efficiency. Therefore, the measurement process is divided into two parts:

- Measurement of the distillate output and climatological variables for five days, without the installation of reflecting side- and rear walls with additional distillate troughs
- Same procedure with installed side- and rear-wall reflectors

In addition to this, the quality of the produced distillate will be determined, resulting in a comparison between raw water quality (see section 3.1.2) and distillate quality under consideration of the current limits established in the NOM of potable water for human consumption (see Coutiño, 2000). Whereas the raw water quality is determined directly in the raw water storage tank, the distillate quality is measured in three different arrangements:

1. Distillate quality in the collection vessel (Erlenmeyer flask)
2. Distillate quality in the collection vessel with added marble chips
3. Distillate quality in the *Zeer pot*

Whereas for the distillate quality in the Erlenmeyer flask, the full set of parameters will be determined (according to chapter 3.1.2), the measurements for added marble chips and the Zeer pot are limited to the parameters of conductivity, pH value and alkalinity, which is due to the expected alterations in the mineral content of the distillate (re-mineralization). The results are described in chapter 4.2.4 on page 83.

4.1. Design of test series

Preliminary measurements determined that first fractions of solar radiation are reaching the prototype SDU at about 9:00 of local time. Distillate output and temperature augmentation in the timespan from 7:30 - 9:00 proved to be negligible. For this reason, the following parameters will be automatically measured in an interval of six minutes from 9:00 local time to 20:30 (approximate hour of sunset for the month of July):

- Solar Radiation [W/m^2]
- Raw water temperature in the regulation tank [°C]
- Raw water temperature in the evaporation basin [°C]
- Air temperature inside the SDU [°C]
- Condensing cover temperature inside the SDU [°C]

Ambient temperature [°C], wind speed [m/s] and distillate output [mL] are measured manually in an interval of 30 minutes, due to the small expected variation.

Values of global solar radiation are automatically measured and recorded with a hand-held unit "Mac Solar®" which is mounted next to the SDU at condensing cover inclination (23°). Maximum deviation of the absolute values is <3%. The wind speed at unit height as well as the ambient temperature in the shade are measured with a hand-held thermo-anemometer type "EXTECH® Field Master 451112" which has a deviation of ± 2% for wind speed measurements and ± 1°C as deviation for the temperature measurements. A 12-channel thermocouple scanning thermometer (Cole-Parmer®, model 92000-00), equipped with four thermocouples type "J" is used to automatically measure and record the temperature values for raw water temperature as well as air- and condensing cover temperature inside the SDU. Precision is ± 1 °C. The distillate is recollected in a 500 mL Erlenmeyer flask, from where its exact amount is determined by a measuring cylinder with a precision of 2 mL and a total capacity of 250 mL.

All values are recollected and united in a spread sheet, which provides a tabular overview of the data. Mean values for every half hour are calculated from the data, which is automatically measured every six minutes (temperatures in the SDU and solar radiation), in order to match the manually measured values, i.e. distillate output, ambient temperature and wind speed. Tables of the measurement data are included in appendix A, for convenience the discussion of the measurement data in the following section is made on the basis of charts derived from this data.

4.2. Measurement results

The measurement period was limited to days without rain, due to the construction of the prototype SDU which allows the permeation of rainwater into the distillate trough. Therefore, distillate and rain water would mix and produce a higher quantity of output water than correlates to the system's efficiency. The measurement periods ranged from 13/07/11 to 20/07/11 for the passive SDU prototype with basic design and from 24/07/11 to 29/07/11 for the prototype with augmented condensation surface (reflective side- and rear walls).

4.2.1. Passive SDU prototype (basic design)

In order to describe the dynamics and to investigate the relations between the different parameters and their influence on the distillate yield of the SDU, the recollected data from the complete measurement period (five days) was summarized and average values were determined for a time interval of 30 minutes (see table A.6) throughout a total timespan of 11.5 hours, which is the total daily measurement time frame. By applying this procedure, every data point in the following diagrams represents a mean value derived from five singular measurements. Tables A.1 to A.5 (pages 103 to 107) in the appendix contain the raw data of the daily measurements. Figures B.1 to B.10 (pages 117 to 122) in the appendix represent an illustration of the aforementioned daily

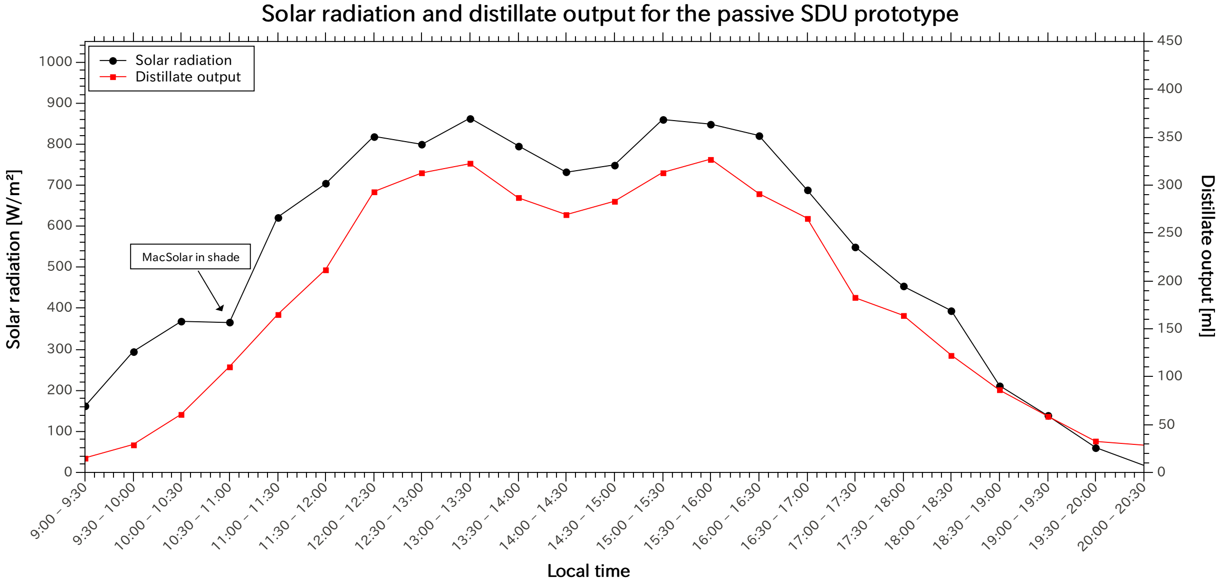


Figure 4.1. Mean values of solar radiation and distillate output for the basic-design SDU during 5 measurement days.

measurement data in the form of solar radiation/distillate output and temperature/wind speed graphs.

Figure 4.1 shows the average values of solar radiation and distillate output for the complete timespan of measurements. It is notable that the distillate output is directly correlating to the amount of incident solar radiation[1]. The major distillate production takes place between 12:00 and 17:00, when the intensity of the sun is highest (power of approximately 700 to 900 W/m^2). Between 9:00 and 12:00, the solar radiation is mainly used for heating of the raw water; between 17:00 and 20:30 the evaporation rate lowers, due to the process using mainly the thermal energy stored in the water. Figure 4.2 illustrates this fact by showing the cumulative distillate production for every measurement day. Whereas the production rate rises slowly between 9:30

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[1] After analyzing the systematic decline of solar radiation between 10:30 and 11:00, it was noted that the measurement device for solar radiation, MacSolar®, was accidentally mounted at a position where it receives shade from a nearby pole for a short period of time. Before starting the second measurement period (SDU with reflective wall coating), the device was moved to a nearby, unshaded location.

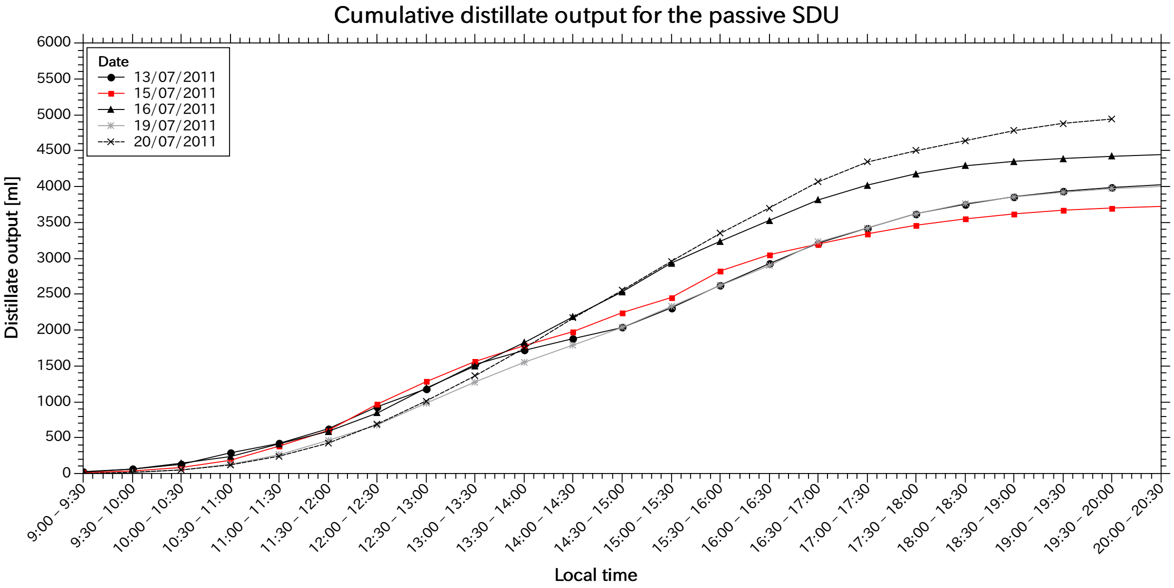

Figure 4.2. Cumulative distillate output for the basic-design SDU as function of local time.

and 12:30, the higher inclination of the curves between 12:00 and 17:00 point to a significant augmentation of distillate quantity over a short timespan. This is the timespan, in which the SDU reaches its highest energy efficiency (see also section 4.2.3). The stall in slope after 17:00 illustrates the aforementioned declining evaporation rate, which is due to the process shifting its energy input slowly from the use of direct solar energy towards the sensible heat stored in the raw water. Figure 4.3 shows the parameters of distillate production in relation to the measured temperature levels. It is notable, that a significant raise in distillate production (> 200 mL) per measurement interval of 30 minutes occurs from a water temperature (evaporation basin) of approximately 56°C onwards. This temperature level is reached usually between 12:00 - 12:30 and stays above this value until at least 17:00. In this time period, variations in basin water temperature are mainly due to changes in the intensity of solar radiation (passing clouds). Every variation towards lower temperature values results in a (temporary) decline of the distillate output rate. During the experiments, this decline in temperature was also induced by occasional manual refills of the evaporation basin, due to the impossibility of the floating mechanism to

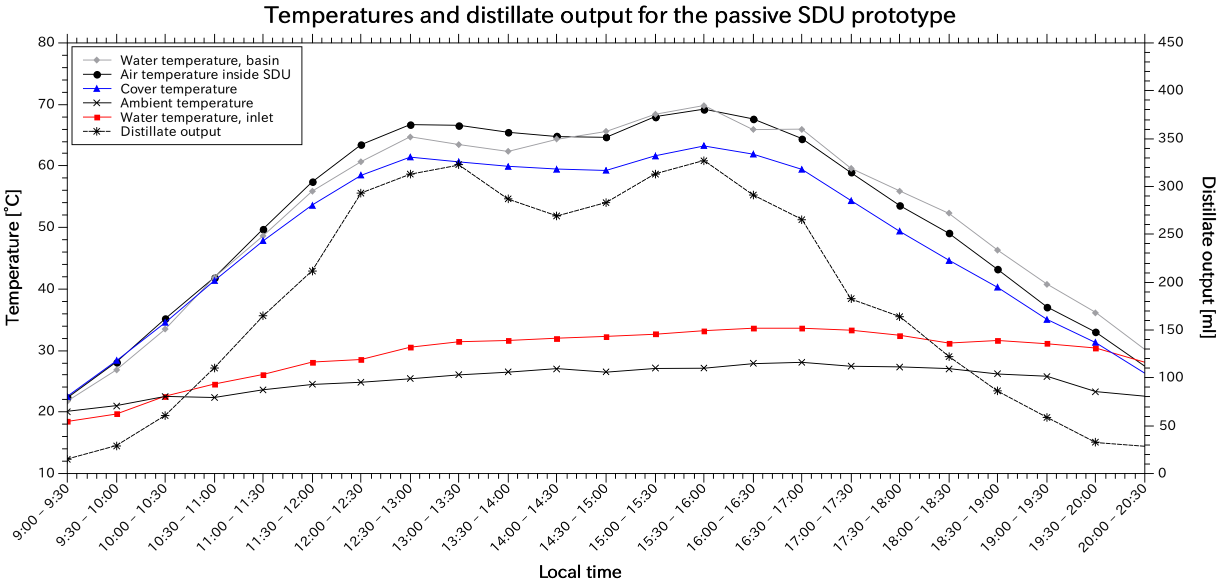

Figure 4.3. Average distillate output for the basic-design SDU in relation to temperature values.

keep the water level constant (see also detailed graphs B.2 to B.10). Whereas ambient temperature and raw water temperature show a constant, nearly linear behavior throughout the day and have little influence on the distillation process, the temperatures inside the SDU show a bigger variation. The main influence factor for this behavior are the variations in basin water temperature and solar radiation intensity, from which the parameters of cover temperature and air temperature inside the SDU are dependent. Curiously, the difference between cover temperature and basin water temperature is not as high as expected, having a mean difference of only 4.6°C instead of at least estimated 10°C for the time interval between 12:00 and 17:00 [2]. The most plausible reason for this is the installation of the thermocouple for cover temperature measurement at the top of the glass cover, without shielding it from the direct solar radiation [3]. Another point of interest is the crossing between the curves of cover temperature and basin

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[2] The mean difference was calculated by subtracting the average basin water temperature from the average glass cover temperature in the time interval of 12:00 to 17:00. The values were taken from table A.6.

[3] For the SDU with reflective side- and rear walls, the sensor was relocated and covered with a piece of aluminum foil to avoid the exposure to direct solar radiation.

water temperature in the first half of the day: as the basin water temperature exceeds the value of the cover temperature, the distillate output starts to raise rapidly. In the morning, the glass cover heats up more rapid than the water in the evaporation basin, due to its lower heat capacity. Due to this phenomenon, an effective distillation process can only take place after the raw water temperature in the evaporation basin exceeded the cover temperature.

Air temperature inside the SDU and basin water temperature do not differ significantly from each other throughout the day, variations between 12:00 and 17:00 are due to the inflow of ambient-temperature water (resulting in a decline of the basin water temperature towards the air temperature) or passing clouds. The effect of passing clouds is a fast decline of the air temperature towards the basin water temperature, due to its lower heat capacity (in comparison to water). After 17:00, the basin water temperature raises evidently above the value of the air temperature inside the SDU, because of the declining quantity of solar radiation reaching the aperture area, which first has an effect on the air temperature, due to its low heat capacity and afterwards on the water temperature in the evaporation basin. Figure 4.4 proves, that the wind speed has no influence on any of the measured temperatures. The reason for this may be sought in the orientation of the SDU: whereas the predominant wind direction during the measurement period was north-east, the prototype unit was orientated towards south, in order to maximize the quantity of incident solar radiation. Another fact is, that either wind velocity and wind direction changed frequently, due to the turbulences generated by the surrounding buildings.

The following table 4.1 shows the recorded maximum and minimum values during the measurement period in connection with their date and time of occurrence. As mentioned above, the wind speed is not considered to have any direct or indirect influence on the distillate yield and is therefore not listed in the table. Concerning the daily distillate output, the maximum quantity was reached on 20/07/2011 with a total amount of 4940 mL and the minimum quantity on 15/07/2011 with a total amount of 3722 mL. The mean value for the distillate output, taking into account all five measurement days is 4232 mL.

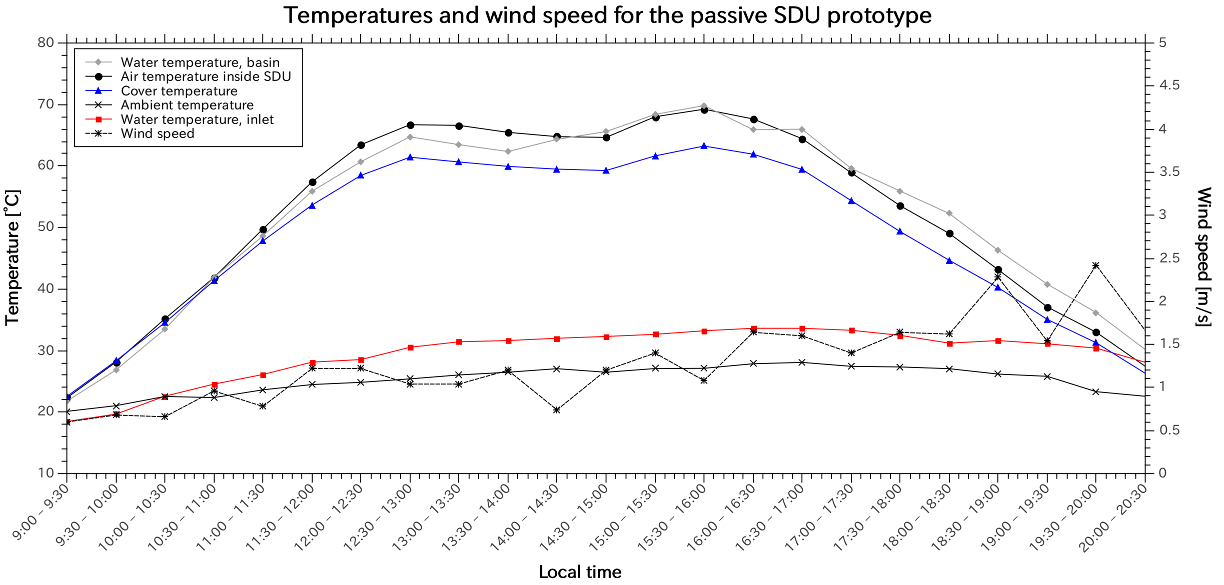

Figure 4.4. Average wind speed in relation to temperature values for the basic-design SDU during 5 measurement days.

Table 4.1. Maximum and minimum values of selected parameters for the SDU with basic design.

Unit	**Maximum value**	**Minimum value**	**Date**	**Time**
Solar radiation	1089 W/m^2	-	13/07/11	15:06
Distillate output	420 mL	-	20/07/11	14:00
Air temperature inside SDU	81.5 °C		20/07/11	14:42
		14.8 °C	13/07/11	08:12
Water temperature, inlet	39.3 °C		20/07/11	17:06
		15.2 °C	16/07/11	09:00
Water temperature, basin	80.4 °C		20/07/11	14:36
		14.2 °C	13/07/11	08:12
Cover temperature	74.0 °C		20/07/11	14:30
		15.8 °C	13/07/11	08:12
Ambient temperature	30.1 °C		13/07/11	16:00
		19.1 °C	19/07/11	09:00

4.2.2. Passive SDU prototype with reflective side- and rear walls

For the measurement period of the SDU prototype with reflective side- and rear walls, the sensor for air temperature was reallocated to the aluminum foil inside the SDU, because the measured values for air temperature and basin water temperature did not differ significantly from another and showed a linear dependency in the period of maximum distillate output from 12:30 to 17:00. Figure 4.5 shows the curves of solar radiation and distillate output, calculated from the average values throughout the measurement period (see table A.13). The corresponding daily measurement data is to be found in tables A.8 to A.12 on page 110 to 114 and the detailed graphs in figures B.12 to B.21 (pages 124 to 129). Although the general curve progression is very similar to the SDU with basic design, the quantity of produced distillate per time interval has augmented. In the morning hours, the quantity of distillate exceeds the mark of 200 mL already at 12:00 with solar radiation values of approximately 700 W/m^2 as opposed to the basic design of the SDU, where this level is passed 30 minutes later with solar radiation values of approximately

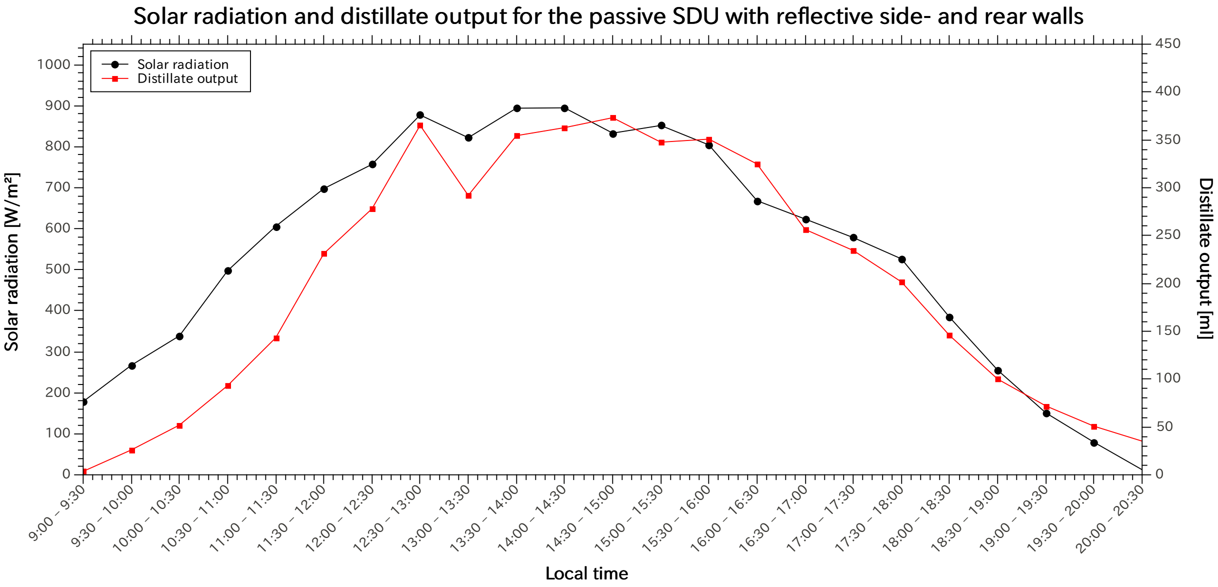

Figure 4.5. Mean values of solar radiation and distillate output for the SDU with reflective side- and rear walls during 5 measurement days.

800 W/m^2. The timespan of efficient distillate production (volume per interval of 30 minutes $\geq$200 mL) is prolonged from 12:00 to 18:00, in contrast to the SDU with basic design, where it ranges from 12:30 to approximately 17:00. Figure 4.6 confirms this statement in the form of clearly extended ascending slopes of the cumulative distillate output between 12:00 and 17:30 - 18:00, depending on the course of every single curve. It is notable, that by application of the reflective aluminum foil inside the SDU the values of total daily distillate yield could be raised in comparison to the basic design of the SDU. The maximum distillate yield was reached at 27/07/2011 with a total distillate quantity of 5588 mL.

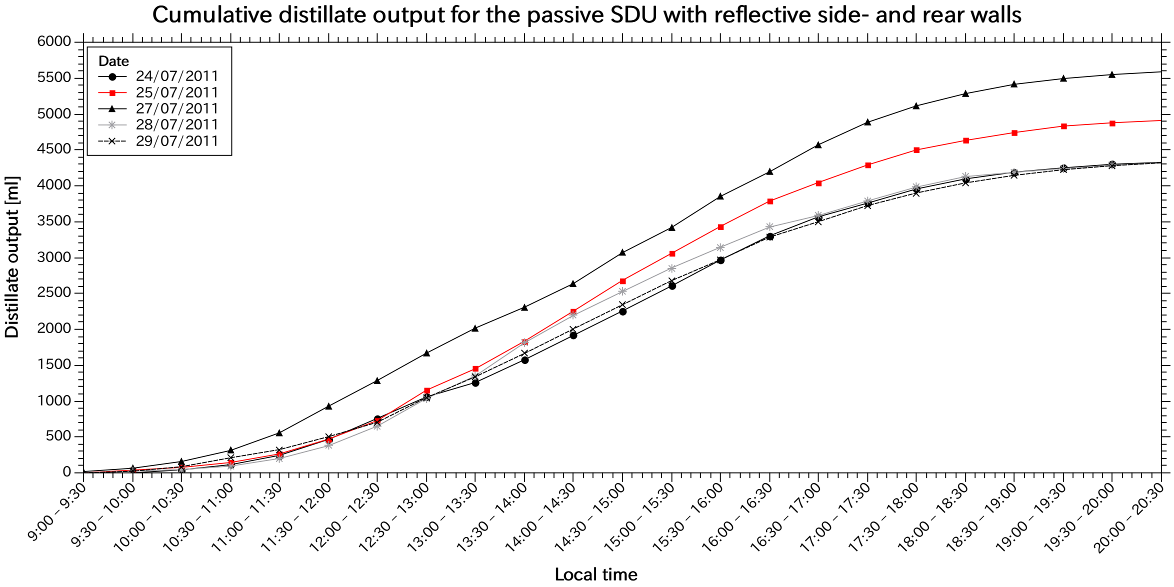

Figure 4.6. Cumulative distillate output for the SDU with reflective side- and rear walls as function of local time.

The reason for prolongation of the timespan of efficient distillate production can clearly be attributed to the use of reflective wall coating, which is augmenting the quantity of usable energy for raw water heating. The additional distillate canals at the bottom of the wall coating are facilitating the collection of additional distillate, which is condensing at the walls. Therefore, the reason for the distillate yield being $\geq$ 200 mL already at 12:00 is also attributed to the collection of additional distillate in the canals, because in comparison to the first measurement series, the raw water temperature has a value of only 50°C (as opposed to 60°C in the first series). Figure 4.7 proves, that also the assumption of the distillate yield rising significantly in the moment of the basin water temperature exceeding the cover temperature (which was valid for the SDU with basic design) is not applicable if the SDU is equipped with reflective coating: due to the aluminum foil having a lower temperature than the glass cover (until 16:00), the water vapor has an “alternative” condensing surface, resulting in a distillate output greater than 200 mL already at 12:00, although the basin water temperature would have exceeded the cover temperature not until 13:00. The advantage of this effect is a higher total distillate output at lower raw water temperatures. The period of high distillate output (V≥ 200 mL) continues as long as the water

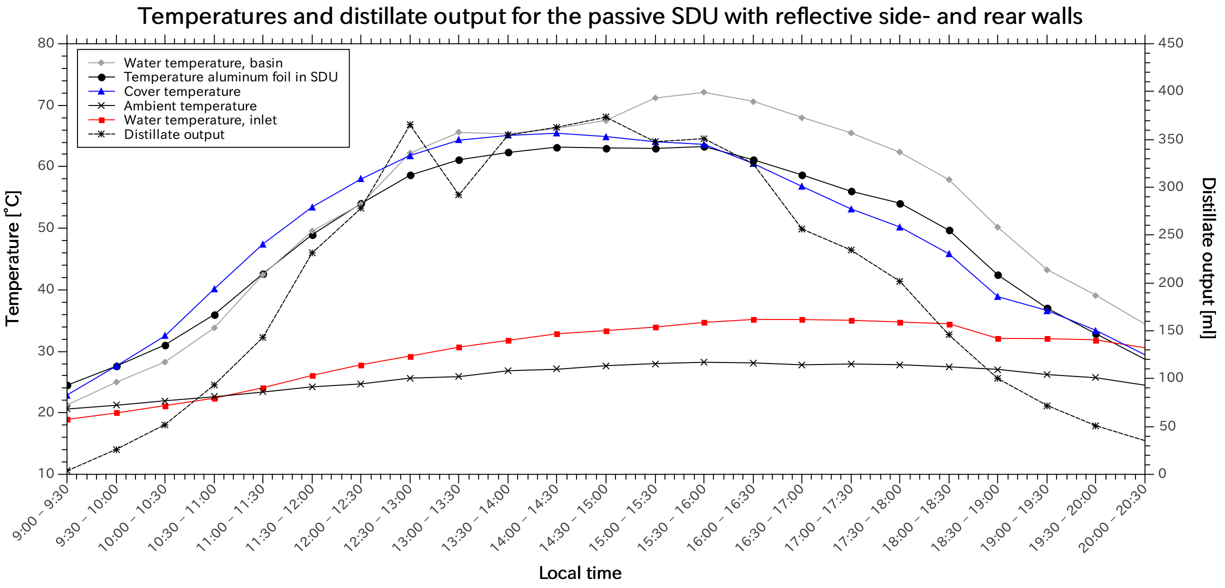

Figure 4.7. Mean values of temperature and distillate output for the SDU with reflective side- and rear walls during 5 measurement days.

temperature in the evaporation basin remains superior to 60°C.

A remarkable detail imposes the course of the basin water temperature at 16:00 local time: both SDU designs have their absolute peak in basin water temperature at this moment (slightly above

70°C), but opposed to the basic-design prototype, the basin water temperature of the second unit does not decline as rapidly. Due to the installed aluminum foil, a bigger quantity of solar radiation gets redirected into the evaporation basin, which would otherwise be lost for the process. Against all expectations, the distillate yield is not congruent to the prolonged higher level of water temperature although the temperatures of the glass cover, as well as the aluminum foil, are decreasing remarkably in last hours of the day. This phenomenon seems contradictory to the theory established in literature that a high temperature difference between basin water and cover is necessary to provide a high distillate output. A probable explanation could be that with lower air temperatures inside the enclosure of the SDU, which is not only a function of the basin water- but also the cover- and aluminum foil-temperature, the formation of water vapor decreases, although the basin water theoretically offers a sufficient temperature for the evaporation process. Practically, the colder air inside the distillation chamber slows down the upward movement of the water vapor. Therefore it is also plausible, that the distillate output is a function rather of the incident solar radiation (and therefore the air temperature inside the SDU), than of the basin water temperature. A comparison between figure 4.7 and 4.5 approves this statement. Another factor contributing to the fast decline of cover- and aluminum foil-temperature could be the wind speed, which is in general slightly elevated in the evening hours. Due to the extension of the aluminum foil to the outside of the SDU, the inside of the walls is prone to cool down because of the high thermal conductivity of the aluminum. This is not the case for the basic-design prototype, where the glass cover thermally shields the inside of the distillation chamber. According to the recorded measurement data, the cooling of the aluminum foil on the inside of the distillation chamber has a slightly negative impact onto the distillate yield. Figure 4.8 shows the average temperature levels in conjunction with the recorded wind velocities. The recommendation in this case is to use reflective wall coating with distillate troughs, but not to extend the used reflective material (aluminum foil) until the outside of the enclosure of the SDU. Table 4.2 summarizes the maximum and minimum values which occurred during the second measurement period. The

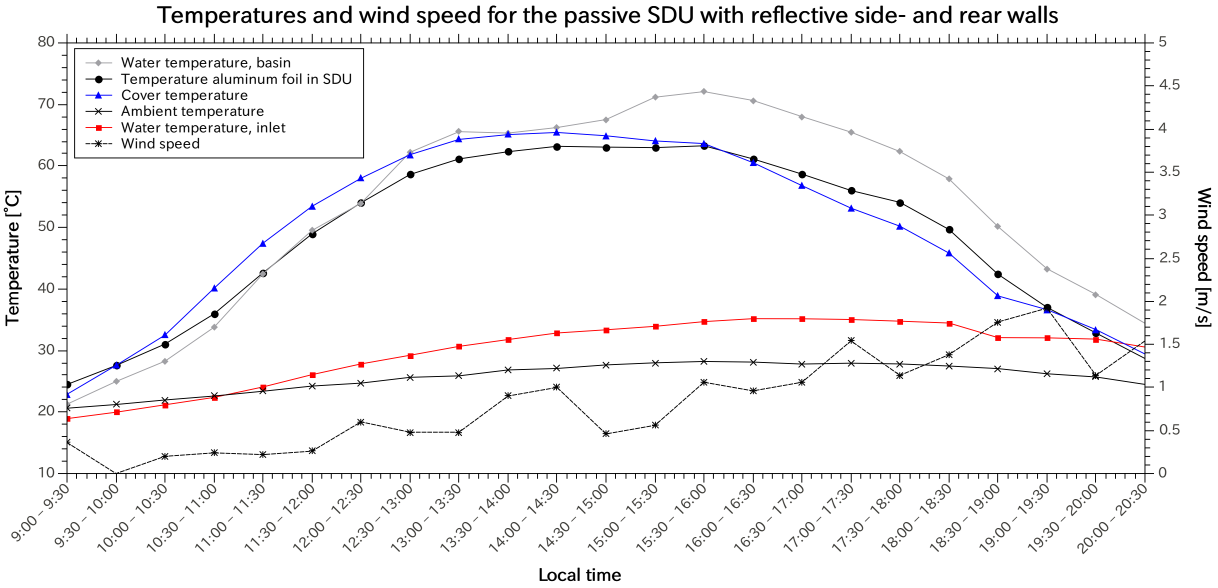

Figure 4.8. Mean values of temperature and wind speed for the SDU with reflective side- and rear walls during 5 measurement days.

Table 4.2. Maximum and minimum values of selected parameters for the SDU with reflective side- and rear walls.

Unit	**Maximum value**	**Minimum value**	**Date**	**Time**
Solar radiation	1129 W/m^2	-	24/07/11	13:30
Distillate output	460 mL	-	28/07/11	14:00
Temperature aluminum foil in SDU	70.1 °C		25/07/11	14:42
		20.8 °C	24/07/11	09:00
Water temperature, inlet	38.7 °C		27/07/11	17:42
		16.8 °C	25/07/11	09:18
Water temperature, basin	78.6 °C		27/07/11	15:48
		16.3 °C	24/07/11	09:00
Cover temperature	73.1 °C		27/07/11	13:36
		19.6 °C	25/07/11	09:06
Ambient temperature	30.2 °C		27/07/11	15:30
		19.0 °C	25/07/11	09:00

maximum daily distillate output occurred on 27/07/2011 with a quantity of 5588 mL, minimum distillate yield was noted for the days of 28/07/ and 29/07/2011 with a quantity of 4320 mL and the average value for the entire measurement period accounts with 4694 mL.

4.2.3. Energy efficiency

In order to determine which SDU design uses the incident solar radiation more effectively and to categorize the prototype units according to existing SDUs, it is useful and necessary to calculate the energy efficiencies of each design.

As mentioned in chapter 2.2, it is sufficient to use the following formulas to make a rough estimation of the overall energy efficiency of a SDU:

$$\eta_{SDU} = \frac{\Delta H_{vap} * m_{D_{int}}}{Q_{sol_{int}}}$$

For the calculation of $Q_{sol_{int}}$ for a certain time interval, it is necessary to multiply the incident solar power P_{sol} [W/m^2] with the length of the interval t_{int} [h] and the size A_{evap} of the area [m^2], which is heated by the solar radiation.

$$Q_{sol_{int}} = P_{sol} * t_{int} * A_{evap}$$

In the case of solar distillation, the heated area is the evaporation basin, which has the size of $1.45 \times 0.75 = 1.0875$ m^2. The efficiency was calculated for every time interval of 30 minutes of every measurement day, using the described formulas. In a second step, mean values over 5 days were calculated for every interval. The values for ΔH_{vap} are taken from table C.1 on page 131. For unit conformity, the distillate output has to be transformed from milliliters to kg; this is done by division of the distillate quantity by 1000 [4]. The quantity of solar radiation per time interval and area ($Q_{sol_{int}}$) has to be divided by 1000 to convert the unit [Wh] to [kWh]; the value in [kWh] has to be transformed to [kJ] for unit conformity with the enthalpy of vaporization, ΔH_{vap} (1 kWh $\widehat{=}$ 3600 kJ). Table 4.3 shows the averaged efficiencies for time intervals of 30 minutes, which have been calculated from the data for each five measurement days. The mean

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[4] For a precise transformation of the units, the exact distillate temperature would be needed, but for the approximate character of the efficiency calculation, the division by 1000 is sufficient.

Table 4.3. Average efficiencies for both design versions of the SDU prototype.

Time	**SDU with basic design**	**SDU with reflective side- and rear walls**
9:00 - 9:30	0.12	0.12
9:30 - 10:00	0.12	0.15
10:00 - 10:30	0.21	0.19
10:30 - 11:00	0.37	0.23
11:00 - 11:30	0.32	0.29
11:30 - 12:00	0.36	0.40
12:00 - 12:30	0.43	0.44
12:30 - 13:00	0.47	0.50
13:00 - 13:30	0.45	0.43
13:30 - 14:00	0.44	0.48
14:00 - 14:30	0.45	0.49
14:30 - 15:00	0.45	0.55
15:00 - 15:30	0.43	0.49
15:30 - 16:00	0.46	0.52
16:00 - 16:30	0.42	0.60
16:30 - 17:00	0.46	0.49
17:00 - 17:30	0.41	0.49
17:30 - 18:00	0.43	0.46
18:00 - 18:30	0.38	0.51
18:30 - 19:00	0.56	0.55
19:00 - 19:30	0.57	0.61
19:30 - 20:00	1.04	0.80
20:00 - 20:30	2.49	3.54
Mean value 12:00 - 17:00	0.45	-
Mean value 12:00 - 18:00	-	0.49

values for the overall daily efficiency of the two prototype SDUs were determined according to the timespan of efficient distillate output ($V_D \geq 200$ mL) for each prototype - see also chapters 4.2.1 and 4.2.2. Figure 4.9 shows the curves of solar radiation and energy efficiency for the SDU prototype with basic design. As mentioned before, the timespan from 9:00 to 12:00 is mainly used for heating the raw water, which results in a low energy efficiency (because of low distillate output rate). In the timespan between 12:00 and 17:00, the energy efficiency stabilizes and reaches values between 36% and 47% (marked by the yellow box in the graph). Although the energy efficiency shows a similar course until 18:30, this timespan is not taken into account for the calculation of the mean daily efficiency, because the distillate output per time interval of 30 minutes falls below the value of 200 mL (see also figure B.11 on page 123). Between 18:30 and 20:30, the energy efficiency rises to unreal values, due to the declining

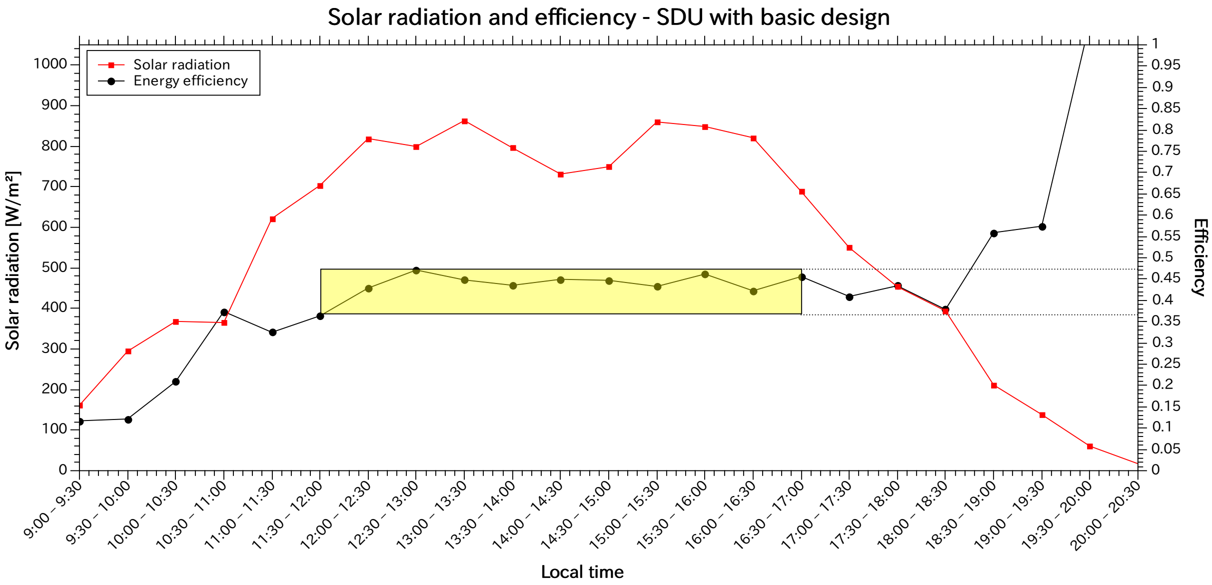


Figure 4.9. Insolation and energy efficiency for the basic-design SDU.

values of solar radiation and the still warm water in the evaporation basin. The energy efficiency is "inverting" with the water in the evaporation basin bearing a higher energy content than the rest of incoming solar radiation. Therefore, the efficiency values from 18:30 onwards can not be taken into account for calculations. Figure 4.10 shows the graphs of basin water temperature and energy efficiency for the basic-design prototype, from which can be concluded, that a raw water temperature of at least 50°C is necessary in the evaporation basin to reach satisfactory values of energy efficiency. Figure 4.11 illustrates the courses of solar radiation and energy efficiency for the SDU with reflective side- and rear walls. Like in the first SDU design, the energy efficiency starts to reach constantly high values from 12:00 onwards, with distillate output rates superior to 200 mL per time interval (see also figure B.22 on page 130). The values of energy efficiency vary between 40% and 60% in this period of time - until 18:00, when the distillate rate drops below the level of 200 mL. In comparison to the SDU with basic design, the installation of reflective side- and back walls leads to a prolonged period of high distillate output rates and a higher peak efficiency (60% instead of 47% for the basic-design SDU). The temperature level

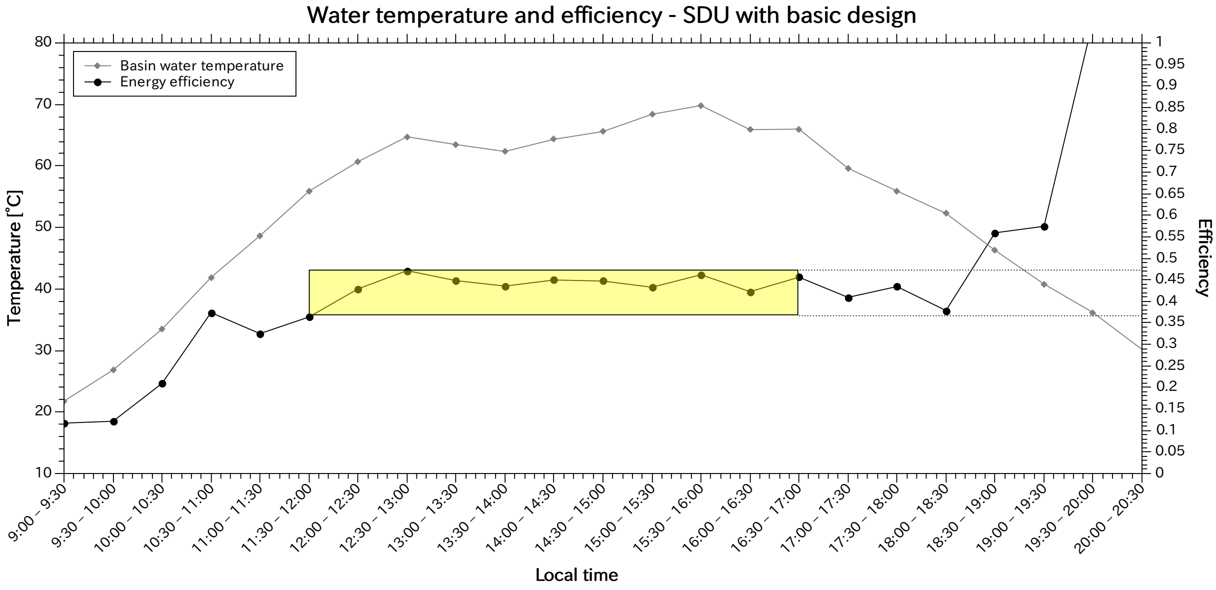


Figure 4.10. Basin water temperature and energy efficiency for the basic-design SDU.

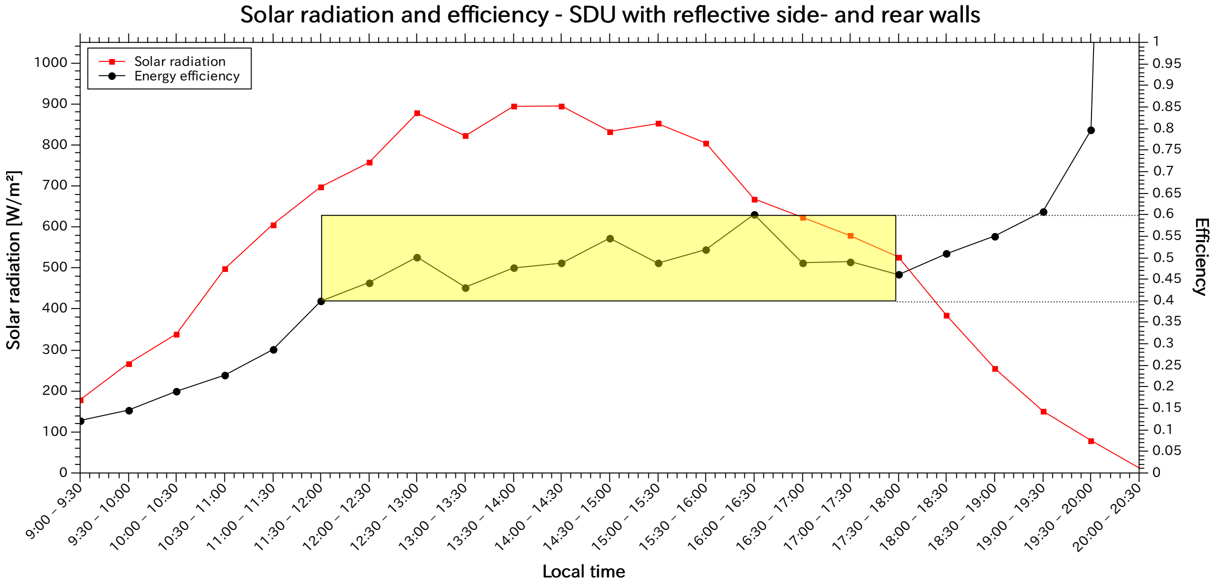


Figure 4.11. Insolation and energy efficiency for the SDU with reflective side- and rear walls.

from which the distillation process can be regarded as efficient in terms of energy efficiency and distillate output is also 50°C as in the basic-design SDU (see figure 4.12).

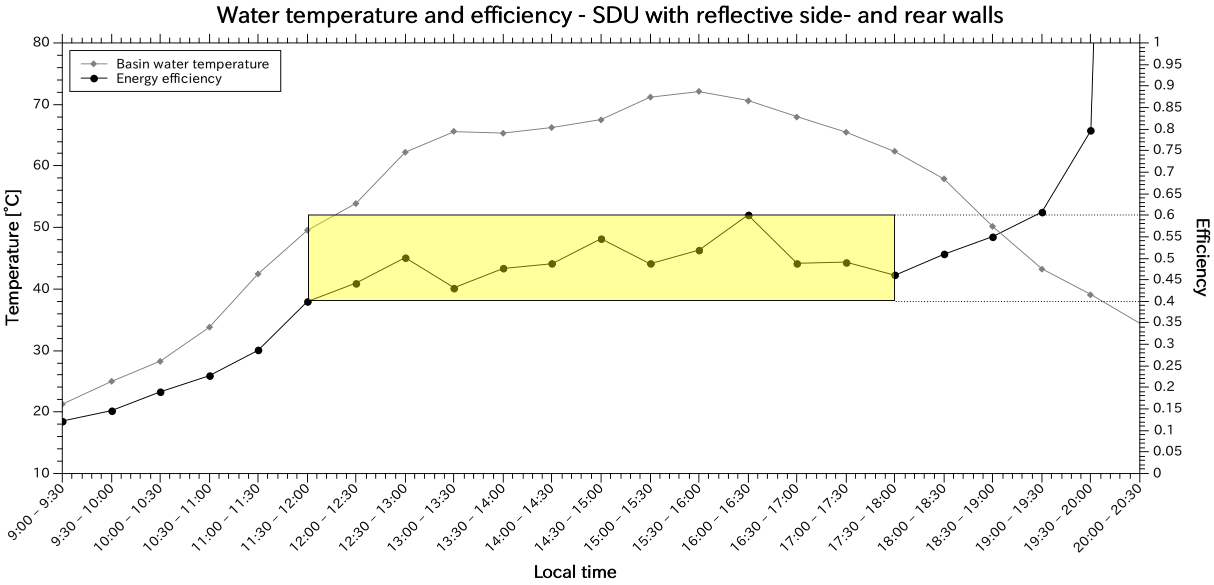


Figure 4.12. Basin water temperature and energy efficiency for the SDU with reflective side- and rear walls.

4.2.4. Distillate quality

Basic measurements of raw water- and distillate quality were made during the performance evaluation in order to determine the parameters of pH and conductivity. For measuring the pH value, a handheld pH/mV/Thermometer type “Spectrum Technologies® IQ150” with a precision of ±0.01 pH units was used and for conductivity measurements a handheld equipment type “Horiba® U-10”, with a precision of ± 1 %. The results of preliminary measurements of the distillate quality, taken directly in the Erlenmeyer flask, are presented in table 4.4. The raw water source was tap water from the Faculty of Engineering of the UASLP. The determined values

Table 4.4. Basic values of distillate quality.

Value	**Raw water**	**27/07/2011**	**28/07/2011**	**29/07/2011**
pH	8.80	4.65	4.27	4.82
Conductivity [mS/cm]	0.324	0.010	0.019	0.008

of conductivity of the distillate lead to the conclusion, that the prototype SDU successfully removed minerals and salts from the raw water. In comparison to other SDUs (see Hanson et al., 2004), the pH value of the distillate is low, and not in the range for drinking water, according to the NOM (permitted range: 6.5 - 8.5 pH units). It was not possible to determine the exact reason for the low pH value, but it is expected that it is a result of either the "acidification" of the distillate in the process of condensation and collection (enrichment with CO_2 and formation of carbonic acid - H_2CO_3) or a chemical reaction of the distillate with the aluminum foil and/or its surfactants. It has to be mentioned that the used aluminum foil was not labeled as "food-grade" and therefore its surface may be treated with chemical substances.

Raw water obtained from the municipality of *Las Vigas* in the project region and the distillate output were screened for the parameters mentioned in chapter 3.1.2, according to the NOM for drinking water, in order to determine the aptitude of the SDU prototype to efficiently purify the type of raw water common to the Altiplano region.

In addition to the measurements of distillate quality directly in the Erlenmeyer flask, two auxiliary arrangements were made in order to improve the parameters of pH (low value in basic measurements) and conductivity (which is an indicator for the mineral content of the water). According to McCracken and Gordes (1985), the addition of marble chips to the distillate contributes to the re-mineralization of the water, thus enhancing its physical properties for human consumption. Therefore, the first arrangement consists in the addition of 50 g of marble stones to 200 mL of distillate. The residence time was 22 hours.

The second arrangement consists in the application of the aforementioned *Zeer pot* for distillate water storage, in order to determine its effect on the distillate quality. A quantity of 600 mL of distillate was kept for 16 hours in the pot.

The determination of quantity of microorganisms, coliform bacteria, fluorides, nitrates, chlorides and total hardness was done in the laboratory of Chemical and Environmental Engineering, Faculty of Chemistry of the UASLP. The parameters of arsenic, lead and copper were determined by atomic absorption spectrophotometry (Varian® SpectrAA-220), either by acetylene / nitrogen dioxide flame or graphite tube furnace (as indicated in table 4.5). Conductivity and pH values were measured with the same equipment as for the determination of the basic water quality. For turbidity measurements, the handheld equipment "Horiba® U-10" was used and the values of alkalinity were determined by titration of the specimens with a solution of sufluric acid (0.02 M). Every parameter of water quality was measured twice for each assembly (except for arsenic, copper and lead which were determined by spectrophotometry which requires three measurements per specimen), in order to minimize the possibility of errors. Table 4.5 shows the determined parameters (mean values) for raw water- and distillate quality with and without

Table 4.5. Parameters of raw water and distillate quality

Parameter and unit	**Raw water**	**Distillate**	**Distillate with marble chips**	**Limit established in NOM for drinking water**
Color (units on Pt/Co - scale)	clear	clear	clear	20
Odor and taste	stale	wood and linseed oil	wood and linseed oil	-
Turbidity [NTU]	0	0	0	5
Conductivity [mS/cm]	0.349	0.013	0.058	-
Alkalinity [mg $CaCO_3$/L]	242	not detected	50	-
pH [pH units]	8.5	4.77	7.77	6.5 - 8.5
Mesophilic aerobic microorganisms [CFU/100 ml]	4008	not detected	-	Absence or not detectable
Total coliform bacteria [MPN/100 ml]	not detected	not detected	-	Absence or not detectable
Fecal coliform bacteria [MPN/100 ml]	not detected	not detected	-	Absence or not detectable
Fluorides [mg/L]	0.22	0.13	-	1.5
Nitrites [mg/L]	0.02	0.02	-	1.00
Nitrates [mg/L]	4.41	1.20	-	10.0
Chlorides [mg/L]	10	1.75	-	250.0
Total hardness [mg $CaCO_3$/L]	179	8.5	-	200.0
Arsenic [µg/L][*]	245 ± 26.1 µg/L	< 3 µg/L	-	10.0
Copper [µg/L][•]	43.5 ± 5.5 µg/L	7.3 ± 2.1 µg/L	-	2000.0
Lead [µg/L][•]	2.7 ± 0.2 µg/L	1.1 ± 0.1 µg/L	-	10.00

[*] - spectrophotometry with acetylene / nitrogen dioxide flame

[•] - spectrophotometry with graphite tube furnace marble chips in relation to the values of the present NOM (as described by Coutiño, 2000). The measurement results of the *Zeer pot* are not included, due to the use of cement at its bottom, which influenced the values of pH, conductivity and alkalinity. Furthermore, the majority of the distillate permeated through the walls of the inner pot towards the sand layer - thus making a precise determination of the aforementioned parameters impossible. Nevertheless, the *Zeer pot* is considered as a useful additional device, but further studies towards its design and use with distillate have to be conducted.

The obtained measurement results prove that the prototype SDU is efficient in the removal of salts (parameters of fluorides, nitrates, hardness, alkalinity and pH), toxic substances (fluorides, arsenic, copper and lead) and bacteria (mesophilic microorganisms).

The post-treatment of the distillate with marble stones is appropriate to rise the low pH-value of the distillate and for its partial re-mineralization (values of conductivity and alkalinity), thus making it conform with the values of the NOM for drinking water. The observed effects are to be attributed to the addition of calcium carbonate from the marble stones. Depending on the residence time of the stones in the distillate, the values of pH, conductivity and alkalinity (evidence for the presence of calcium carbonate) are rising. It is recommended to determine a minimum residence time in future research in order to optimize the effect and to provide the users of a SDU with information towards the application of the material. Also further studies towards the detailed determination of the quality of the re-mineralized distillate should be conducted.

4.3. Observations during the experiments

The adjustment of the height of the regulation tank in order to provide the correct water level in the evaporation basin as well as a constant refill proved to be a difficult task, which could not be solved entirely in the end, thus partial manual refill of the evaporation basin had to be applied. It is necessary to adjust primarily the level of the floating mechanism and afterwards the height of the regulation tank by millimeters, until the desired effect is reached. Optionally, the valve could be replaced with a more precise regulation mechanism which, on the other hand is probable to cause elevated costs.

The efficiency of raw-water pre-heating proved to be lower than expected. Instead of pre-heating the raw water to a level of expected 50 to 60°C, only 25 to approximately 35°C were reached during 12:00 and 18:00. This is most probably due to the non-isolated regulation tank and the short piece of flexible hose which connects the raw water storage tank with the regulation tank. Furthermore, this piece of hose was not treated with black paint. A longer, black-painted hose which is broadly exposed to solar radiation would raise the effect.

The use of aluminum foil for the distillate trough is seen to be adequate in terms of mechanical stability and distillate runoff properties. Initial problems of joining the distillate trough with the drainage pipe could be solved by the installation of a small funnel made of recycled beverage cans on top of the pipe. The length of the drainage pipe (50 cm) effectively cools down the distillate about some degrees on its way to the collection vessel.

4.4. Error analysis and possibilities of improvement

The sources for systematic measurement errors during the experimental phase have been tried to minimize, but nevertheless, such errors can never be completely precluded. Mainly in the measurements of wind speed, ambient temperature and distillate output, these errors could have occurred. As the measuring device for wind speed does not include an indicator for wind direction, the measured values are tending to be potentially lower than the real ones - in the range of 0.1 to 0.2 m/s, because it could not always be guaranteed that the device was correctly adjusted towards the wind direction. The ambient temperature was always measured in the shade near the SDU prototype, but nevertheless the surrounding stone balustrade may have had an influence on the temperature measurements (most notably in the evening hours, for its effect of heat storage) - in the range of approximately + 0.1 to + 0.5°C. For measuring the distillate output, a graduated cylinder with a total capacity of 250 mL was used. In the morning hours, the small distillate quantities did not always reach the minimum measurement mark of the cylinder, so that the value had to be estimated by using a ruler (estimated inaccuracy ± 2 mL). In the hours of high productivity, the distillate output had to be measured in two steps, because of the insufficient capacity of the cylinder (for output greater than 250 mL). This possibly led to an inaccuracy of ± 4 mL, due to the decanting of the Erlenmeyer flask into the cylinder (distillate losses due to spilling and gains due to remnant water drops in the graduating cylinder).

4.4.1. Constructional deficiencies

During the process of construction and first test runs of the SDU, various deficiencies in design and construction have been detected, which demand for optimization in further constructions or prototypes. The following issues have been detected:

1. The wood glue (especially when mixed with saw dust) which has been used to join the wood boards and fill cavities macerates in contact with water vapor (or water). This causes pressure on the wood and leads to warping. *Proposed solution: avoiding the use of glue at parts which are probable to be in contact with water (vapor) and use screws or similar connections. Silicone may be applied as alternative sealant, if the affected parts are not in direct contact with the distillate.*

2. Wood is warping when in excessive contact with water (e.g. spills of the basin or condensate accumulations). During the test phase without the reflective side- and rear wall coating, the wooden rear wall of the case was warping excessively due to distillate runoff and had to be stabilized (see figure 4.15(b)). *Proposed solution: Better impregnation of the wood by surface sealants (varnishes) - disadvantage: these products often contain noxious substances. The alternative installation of reflecting rear- and side walls with distillate troughs helps to minimize this problem by discharging condensate which otherwise would wet the wooden base or run down the walls*

3. Water vapor is condensing at the bottom side of the distillate trough. The water is dripping down, thus wetting the wooden base. Basically, this form of condensation is a highly desirable effect, which occurs due to the temperature difference of the aluminum foil as opposed to the air temperature inside of the distiller and which is utilized by the reflecting side walls with distillate trough. Nevertheless, this form of condensation is not exploitable in the unit and therefore to be seen as losses. Figure 4.13 shows a close-up (top) view of

the phenomenon. *Proposed solution: A slightly higher inclination of the distillate trough*

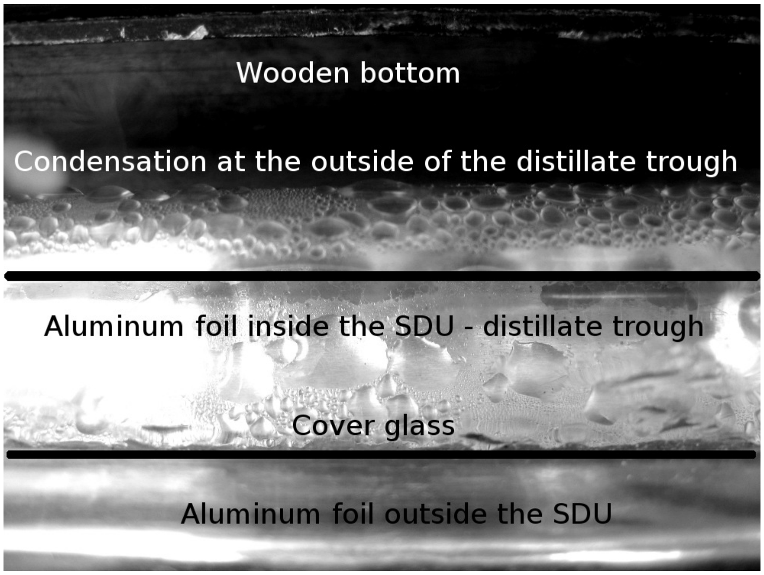


Figure 4.13. Condensation at the outer brim of the distillate trough (towards basin).

could favor the draining of this part of condensate which would run off the bottom side of the distillate trough and be recollected at the drainage pipe. To realize this measure, the front part of the distiller's case would have to be constructed at least one centimeter higher.

4. The evaporation basin bends under excessive solar radiation in absence of water (see figure 4.14), thus leading to an inhomogeneous distribution of the raw water and the deposition of salts contained in it. During the experimentation period this happened due to a maladjusted floating valve. *Proposed solution: A constant water level has to be guaranteed throughout the day and necessary maintenance or cleaning work should be postponed to the evening hours. Additionally, the evaporation basin should be made of a slightly thicker metal sheet (at least 4 mm). A different (more precise) floating mechanism is necessary to guarantee a constant water level.*

Figure 4.14. Evaporation basin with dry spot and encrusted salts originating from the raw water.

5. Difficult handling of the glass sheet while inserting it into the slot of the case. Furthermore the glass bends slightly down horizontally at insertion, due to its own weight. This causes difficulties inserting it into the slot at the front side of the distiller. The removable part of the rear wall is prone to vapor leakage due to the gaps at the side and bottom of it, which lead to warping. Vapor leakage at aforementioned places was detected during the measurements; the gaps were therefore sealed provisionally with silicone glue. *Proposed solution: The design of the SDU should be changed towards a horizontal placement of the glass (shutting the SDU with the cover glass from above instead of inserting it into slots), which could then be fixed by a wooden frame from the top. The front side glass slot can be kept, for it is necessary to sustain the cover glass and form a profile for the distillate trough.*

6. The distiller's front wall is pushed out by the weight of the cover glass and / or its expansion when heated. Figure 4.15(a) shows the front side stabilization. *Proposed solution: Joining of the front wall with the side walls on the inside of the distiller, rather than fixing it to the side walls and bottom from the outside.*

(a) Fixation of the front side.

(b) Stabilization of the rear wall with vertical bars.

Figure 4.15. Measures against instability and vapor leakage.

7. Rainwater can enter the distillate trough from outside by passing gaps between the cover glass and the slot on the front side. *Proposed solution: Either this effect can be tolerated (rainwater contains few contaminants) or an additional frame made of aluminum foil is installed on the lower side of the cover glass and fixed with silicone. The frame can overlap the front side of the distiller and thus discharge the rain water.*

8. The aluminum foil of the distillate trough and the side walls shows irregular signs of oxidation at some parts. Probably this is due to a reaction of a chemical (oil?) used to impregnate the surface of the aluminum foil with the hot water vapor. *Proposed solution: This phenomenon has to be investigated further in order to determinate if it is destructive or has impacts on the product water quality. Alternatively, plastic-coated aluminum foil might be used.*

9. Fast buildup of salt crusts in the evaporation basin which are floating on the water surface (see figure 4.16). *Proposed solution: The evaporation basin has to be equipped with a possibility of raw water discharge, e.g. an additional outlet tube, thus facilitating a*

"flushing" of the basin with raw water, which removes the crystallized salts and lowers the overall salt concentration in the raw water.

Figure 4.16. Evaporation basin with crystallized salts after one week of constant operation.

10. The distillate smells and tastes of linseed oil. *Proposed solution: Wait until this effect has diminished; it is of temporary nature due to the dissolution of ethereal oils from the superficial layers of linseed oil by the water vapor.*

4.5. Discussion of the obtained results

The determined values for energy efficiency and distillate output of both design variations of the passive SDU prototype are very satisfactory and in accordance with the estimated values of distillate yield presented in table 3.3 in chapter 3.1.1. For the passive SDU with basic design, an average daily yield of 4.34 L for the month of July was expected (calculated from 4.02 L/m^2 ×1.0875 m^2 for an efficiency of 45%) and a value of 4.32 L was determined by the measurements. The passive SDU with reflective side- and rear walls had an average daily distillate output of 4.69 L - the estimated value (for an efficiency of 50%) was 4.86 L.

Porta et al. (1998) describe an array of SDUs in the federal state of Baja California Sur, which has an average yearly output of 4.2 L/m^2. The value for the average yearly distillate output of the basic-design SDU prototype with an efficiency of 45% is estimated to be 4.17 L/m^2 for the municipality of Charcas (SLP), and therefore congruent with literature. Foster et al. (2005) attribute a production rate of 0.8 liters per hour of sunshine to commercial solar distillers, developed by the company SolAgua®. This value matches closely the production rate of the SDU prototype with reflective side- and rear walls during the noon hours.

It can be concluded that under Mexican climate conditions the obtained values for distillate output and energy efficiency are realistic and reproducible. With efficiency values of 45% and 49%, the built prototype is technically efficient enough for the use in further field studies. The achieved values of distillate output are very satisfactory for the working principle of passive SDUs and the installation of reflective side- and rear walls inside the SDU has proven to be useful in raising the distillate yield by an average of 3.5% and the overall energy efficiency by 5%. An augmentation of at least 20% in energy efficiency attributed to the installation of reflective side- and back walls, as predicted by Al-Hayek and Badran (2004) and Abdallah et al. (2008) could not be observed.

It has to be stated that the achieved daily distillate yield is not sufficient for the supply of the basic drinking water needs for a family of four members. Therefore it is necessary to investigate the performance of the proposed active SDU with additional SAC, which should be able to double the average daily distillate yield. The investigated SDU prototype could provide drinking water for only one to two persons per day.

4.6. Considerations for daily use and maintenance

The following recommendations are given (to users) in order to optimize the daily distillate output and to keep the SDU in a good state:

- Cleaning of the cover glass at least every three days to avoid the buildup of dust, which is constraining the entrance of solar radiation towards the evaporation basin. If this measure is not taken, the distillate yield will decline by approximately 10% (McCracken and Gordes, 1985).
- It is estimated that the wooden case of the SDU needs to be treated with linseed oil from time to time, in order to avoid rotting and the growth of fungus. An appropriate time interval seems to be every three months (estimated value, detailed investigations still have to be made). One liter of linseed oil is sufficient to apply four layers on the in- and outside of the SDU.
- Removal of the cover (or alternatively only a part of the rear wall) at least once a month, to dry the distillation chamber and to avoid too strong humidification and warping of the wooden enclosure. At the same time, the distillate trough can be revised for dust and other impurities which may have permeated to the inside of the SDU in the passing of one month.
- Flushing or cleaning of the evaporation basin at least once a month, in order to remove deposited salts which can corrode the basin if their concentration gets too high or reflect the solar radiation if they build a (floating) crust.
- Periodical refill of the raw water storage tank - depending on its size. It is vital that the evaporation basin constantly keeps a certain water level, to avoid the formation of “dry spots” and mineral deposits from the raw water, which are very hard to remove without impairing the layer of black paint.

- Periodical cleaning of the distillate collection vessel, in order to avoid the growth of algae and bacteria. It is recommendable to use at least two vessels, which can be interchanged periodically (approximately every two days). If clay pots are used as collection vessels, it should be sufficient to expose one pot (which is meant to be interchanged) to direct solar radiation for at least one day, in order to dry and disinfect it (by means of ultraviolet radiation) before swapping it with the one currently in use.

The additional costs caused by these measures are very low (only the linseed oil accounts with 86 MXN (approx. 7.30 US$) every three months), but it has to be recognized that the technology needs some manual labor to provide a constant and reliable distillate output.

5. Summary and conclusions

The technology of solar distillation can be seen as a developed and adequate method of water purification, especially in regions with high solar radiation values. The developed prototype designs proved to be functional and provided excellent results regarding energy efficiency (45 and 49%) and distillate output in the context of passive solar distillation. The applied techniques of passive energy augmentation (low water level of 5 mm, reflective aluminum foil and raw water pre-heating in the storage tank) proved to be effective. Nevertheless, the quantity of distillate which the SDU prototype produced (4.32 and 4.69 L per day in average) is not sufficient for the supply of a family of four members in the Altiplano region. Therefore it is necessary to construct and investigate the proposed second, active, prototype SDU which is likely to produce at least the double quantity of water per day and square meter.

Regarding the distillate quality, it has to be noted that all important contaminants could be removed from the raw water. Issues of low pH-values and lack of minerals of the distillate could successfully be resolved by the addition of marble stones to the collection vessel. Therefore their use is strongly recommended as post-treatment of the distillate and should be considered in future implementations of the technology.

The construction costs for the SDU proved to be high (about 500 US$), mainly due to the use of special hardwood for the distillation chamber and aluminum sheet for the evaporation basin. Therefore, the economical feasibility is not given and further research towards alternative materials has to be made in order to lower the construction costs.

5.1. Interpretation of the results in the context of the study area and recommendations

Considering the climatological values (ambient temperature and intensity of solar radiation) for the municipality of Charcas (SLP) (see tables 3.1 and 3.2), an implementation of the technology of solar distillation for the purpose of small-scale drinking water supply in the Altiplano region is highly favorable. The high values of solar radiation and ambient temperature around noon provide a good base for an efficient functioning of a SDU. Especially in the period before the rainy season commences (months of March to June), the values of solar radiation promise a high distillate output. The geological height of Charcas (SLP), 2,057 meters above sea level, additionally favors a high evaporation rate, due to the low ambient pressure (811 hPa in comparison to 1013 hPa at sea level).

Although the applied working principle proves to deliver satisfactory results, the case of the SDU should be constructed from another material than swamp cypress wood. Alternatives are mesquite wood (which is more durable and resistant against warping, but also imposes a higher cost) or even common brick stones used for ordinary construction works. A construction of metal (aluminum) would be an option, but is estimated to cause at least the same costs as the prototype construction of swamp cypress wood; it is prone to bear even higher additional costs, due to the necessity of a specialized workshop and -tools for its handling. The evaporation basin which is made from cost-intense aluminum sheet in the prototype SDU could be replaced by black tiles in a future prototype construction of brick stones, thus saving costs and at the same time being more robust towards aggressive compounds (dissolved salts) in the raw water. Further investigation has also be done towards the implementation of the proposed active SDU, because it offers an elevated distillate output rate at only a very slightly elevated material price. This is due to the use of recycled aluminum beverage cans for the absorber of the SAC and plywood from recycled transport pallets for its case.

Summarizing, the technology of solar distillation proves to be an appropriate solution for the purification of contaminated water in the Altiplano region. The economical feasibility is not yet given and further research towards economical and durable construction materials has to be made. The thesis is to be understood as an attempt towards this direction. With the described economical and uncomplicated advance towards active solar distillation, a sufficient distillate output for a family of four members is manageable.

Appendices

A. Measurement data

A.1. Data for the passive SDU prototype (basic design)

Table A.1. Measurement data for 13/07/2011.

Time	**Solar radiation [W/m^2]**	**Air temperature inside SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [ml]**
8:00 - 8:30	43.8	16.6	18.5	16.0	16.5	19.5	0.3	0
8:30 - 9:00	94.6	17.0	16.6	16.0	19.8	20.5	0	0
9:00 - 9:30	134.8	24.3	20.4	23.4	26.2	21.5	0.5	26
9:30 - 10:00	314.6	29.3	20.7	28.9	30.9	22.5	0.5	36
10:00 - 10:30	300.6	37.9	24.6	39.3	37.2	24	0.5	66
10:30 - 11:00	520.2	43.5	23.7	45.3	44.1	22.6	1.5	160
11:00 - 11:30	481.6	51.4	27.3	52.7	51.2	25	0	132
11:30 - 12:00	699	55.3	28.3	57.2	54.5	25.5	0.8	204
12:00 - 12:30	885.4	65.5	28.9	64.5	61.9	26.2	0.7	306
12:30 - 13:00	597	65.5	30.8	64.5	62.5	26.5	0.7	250
13:00 - 13:30	878.8	67.7	31.2	66.6	63.9	26	0.7	340
13:30 - 14:00	484	60.4	31.9	61.1	59.3	27	0.5	196
14:00 - 14:30	354.8	53.2	31.7	54.8	52.2	27.5	0.3	164
14:30 - 15:00	540.8	50.7	31.5	53.2	49.5	26.5	1.5	154
15:00 - 15:30	852.4	60.9	31.7	62.7	58.6	28.8	1	274
15:30 - 16:00	922.2	65.7	32.7	67.3	64.0	28.3	1.2	316
16:00 - 16:30	815.4	64.5	32.8	67.1	64.4	30.1	1.5	300
16:30 - 17:00	647	60.3	32.8	64.1	61.6	30	1.3	286
17:00 - 17:30	631	56.8	32.1	61.4	57.7	28	0.5	210
17:30 - 18:00	490.6	52.4	31.5	57.2	52.8	27.5	1.5	202
18:00 - 18:30	359	47.1	30.6	51.2	47.0	28.2	1.8	130
18:30 - 19:00	230.8	41.9	30.7	45.2	41.5	26.2	2	106
19:00 - 19:30	196.4	36.7	29.9	40.1	36.4	26.6	1.5	76
19:30 - 20:00	77	33.7	30.4	36.1	33.3	25.6	1.2	52
20:00 - 20:30	21.7	29.3	28.6	30.9	28.7	23.9	1.8	38
SUM	57889							4024

Table A.2. Measurement data for 15/07/2011.

Time	**Solar radiation [W/^{2}]**	**Air temperature inside SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [ml]**
9:00 - 9:30	129.4	22.76	18.06	25.18	22.8	20.5	0.7	12
9:30 - 10:00	222	26.64	18.38	29.92	27.12	20.6	1	24
10:00 - 10:30	293.2	29.52	18.78	32.52	29.78	22	1.1	48
10:30 - 11:00	378	38.86	21.9	42.6	39.8	22.2	1	100
11:00 - 11:30	623.4	49.74	26.44	54.16	50.32	23.5	1.2	198
11:30 - 12:00	722.4	59.26	29.12	60.7	56.12	24.5	1.5	218
12:00 - 12:30	827.8	66.4	30.34	65.52	60.04	24.5	1.6	366
12:30 - 13:00	824.8	69.24	31.42	67.48	63.08	25	1.5	314
13:00 - 13:30	746.8	59.88	32.18	59.6	53.76	26.5	1.7	282
13:30 - 14:00	824.8	59.32	31.72	59.28	51.64	27	1	220
14:00 - 14:30	696.2	60.78	31.82	56.96	54.66	27	1	196
14:30 - 15:00	627.4	61.38	31.46	60.9	54.88	26.2	1	264
15:00 - 15:30	702.2	63.52	31.4	62.32	56.22	26.1	0.5	210
15:30 - 16:00	929.2	67.28	31.7	66.32	59.48	26.5	1.6	370
16:00 - 16:30	749.8	60.32	31.68	47.56	54.1	27	1.7	226
16:30 - 17:00	522.4	55.9	31.54	56.6	51.44	26	2.5	150
17:00 - 17:30	341.4	50.08	31.12	51.06	45.08	26	2	142
17:30 - 18:00	399.8	46.92	29.86	49.88	42.02	26	2.5	120
18:00 - 18:30	304.2	43.22	28.52	45.22	38.32	24.8	2.5	88
18:30 - 19:00	242	39.34	27.72	40.94	34.62	24.7	3.2	70
19:00 - 19:30	118.6	34.92	28.46	37.52	31.78	24	2	52
19:30 - 20:00	55.8	29	26.9	31.32	26.92	23.1	1.6	30
20:00 - 20:30	23.0	26.1	26.4	28.1	24.9	22.4	1.5	22
SUM	56546							3722

Table A.3. Measurement data for 16/07/2011.

Time	**Solar radiation [W/^{2}]**	**Air temperature inside SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [ml]**
9:00 - 9:30	216.2	22.02	17.34	20.26	22.2	20	0.8	20
9:30 - 10:00	348	29.4	19.18	27.72	29	21.6	0.8	42
10:00 - 10:30	398.4	36.86	21.88	35.7	34.64	23.4	0	82
10:30 - 11:00	315.8	40.82	24.74	41.64	38.18	21.2	1.8	92
11:00 - 11:30	705.8	44.66	22.08	41.76	41.14	24	1	178
11:30 - 12:00	603.4	53.06	25.42	51.52	48.56	24.4	1.8	174
12:00 - 12:30	815.4	57.58	24.94	55.66	52.38	24	1.8	254
12:30 - 13:00	882.4	63.56	27.76	64.54	58.14	25	1.5	348
13:00 - 13:30	900.4	64.72	28.62	51.4	58.34	25.2	1.2	310
13:30 - 14:00	933.2	64.2	28.72	58.62	57.88	25.3	2.5	324
14:00 - 14:30	916	67.2	29.58	67.3	60.08	27.5	1.5	360
14:30 - 15:00	956.2	69.24	30.12	70.02	61.4	25.3	2.2	348
15:00 - 15:30	973	70.36	30.62	70.56	62.12	25	3	400
15:30 - 16:00	745.2	67.24	31.08	67.88	59.7	26	1.5	304
16:00 - 16:30	845.8	66.88	31.3	67.44	58.14	26.2	2.5	290
16:30 - 17:00	765.2	64.22	31.26	65.78	55.96	26.2	2.6	286
17:00 - 17:30	605.4	59.1	31.04	61.64	52.3	26.2	2.4	206
17:30 - 18:00	432.6	53.06	30.68	56.3	47.04	26.2	2.6	160
18:00 - 18:30	377.8	47.24	30.28	50.12	41.94	26	2.2	110
18:30 - 19:00	131.6	38.98	29.34	38.12	35.88	24	2.2	62
19:00 - 19:30	107	31.84	28.72	33.24	29.96	24	2.5	40
19:30 - 20:00	56.2	28.2	27.34	30.82	26.96	22.8	2.5	30
20:00 - 20:30	6.7	24.8	26.0	27.6	23.9	21.4	1.4	24
SUM	65195							4444

Table A.4. Measurement data for 19/07/2011.

Time	**Solar radiation [W/m^2]**	**Air temperature inside SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [ml]**
9:00 - 9:30	126.8	19.86	17.04	18.88	19.12	19.1	0	0
9:30 - 10:00	268	24.34	17.72	20.4	23.78	19.3	0.7	12
10:00 - 10:30	435.8	33.18	20.48	27.56	32.92	21.1	0.7	38
10:30 - 11:00	315.6	40.08	22.84	36.9	39.34	22.8	0.5	78
11:00 - 11:30	664	49.36	24.28	44.4	46.2	22.2	0.5	134
11:30 - 12:00	739.8	58.62	26.16	53.5	53.54	23.9	0.5	200
12:00 - 12:30	705.2	62.64	27.88	60.28	58.04	24.3	0.5	216
12:30 - 13:00	795.4	66.2	30.98	60.92	60.48	25	0.7	302
13:00 - 13:30	826.6	67.94	32.28	67.76	61.72	25.7	0.4	296
13:30 - 14:00	728	67.06	31.72	57.22	61.86	26	0.6	274
14:00 - 14:30	663	63.28	31.62	64.12	58.54	25.8	0.5	240
14:30 - 15:00	625.2	62.06	31.78	64.34	57.22	25.8	0.4	246
15:00 - 15:30	937	68.06	32.32	69.48	60.82	26.5	2	292
15:30 - 16:00	734.8	68.14	33.08	70.28	62.06	26	0.5	292
16:00 - 16:30	821.4	69.44	33.66	70.92	62.54	27	1.5	276
16:30 - 17:00	781	69.02	34.08	70.3	61.42	28.2	1.6	330
17:00 - 17:30	662.8	65.92	34.32	68.28	58.92	27.5	1.6	196
17:30 - 18:00	480.4	59.04	34.18	62.7	52.68	27.5	1.6	198
18:00 - 18:30	428.8	51.2	31.9	55.28	45.2	26.3	1.6	144
18:30 - 19:00	324.6	46.06	33.16	52.08	42.4	27.2	2.2	90
19:00 - 19:30	195.6	40.48	32.98	46.66	37.38	25.5	1	66
19:30 - 20:00	81.8	36.18	33.02	40.88	32	25.1	1.8	50
20:00 - 20:30	17.5	29.7	31.4	34.1	27.8	22.7	2.0	30.0
SUM	61813							4000

Table A.5. Measurement data for 20/07/2011.

Time	**Solar radiation [W/m^2]**	**Air temperature inside SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [ml]**
9:00 - 9:30	199.2	22.6	19.52	21.12	22.44	19.5	1	18
9:30 - 10:00	319.8	30.92	22.42	27.24	30.78	21.2	0.4	32
10:00 - 10:30	412.6	38.38	27.22	32.34	38.2	22.2	1	70
10:30 - 11:00	296.4	46.02	29.54	42.98	45.22	23	0	122
11:00 - 11:30	633.8	53.68	30.5	50.32	50.24	23.4	1.2	182
11:30 - 12:00	753	60.74	31.58	56.58	55.56	24.1	1.5	264
12:00 - 12:30	860.6	65.18	30.64	57.56	60.06	25.2	1.5	324
12:30 - 13:00	897.2	69.16	31.76	66.32	63.02	25.5	0.8	350
13:00 - 13:30	963.8	72.76	32.84	72.06	65.54	26.8	1.2	384
13:30 - 14:00	1009.6	76.38	34.14	75.58	69.04	27.1	1.4	420
14:00 - 14:30	1027	79.46	35.34	78.52	71.98	27.5	0.4	386
14:30 - 15:00	997.2	79.88	36.6	79.56	73.32	28.6	0.9	404
15:00 - 15:30	834.8	77.24	37.22	76.92	70.5	29	0.5	390
15:30 - 16:00	911.6	77.8	37.6	77.34	70.98	28.8	0.6	354
16:00 - 16:30	872.2	77.08	38.64	76.5	70.48	29	1	364
16:30 - 17:00	726.8	72.78	38.42	73.2	66.78	30	0	276
17:00 - 17:30	509.2	62.66	37.98	55.76	57.88	29.5	0.5	158
17:30 - 18:00	464.4	56.28	36.2	53.58	52.2	29.5	0	140
18:00 - 18:30	500.4	56.52	34.78	59.58	51	30	0	140
18:30 - 19:00	128.6	49.44	37.22	55.08	46.78	28.8	1.8	102
19:00 - 19:30	74.8	41.56	35.4	46.52	39.88	29	0.7	60
19:30 - 20:00	32	37.8	34.4	41.8	37.2	20	5	-
20:00 - 20:30	-	Measure	ments	termi	nated	due to	hurricane	-
SUM	66840							4940

Table A.6. Mean values of measurement data for the timespan 13/07/2011 - 20/07/2011.

Time	**Solar radiation [W/m^2]**	**Air temperature inside SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [mL]**
9:00 - 9:30	161.28	22.308	18.468	21.776	22.552	20.12	0.6	15.2
9:30 - 10:00	294.48	28.12	19.672	26.836	28.312	21.04	0.68	29.2
10:00 - 10:30	368.12	35.172	22.584	33.476	34.54	22.54	0.66	60.8
10:30 - 11:00	365.2	41.864	24.548	41.88	41.332	22.36	0.96	110.4
11:00 - 11:30	621.72	49.772	26.112	48.66	47.828	23.62	0.78	164.8
11:30 - 12:00	703.52	57.404	28.124	55.9	53.652	24.48	1.22	212
12:00 - 12:30	818.88	63.468	28.54	60.708	58.48	24.84	1.22	293.2
12:30 - 13:00	799.36	66.724	30.536	64.748	61.436	25.4	1.04	312.8
13:00 - 13:30	863.28	66.608	31.428	63.476	60.66	26.04	1.04	322.4
13:30 - 14:00	795.92	65.476	31.632	62.36	59.948	26.48	1.2	286.8
14:00 - 14:30	731.4	64.78	32.004	64.336	59.5	27.06	0.74	269.2
14:30 - 15:00	749.36	64.652	32.296	65.6	59.268	26.48	1.2	283.2
15:00 - 15:30	859.88	68.016	32.644	68.4	61.648	27.08	1.4	313.2
15:30 - 16:00	848.6	69.236	33.224	69.824	63.252	27.12	1.08	327.2
16:00 - 16:30	820.92	67.652	33.624	65.908	61.924	27.86	1.64	291.2
16:30 - 17:00	688.48	64.452	33.624	65.988	59.444	28.08	1.6	265.6
17:00 - 17:30	549.96	58.912	33.304	59.62	54.384	27.44	1.4	182.4
17:30 - 18:00	453.56	53.548	32.476	55.928	49.348	27.34	1.64	164
18:00 - 18:30	394.04	49.052	31.212	52.288	44.684	27.06	1.62	122.4
18:30 - 19:00	211.52	43.152	31.632	46.292	40.236	26.18	2.28	86
19:00 - 19:30	138.48	37.096	31.1	40.812	35.072	25.82	1.54	58.8
19:30 - 20:00	60.56	32.976	30.404	36.176	31.268	23.32	2.42	32.4
20:00 - 20:30	17.21	27.45	28.096	30.175	26.308	22.58	1.66	28.5

Table A.7. Values of cumulative distillate output for the SDU with basic design.

Time	**13/07/11**	**15/07/11**	**16/07/11**	**19/07/11**	**20/07/11**
9:00 - 9:30	26	12	20	0	0
9:30 - 10:00	62	36	62	12	18
10:00 - 10:30	128	84	144	50	50
10:30 - 11:00	288	184	236	128	120
11:00 - 11:30	420	382	414	262	242
11:30 - 12:00	624	600	588	462	424
12:00 - 12:30	930	966	842	678	688
12:30 - 13:00	1180	1280	1190	980	1012
13:00 - 13:30	1520	1562	1500	1276	1362
13:30 - 14:00	1716	1782	1824	1550	1746
14:00 - 14:30	1880	1978	2184	1790	2166
14:30 - 15:00	2034	2242	2532	2036	2552
15:00 - 15:30	2308	2452	2932	2328	2956
15:30 - 16:00	2624	2822	3236	2620	3346
16:00 - 16:30	2924	3048	3526	2896	3700
16:30 - 17:00	3210	3198	3812	3226	4064
17:00 - 17:30	3420	3340	4018	3422	4340
17:30 - 18:00	3622	3460	4178	3620	4498
18:00 - 18:30	3752	3548	4288	3764	4638
18:30 - 19:00	3858	3618	4350	3854	4778
19:00 - 19:30	3934	3670	4390	3920	4880
19:30 - 20:00	3986	3700	4420	3970	4940
20:00 - 20:30	4024	3722	4444	4000	-

A.2. Data for the passive SDU prototype with reflective side- and rear walls

Table A.8. Measurement data for 24/07/2011.

Time	**Solar radiation [W/m^2]**	**Temperature aluminum foil in SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [ml]**
9:00 - 9:30	263.8	24.68	19.18	20.02	24.36	20.4	0	0
9:30 - 10:00	190.4	28.38	21.08	24.84	27.64	20.2	0	0
10:00 - 10:30	302	26.78	20.88	22.76	30.18	20.7	0	42
10:30 - 11:00	548.6	34.12	22.04	26.38	42.34	22.6	0	72
11:00 - 11:30	637.8	42.08	24.24	39.16	48.76	23	1.1	130
11:30 - 12:00	708	48.8	25.9	49.52	53	24	0.8	222
12:00 - 12:30	741.2	54.4	27.22	56.72	57.34	24.4	0.9	294
12:30 - 13:00	834	58.22	28.74	62.06	59.94	25.4	0.9	298
13:00 - 13:30	491.8	56.2	30.36	61	57.8	25.6	0.8	202
13:30 - 14:00	740.4	58.86	30.88	64.44	59.6	27.6	1.5	316
14:00 - 14:30	879	61.3	32.08	67.48	61.66	27.1	0.7	340
14:30 - 15:00	646	58.28	32.62	64.68	58.72	26.5	1.7	340
15:00 - 15:30	909.2	61.4	32.78	68.82	60.08	26.5	1	348
15:30 - 16:00	860	63.26	33.2	70.02	60.92	26.6	1	362
16:00 - 16:30	722.8	63.5	34.22	69.46	60.54	27.2	0.5	336
16:30 - 17:00	658.6	61.98	34.34	67.42	56.68	27.3	2.1	266
17:00 - 17:30	410.8	54.26	34.06	59.96	49.24	27.5	1	190
17:30 - 18:00	552.8	53.46	33.1	53.74	46.32	27.3	0.8	198
18:00 - 18:30	395.6	48.88	32.66	50.38	42.78	27.7	1.6	140
18:30 - 19:00	289.4	41.92	29.86	45.88	36.16	26.4	1.6	94
19:00 - 19:30	164.8	37.52	30.36	40.62	35.34	26	0.5	60
19:30 - 20:00	69.8	33.98	31.98	37.6	34.18	24.8	1.6	50
20:00 - 20:30	10.6	29.3	31.2	33.4	30.0	24.2	1.4	32
SUM	59961							4332

Table A.9. Measurement data for 25/07/2011.

Time	**Solar radiation [W/m^2]**	**Temperature aluminum foil in SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [ml]**
9:00 - 9:30	155	21.54	17.14	19.76	19.94	19	0	0
9:30 - 10:00	237.4	23.02	17	22.46	22.62	19	0	0
10:00 - 10:30	402.6	28.74	18.5	26.5	29.88	19.7	0	38
10:30 - 11:00	420.8	32.56	19.94	31.64	34.12	20.8	0	38
11:00 - 11:30	564.4	38.6	21.28	37.6	42.24	21.4	0	68
11:30 - 12:00	731.8	47.34	23.48	39.28	50.96	22.1	0	120
12:00 - 12:30	803.8	52.14	25.68	47.86	55	23.1	0	206
12:30 - 13:00	865.4	58.2	27	64.4	59.74	23.5	0	260
13:00 - 13:30	915	62.58	28.6	63.16	63.96	23.6	0	422
13:30 - 14:00	934.6	64.3	29.98	65.5	65.06	26	1.5	300
14:00 - 14:30	954.8	67.58	31.6	75.6	67.78	26.3	0.5	382
14:30 - 15:00	917.2	69.02	32.46	77	68.52	26.8	0	420
15:00 - 15:30	843.4	66.66	33.48	72.18	65.74	26.4	0	428
15:30 - 16:00	884.2	66.72	34.96	71.06	65.5	27.1	0	376
16:00 - 16:30	664	63.22	35.42	72.04	59.94	27.2	0.5	376
16:30 - 17:00	736	63.42	35.56	72.28	58.8	27.8	0.7	352
17:00 - 17:30	638	61.86	35.84	69.36	55.82	28	0.5	260
17:30 - 18:00	529.2	57.44	35.26	65.52	51.22	26.8	0.5	244
18:00 - 18:30	412.2	51.84	34.96	60.86	45.7	27.1	0.5	210
18:30 - 19:00	285	43.38	31.94	51.5	38.62	27.6	1	132
19:00 - 19:30	163.4	37.68	32.08	40.46	36.7	26.3	2.5	110
19:30 - 20:00	64.4	33.52	32.88	39.26	34.18	25.5	0.7	90
20:00 - 20:30	13.0	30.3	31.6	35.6	31.6	24.7	1.1	39.0
SUM	65592							4910

Table A.10. Measurement data for 27/07/2011.

Time	**Solar radiation [W/m^2]**	**Temperature aluminum foil in SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [ml]**
9:00 - 9:30	185	29.42	19.92	20.92	26.4	21	0.8	18
9:30 - 10:00	304.6	35.6	23.08	28.82	35.54	22.7	0	46
10:00 - 10:30	431.6	40.66	24.86	36.46	42.76	23.6	0.5	94
10:30 - 11:00	544.8	46.5	26.24	44.54	51.1	23.8	0	154
11:00 - 11:30	647.2	51.84	27.56	52.74	56.8	24.4	0	246
11:30 - 12:00	742.2	57.38	30.38	60.12	62.18	25.4	0	370
12:00 - 12:30	811.2	61.48	32.04	66.04	65.62	25.6	1	360
12:30 - 13:00	884.2	65.7	32.66	72.28	68.88	28	0	380
13:00 - 13:30	924.4	67.12	33.8	75.74	70.64	27.7	0.5	350
13:30 - 14:00	967.8	63.82	34.64	53.08	67.68	27	0	290
14:00 - 14:30	975.6	61.76	35.08	50.34	65.58	27.6	0	330
14:30 - 15:00	951.4	64.22	35.32	70.1	67.3	29.2	0	430
15:00 - 15:30	926.8	66.68	36.04	77.8	69.06	30	0	350
15:30 - 16:00	904.8	67.36	36.9	78.32	68.7	30.2	1.2	434
16:00 - 16:30	862.8	66.78	37.12	77.56	67.22	29	1.4	342
16:30 - 17:00	785.6	65.72	37.82	76.1	65.18	28.7	0.9	378
17:00 - 17:30	680.6	63.36	38.28	73.86	62.1	29.5	2	312
17:30 - 18:00	572.6	60.28	38.62	70.76	57.82	29.5	0.8	230
18:00 - 18:30	462	56.02	38.42	65.88	52.98	29	1	170
18:30 - 19:00	321.4	48.42	36.16	56.92	44.34	28.5	2.5	130
19:00 - 19:30	176.8	40.88	36.14	49.68	41.22	28	1.8	80
19:30 - 20:00	82.2	35.6	35.42	42.9	36.64	27	2.2	56
20:00 - 20:30	11.2	29.3	32.6	35.7	29.8	26.1	1.5	38.0
SUM	70666							5588

Table A.11. Measurement data for 28/07/2011.

Time	**Solar radiation [W/m^2]**	**Temperature aluminum foil in SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [ml]**
9:00 - 9:30	129.6	24.32	19.56	22.86	21.84	21.6	1	0
9:30 - 10:00	257.2	25.46	19.72	23.32	25.66	22.6	0	24
10:00 - 10:30	286	28	20.5	25.2	28.48	23	0	22
10:30 - 11:00	451.8	31.5	21.74	30.46	34.52	23	0	48
11:00 - 11:30	580	39.4	23.6	38.78	43.82	23.7	0	106
11:30 - 12:00	671.6	45.34	25.38	48.64	50.22	23.7	0.5	178
12:00 - 12:30	787.4	51.82	27.22	57.54	57.1	25	0.5	274
12:30 - 13:00	854.2	57.76	29.26	65.38	62.14	26.2	0.5	384
13:00 - 13:30	910	61.38	30.48	71.04	65.88	26.4	0	316
13:30 - 14:00	934.2	64.22	32.12	74.5	68.26	26.8	0.5	460
14:00 - 14:30	900.6	65.28	33.12	67.88	68.62	27	1.8	382
14:30 - 15:00	972.2	65.18	33.6	57	68.26	28.1	0	332
15:00 - 15:30	771.2	62.82	34.26	67.94	65.62	29.3	0.8	328
15:30 - 16:00	620.8	61.98	35.08	72.06	64.36	29.5	1.5	290
16:00 - 16:30	427.2	55.1	35.18	65.44	57.3	29.5	0.8	280
16:30 - 17:00	413.6	49.36	34.34	59.9	51.28	28.1	0	162
17:00 - 17:30	644.6	50.6	33.86	62.32	50.2	27.6	2.6	202
17:30 - 18:00	473.2	50.8	34.18	61.68	49.86	29	1.8	194
18:00 - 18:30	192	43.9	33.6	53.92	43.84	27.1	2	146
18:30 - 19:00	75.6	36.54	32.1	45.16	37.52	26.6	1.3	60
19:00 - 19:30	80	32.06	30.42	39.64	33.24	25.4	1.8	52
19:30 - 20:00	84.2	29.42	28.94	36.32	30.04	26.2	0	46
20:00 - 20:30	14.0	26.7	28.2	33.0	27.3	24.2	1.7	34.0
SUM	57569							4320

Table A.12. Measurement data for 29/07/2011.

Time	**Solar radiation [W/m^2]**	**Temperature aluminum foil in SDU [°C]**	**Water temperature, inlet [°C]**	**Water temperature, basin [°C]**	**Cover temperature [°C]**	**Ambient temperature [°C]**	**Wind speed [m/s]**	**Distillate output [ml]**
9:00 - 9:30	159.8	22.44	18.84	22.8	21.88	21.1	0	0
9:30 - 10:00	346.2	25.36	18.96	25.36	26.44	21.6	0	22
10:00 - 10:30	272.6	31.08	21.14	30.42	31.24	22.8	0.5	64
10:30 - 11:00	522.2	35.06	21.92	35.84	38.48	22.8	1.2	124
11:00 - 11:30	600.4	41.18	23.72	44.1	45.64	24.4	0	114
11:30 - 12:00	636	45.9	25.24	50.02	50.84	25.9	0	180
12:00 - 12:30	641.2	50.22	26.94	41.52	54.96	25.4	0.6	202
12:30 - 13:00	949.2	53.2	28.48	47	58.46	25.1	1	342
13:00 - 13:30	869	58.44	30.12	56.94	63.3	26.1	1.1	292
13:30 - 14:00	892.8	60.38	31.28	69.22	64.88	26.8	1	324
14:00 - 14:30	764.2	60.06	32.36	69.94	63.6	27.4	2	342
14:30 - 15:00	679	58.62	32.84	68.94	61.74	27.7	0.6	336
15:00 - 15:30	808.6	57.34	33.1	69.14	59.84	27.8	1	336
15:30 - 16:00	752	57.08	33.34	68.98	58.72	27.7	1.6	292
16:00 - 16:30	665	57.12	33.94	68.74	57.72	27.7	1.6	314
16:30 - 17:00	524.4	52.9	33.74	64.42	52.08	27.1	1.6	216
17:00 - 17:30	518.2	49.98	33.16	61.98	48.36	27.1	1.6	224
17:30 - 18:00	505	48.42	32.68	59.98	45.8	26.5	1.8	176
18:00 - 18:30	459.2	47.72	32.7	58.42	43.88	26.5	1.8	140
18:30 - 19:00	304.2	41.74	30.42	51.26	37.74	26.2	2.4	106
19:00 - 19:30	170	36.94	31.3	46.06	36.72	25.4	3	78
19:30 - 20:00	96.4	31.72	30.06	39.48	31.94	25	1.2	56
20:00 - 20:30	13.2	27.9	29.2	34.5	28.4	23.5	2.1	40.0
SUM	60641							4320

Table A.13. Mean values of measurement data for the timespan 24/07/2011 - 29/07/2011.

Zeit	**Solar radiation [W/m^2]**	**Temperature aluminum foil in SDU [°C]**	**Water temp, inlet [°C]**	**Water temp, basin [°C]**	**Glass cover temp [°C]**	**Ambient temp [°C]**	**Wind speed [m/s]**	**Distillate output [mL]**
9:00 - 9:30	178.64	24.48	18.928	21.272	22.884	20.62	0.36	3.6
9:30 - 10:00	267.16	27.564	19.968	24.96	27.58	21.22	0	26
10:00 - 10:30	338.96	31.052	21.176	28.268	32.508	21.96	0.2	52
10:30 - 11:00	497.64	35.948	22.376	33.772	40.112	22.6	0.24	93.2
11:00 - 11:30	605.96	42.62	24.08	42.476	47.452	23.38	0.22	143.2
11:30 - 12:00	697.92	48.952	26.076	49.516	53.44	24.22	0.26	231.2
12:00 - 12:30	756.96	54.012	27.82	53.936	58.004	24.7	0.6	278
12:30 - 13:00	877.4	58.616	29.228	62.224	61.832	25.64	0.48	365.2
13:00 - 13:30	822.04	61.144	30.672	65.576	64.316	25.88	0.48	292
13:30 - 14:00	893.96	62.316	31.78	65.348	65.096	26.84	0.9	354.4
14:00 - 14:30	894.84	63.196	32.848	66.248	65.448	27.08	1	362.8
14:30 - 15:00	833.16	63.064	33.368	67.544	64.908	27.66	0.46	373.2
15:00 - 15:30	851.84	62.98	33.932	71.176	64.068	28	0.56	347.6
15:30 - 16:00	804.36	63.28	34.696	72.088	63.64	28.22	1.06	350.8
16:00 - 16:30	668.36	61.144	35.176	70.648	60.544	28.12	0.96	324.8
16:30 - 17:00	623.64	58.676	35.16	68.024	56.804	27.8	1.06	256.4
17:00 - 17:30	578.44	56.012	35.04	65.496	53.144	27.94	1.54	234.4
17:30 - 18:00	526.56	54.08	34.768	62.336	50.204	27.82	1.14	201.6
18:00 - 18:30	384.2	49.672	34.468	57.892	45.836	27.48	1.38	145.6
18:30 - 19:00	255.12	42.4	32.096	50.144	38.876	27.06	1.76	100
19:00 - 19:30	151	37.016	32.06	43.292	36.644	26.22	1.92	72
19:30 - 20:00	79.4	32.848	31.856	39.112	33.396	25.7	1.14	50.8
20:00 - 20:30	12.4	28.7	30.563	34.423	29.43	24.49	1.54	35.2

Table A.14. Values of cumulative distillate output for the SDU with reflective side- and rear walls.

Time	**24/07/11**	**25/07/11**	**27/07/11**	**28/07/11**	**29/07/11**
9:00 - 9:30	0	0	18	0	0
9:30 - 10:00	0	38	64	24	22
10:00 - 10:30	42	76	158	46	86
10:30 - 11:00	114	144	312	94	210
11:00 - 11:30	244	264	558	200	324
11:30 - 12:00	466	470	928	378	504
12:00 - 12:30	760	730	1288	652	706
12:30 - 13:00	1058	1152	1668	1036	1048
13:00 - 13:30	1260	1452	2018	1352	1340
13:30 - 14:00	1576	1834	2308	1812	1664
14:00 - 14:30	1916	2254	2638	2194	2006
14:30 - 15:00	2256	2682	3068	2526	2342
15:00 - 15:30	2604	3058	3418	2854	2678
15:30 - 16:00	2966	3434	3852	3144	2970
16:00 - 16:30	3302	3786	4194	3424	3284
16:30 - 17:00	3568	4046	4572	3586	3500
17:00 - 17:30	3758	4290	4884	3788	3724
17:30 - 18:00	3956	4500	5114	3982	3900
18:00 - 18:30	4096	4632	5284	4128	4040
18:30 - 19:00	4190	4742	5414	4188	4146
19:00 - 19:30	4250	4832	5494	4240	4224
19:30 - 20:00	4300	4878	5550	4286	4280
20:00 - 20:30	4332	4910	5588	4320	4320

B. Additional illustrations

B.1. Graphs for the passive SDU prototype (basic design)

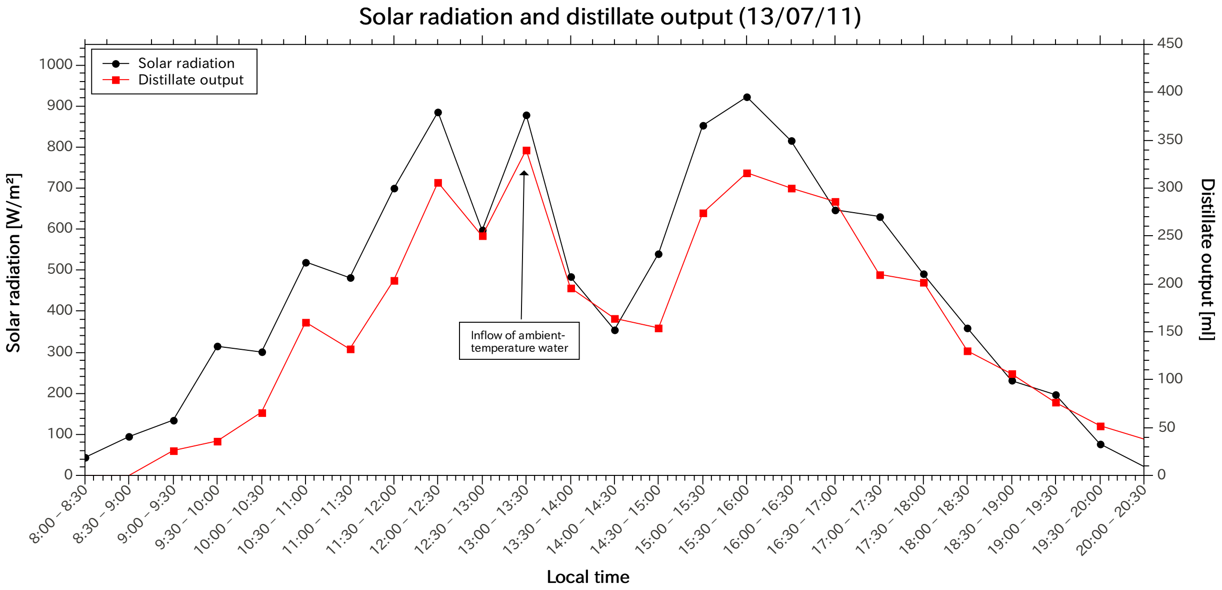


Figure B.1. Insolation and distillate curves for 13/07/2011.

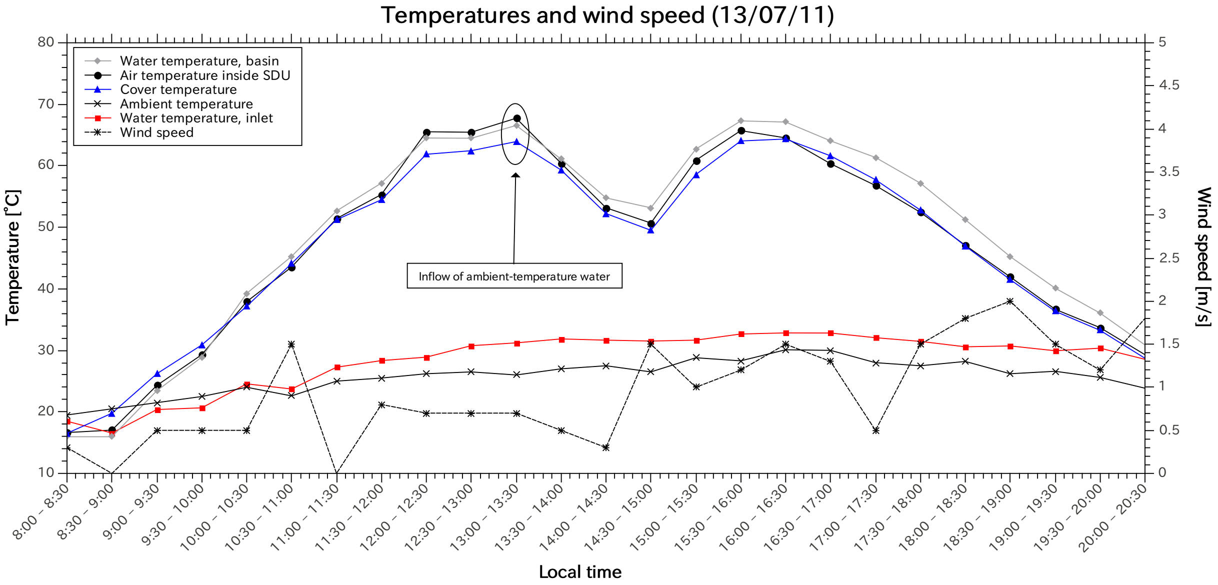


Figure B.2. Temperature and wind speed curves for 13/07/2011.

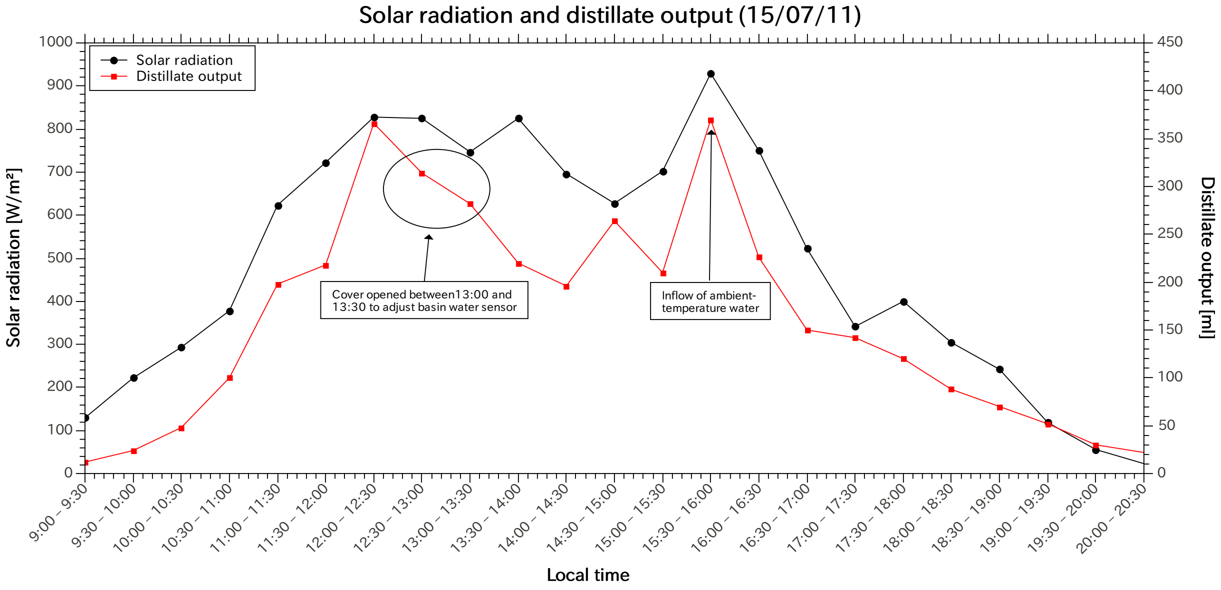


Figure B.3. Insolation and distillate curves for 15/07/2011.

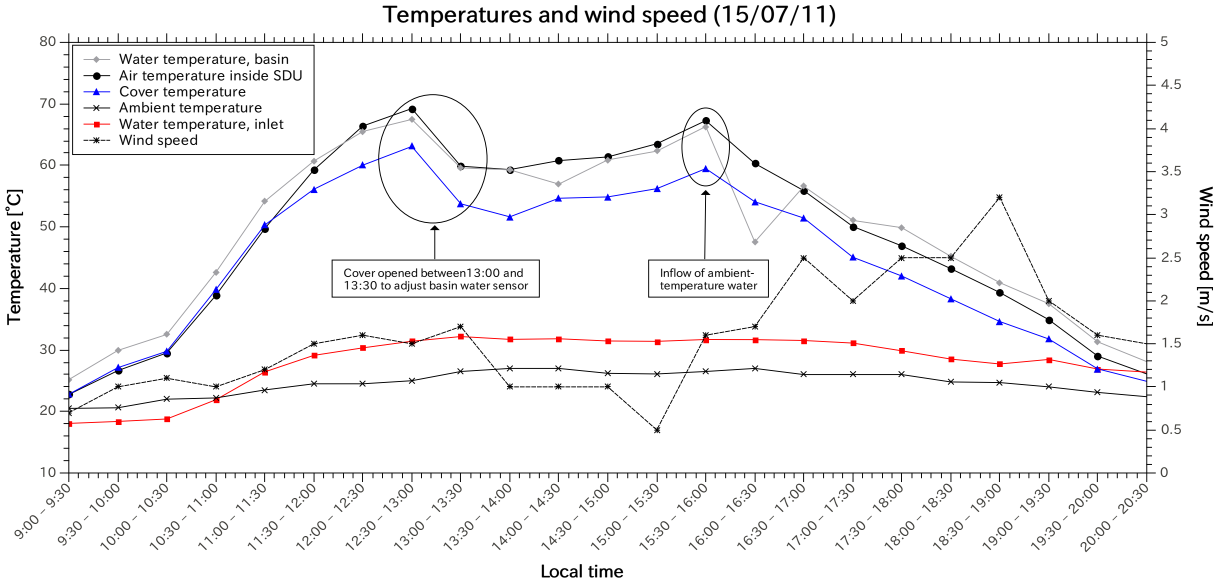


Figure B.4. Temperature and wind speed curves for 15/07/2011.

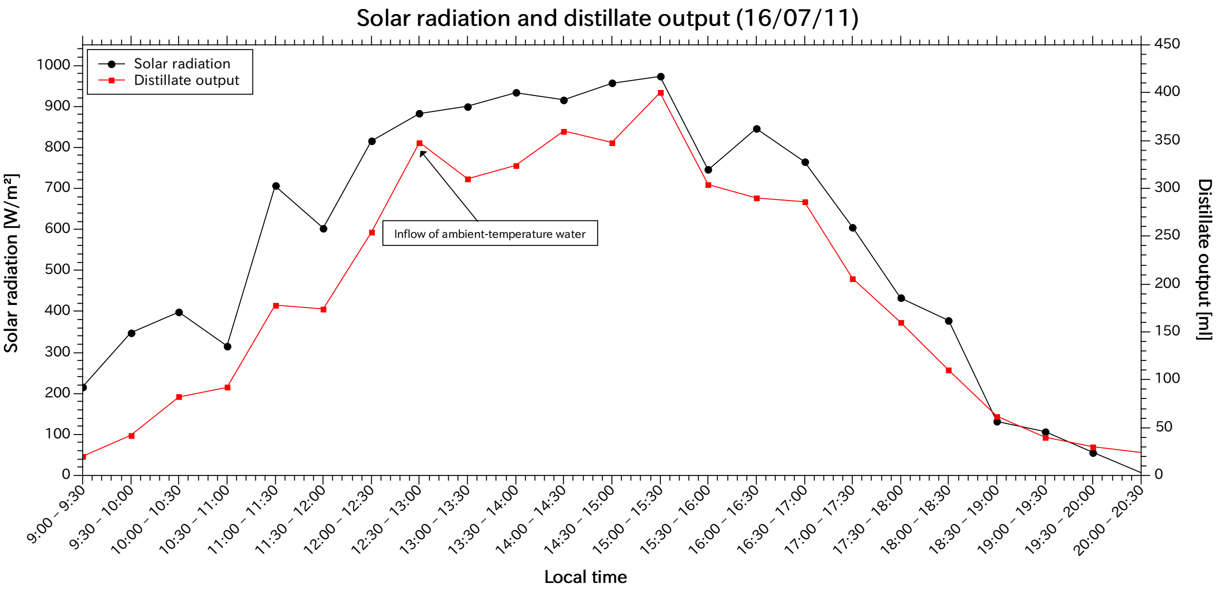


Figure B.5. Insolation and distillate curves for 16/07/2011.

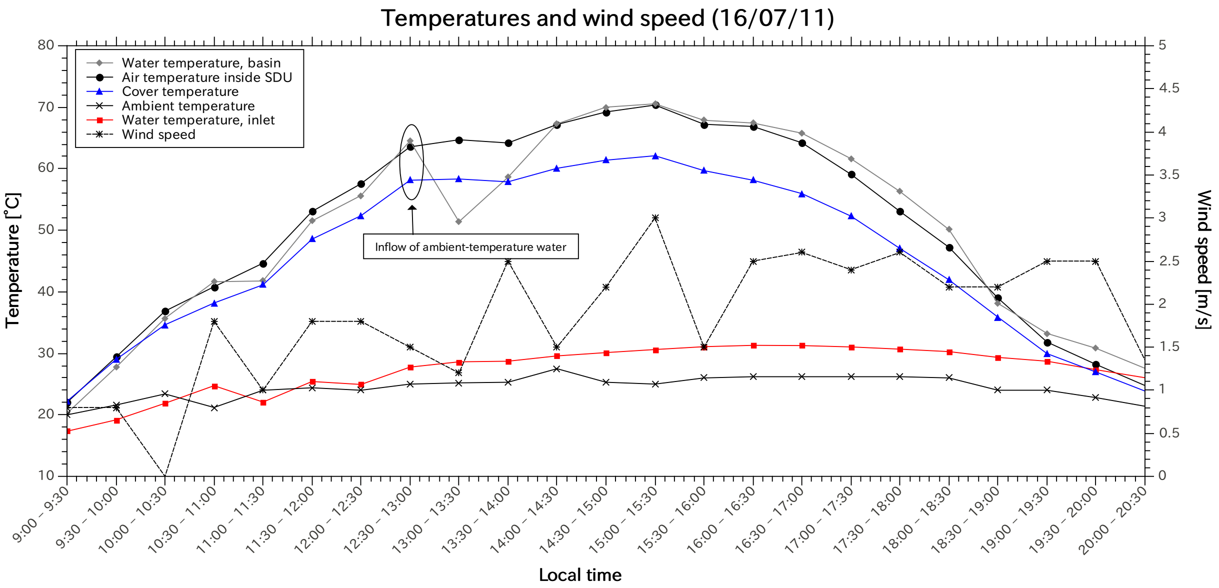


Figure B.6. Temperature and wind speed curves for 16/07/2011.

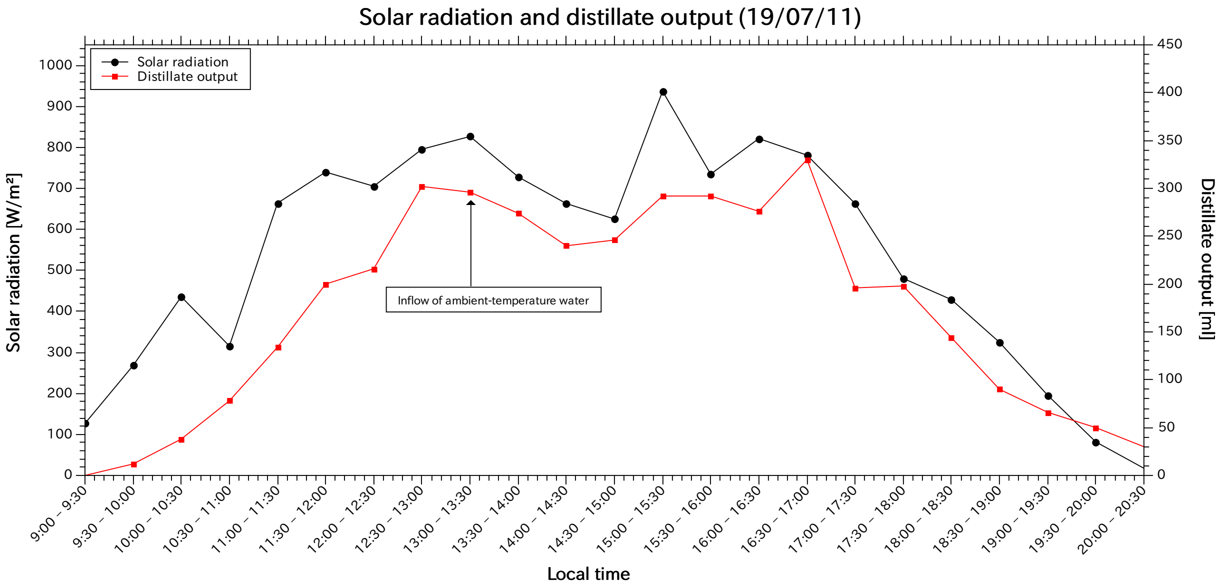


Figure B.7. Insolation and distillate curves for 19/07/2011.

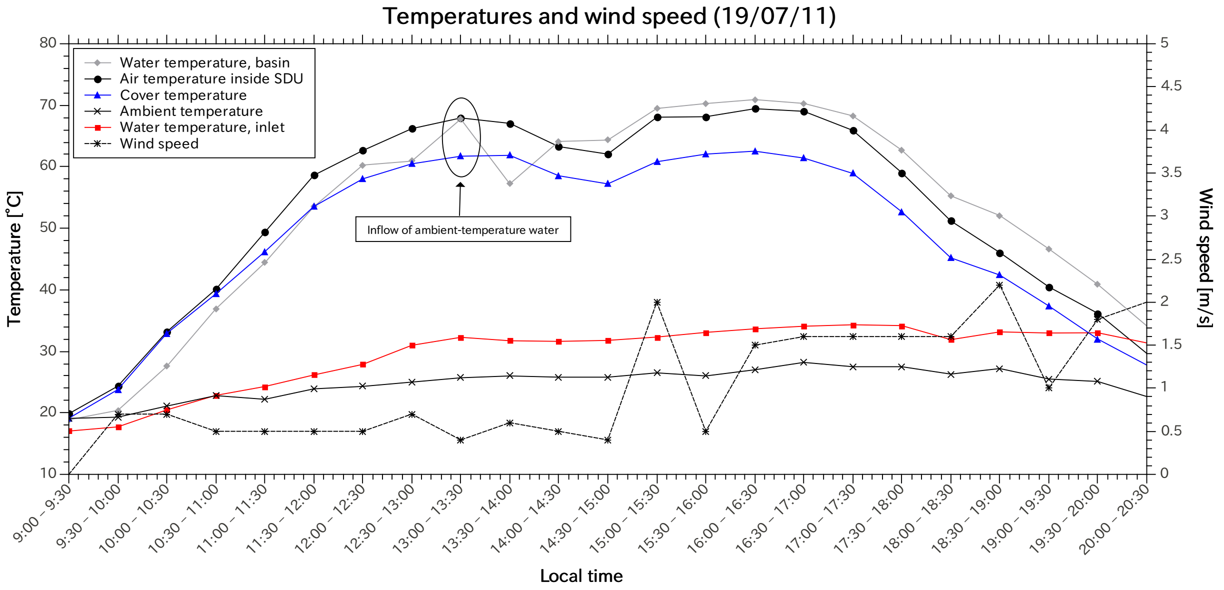


Figure B.8. Temperature and wind speed curves for 19/07/2011.

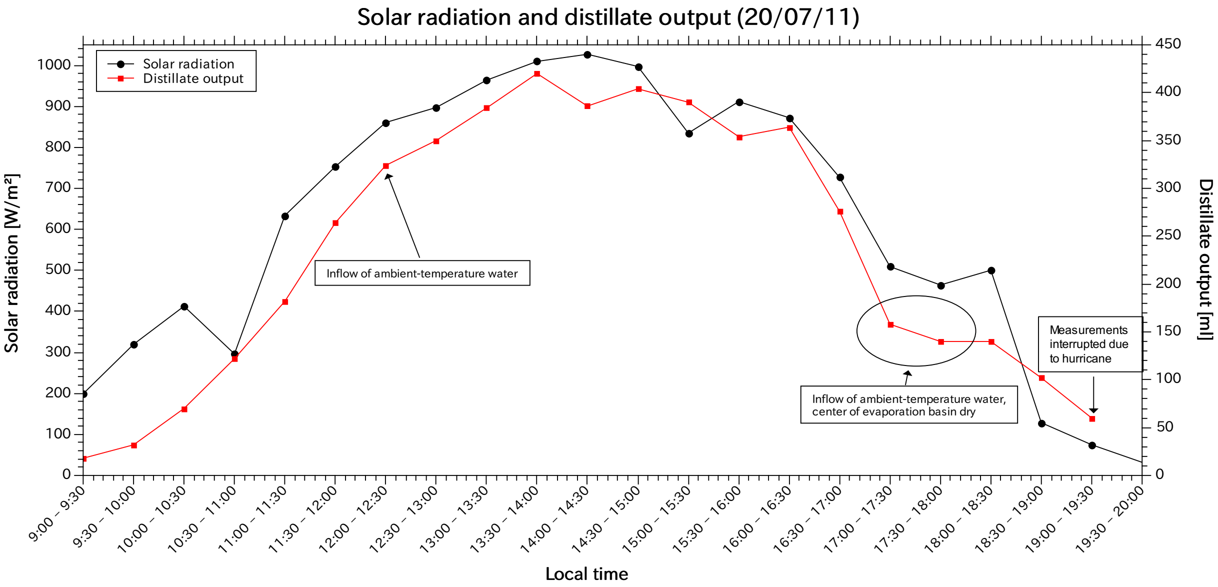


Figure B.9. Insolation and distillate curves for 20/07/2011.

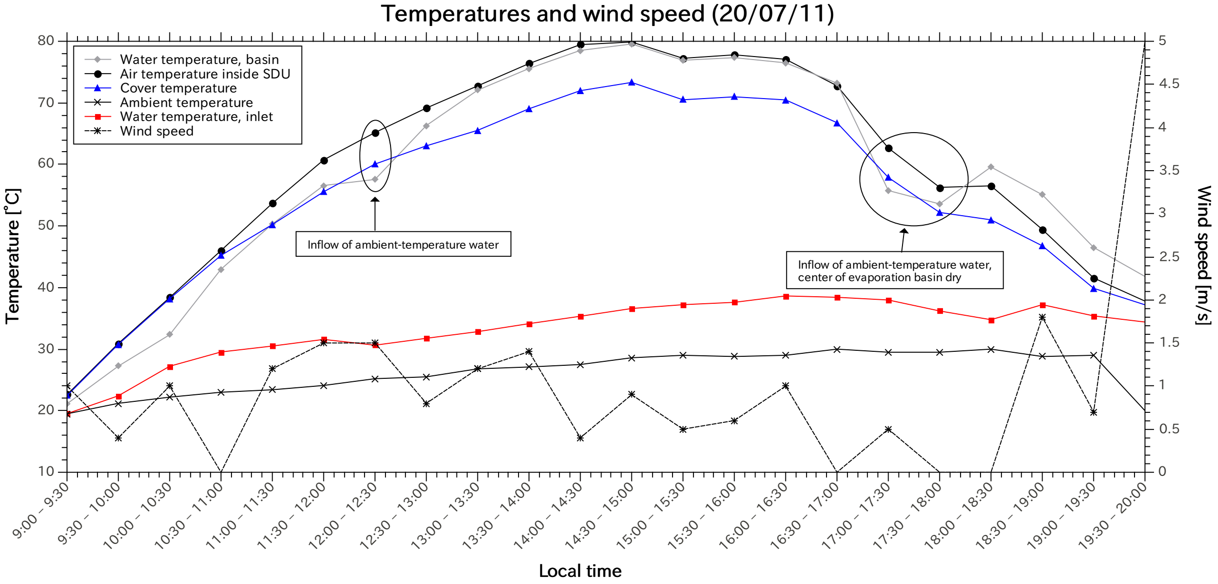


Figure B.10. Temperature and wind speed curves for 20/07/2011.

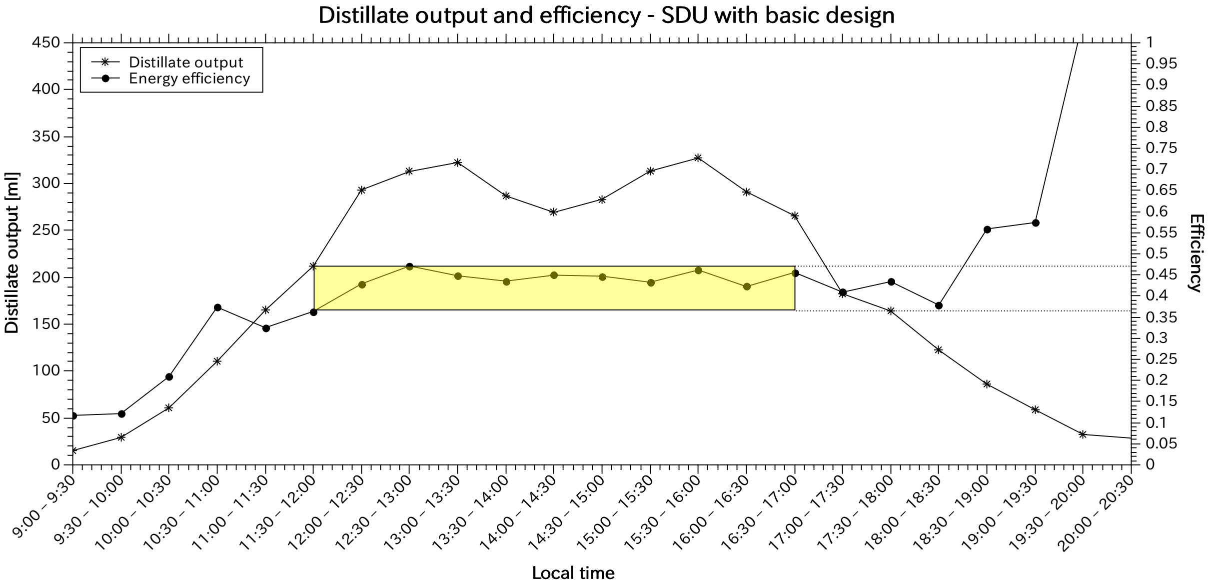


Figure B.11. Distillate output and energy efficiency for the SDU with basic design.

B.2. Graphs for the passive SDU prototype with reflective side- and rear walls

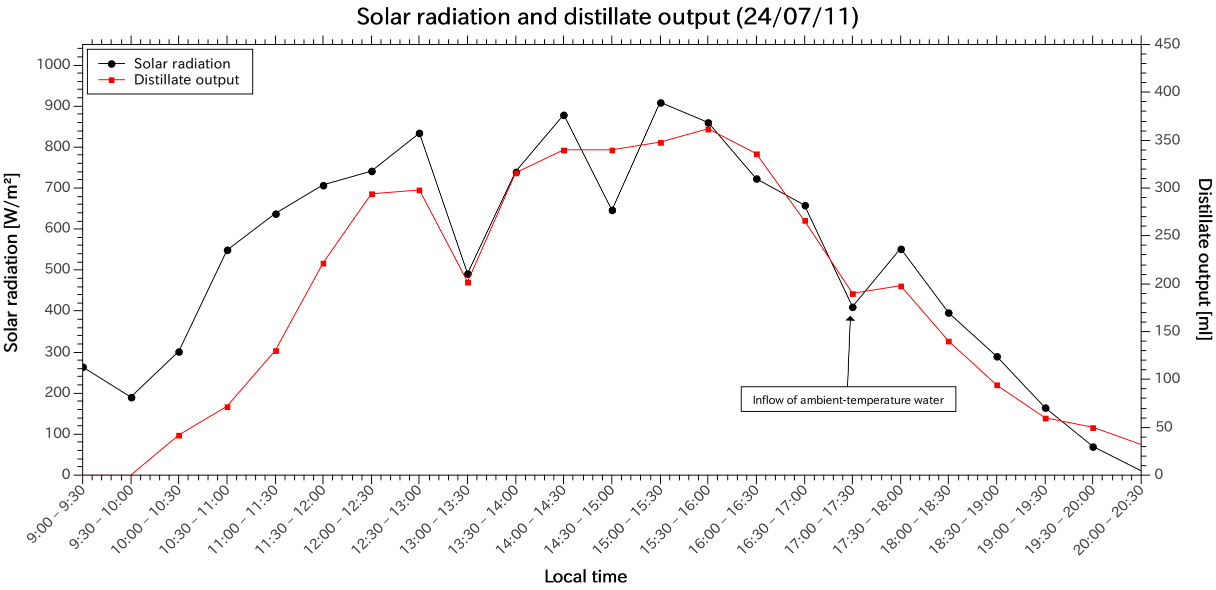


Figure B.12. Insolation and distillate curves for 24/07/2011.

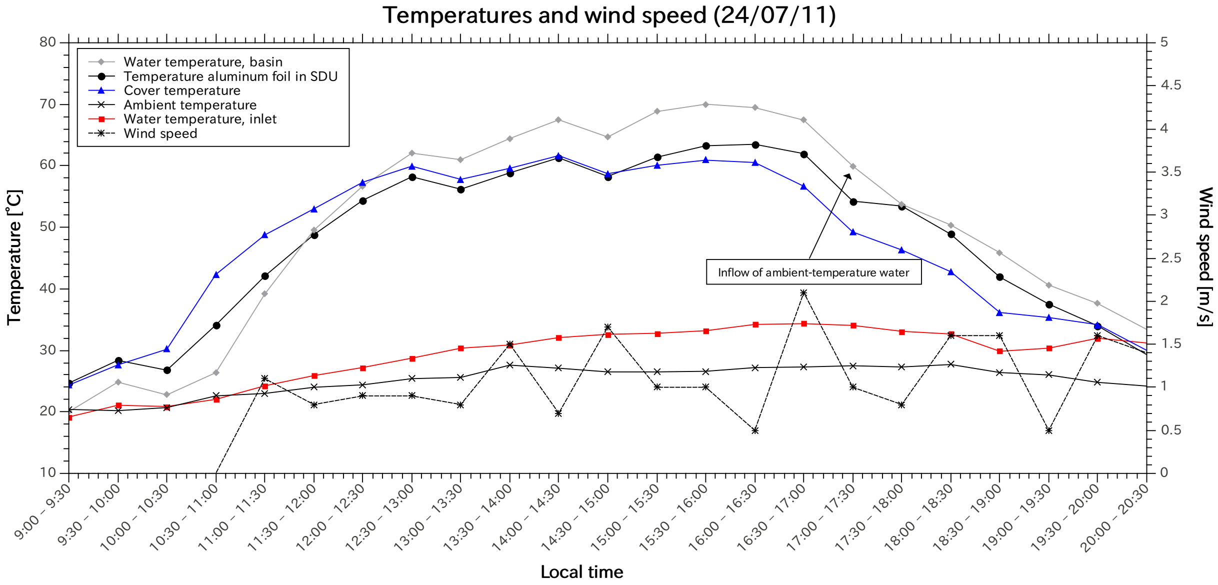
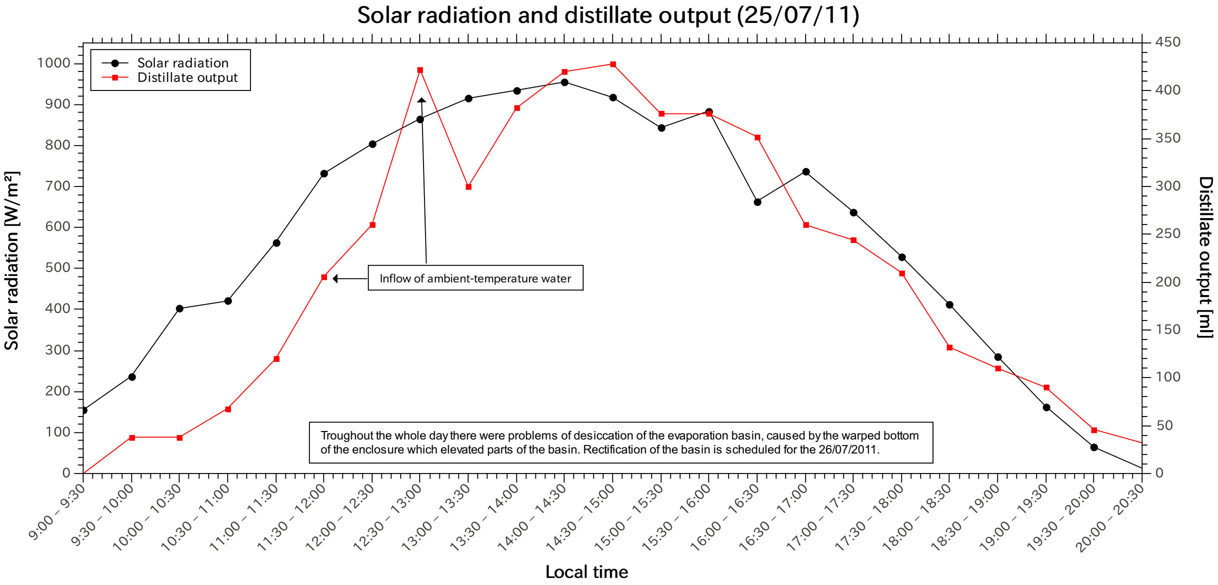


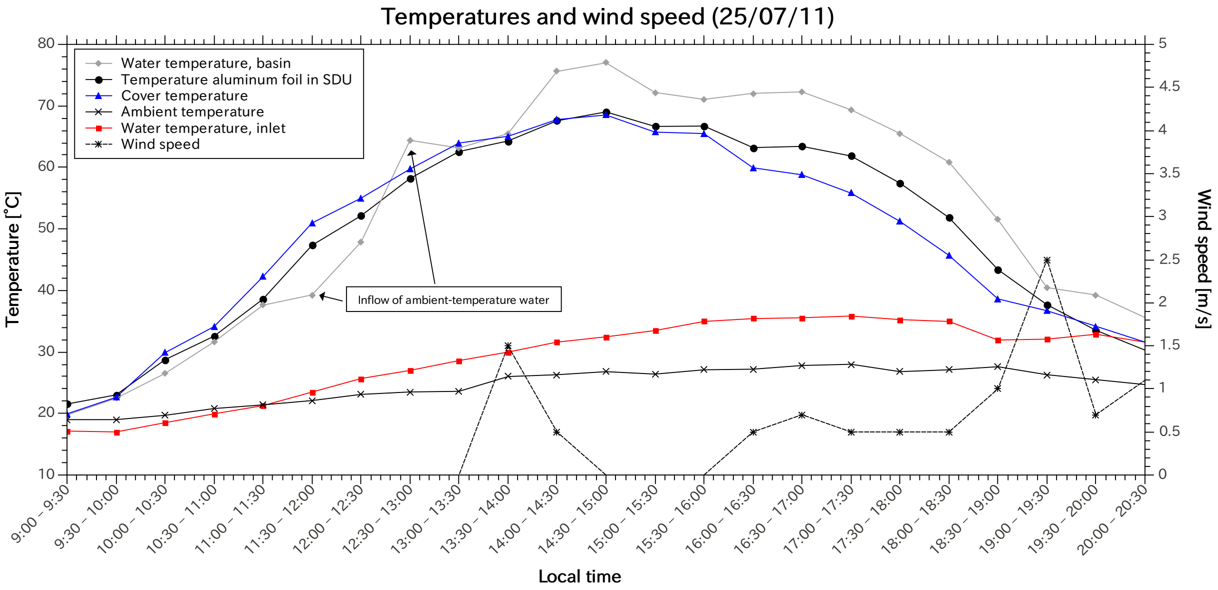
Figure B.13. Temperature and wind speed curves for 24/07/2011.


Solar radiation and distillate output (25/07/11)

Inflow of ambient-temperature water

Troughout the whole day there were problems of desiccation of the evaporation basin, caused by the warped bottom of the enclosure which elevated parts of the basin. Rectification of the basin is scheduled for the 26/07/2011.

Figure B.14. Insolation and distillate curves for 25/07/2011.


Temperatures and wind speed (25/07/11)

Inflow of ambient-temperature water

Figure B.15. Temperature and wind speed curves for 25/07/2011.

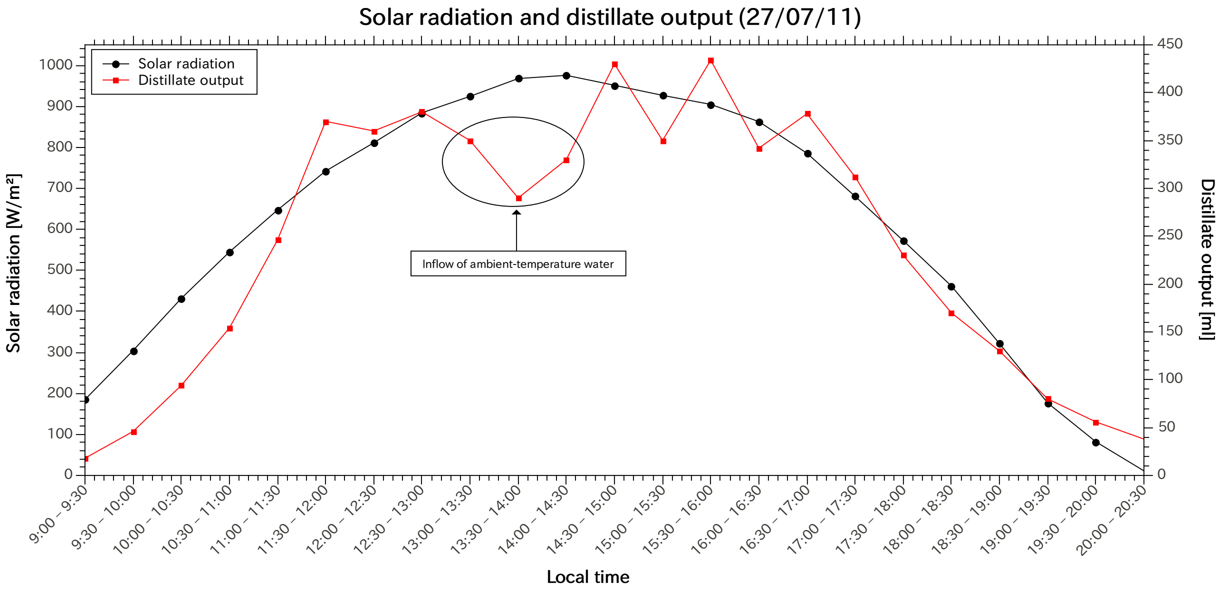


Figure B.16. Insolation and distillate curves for 27/07/2011.

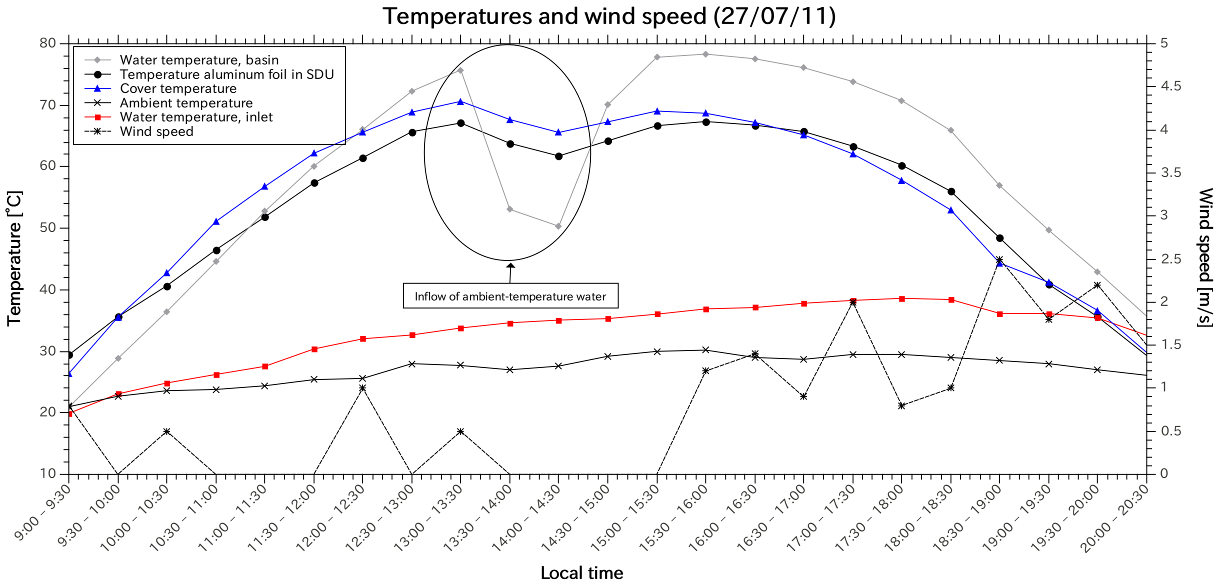


Figure B.17. Temperature and wind speed curves for 27/07/2011.

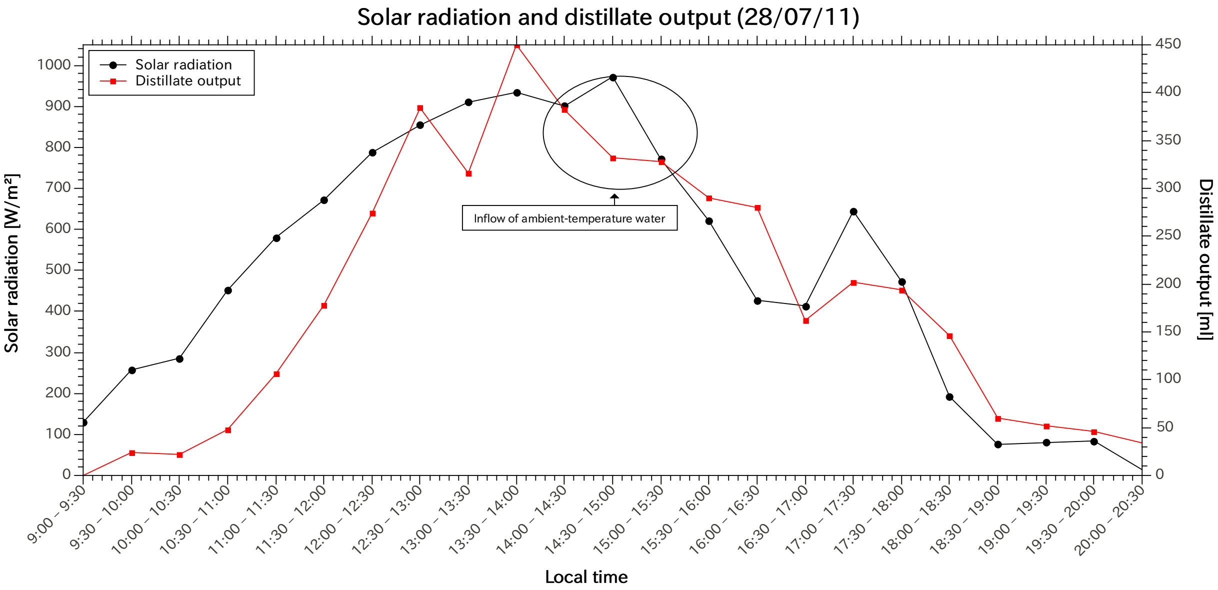


Figure B.18. Insolation and distillate curves for 28/07/2011.

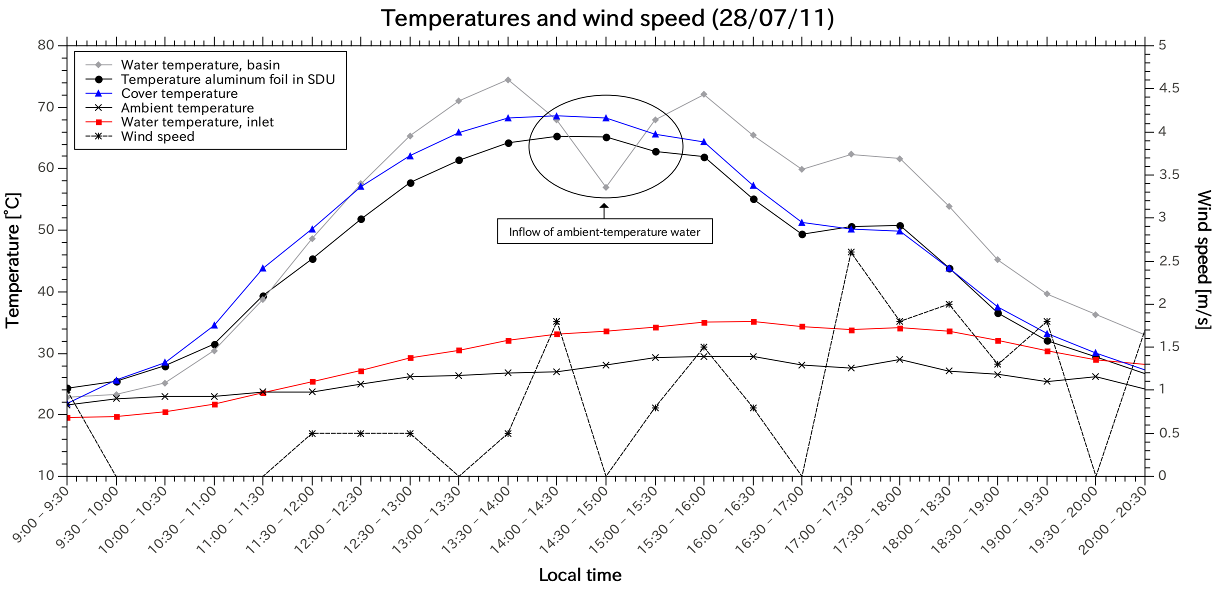


Figure B.19. Temperature and wind speed curves for 28/07/2011.

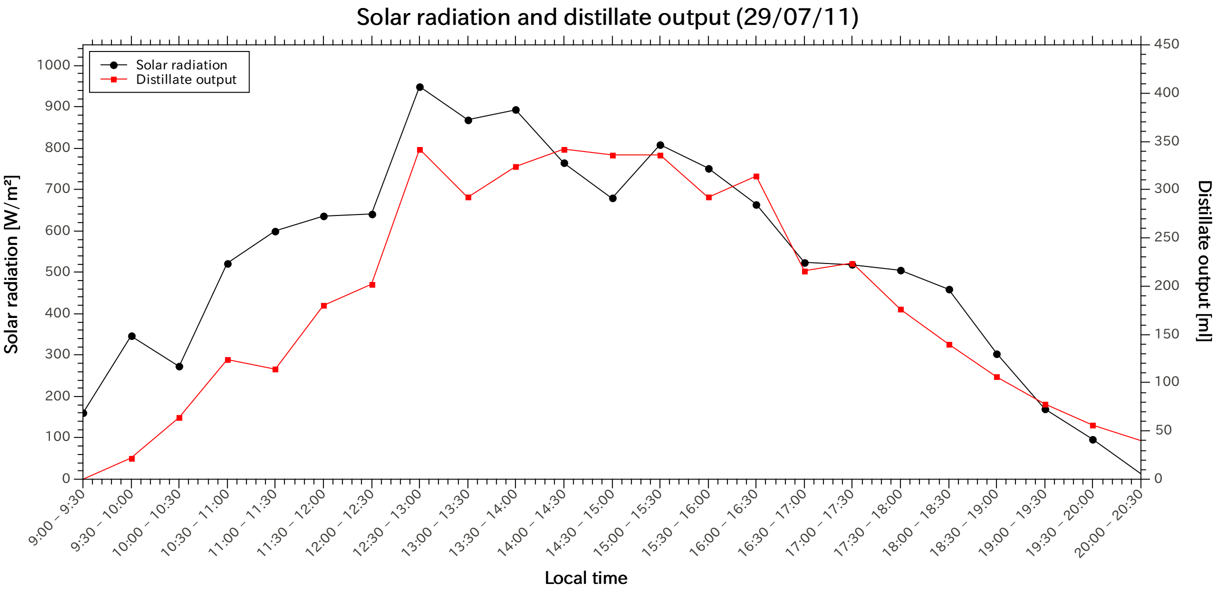


Figure B.20. Insolation and distillate curves for 29/07/2011.

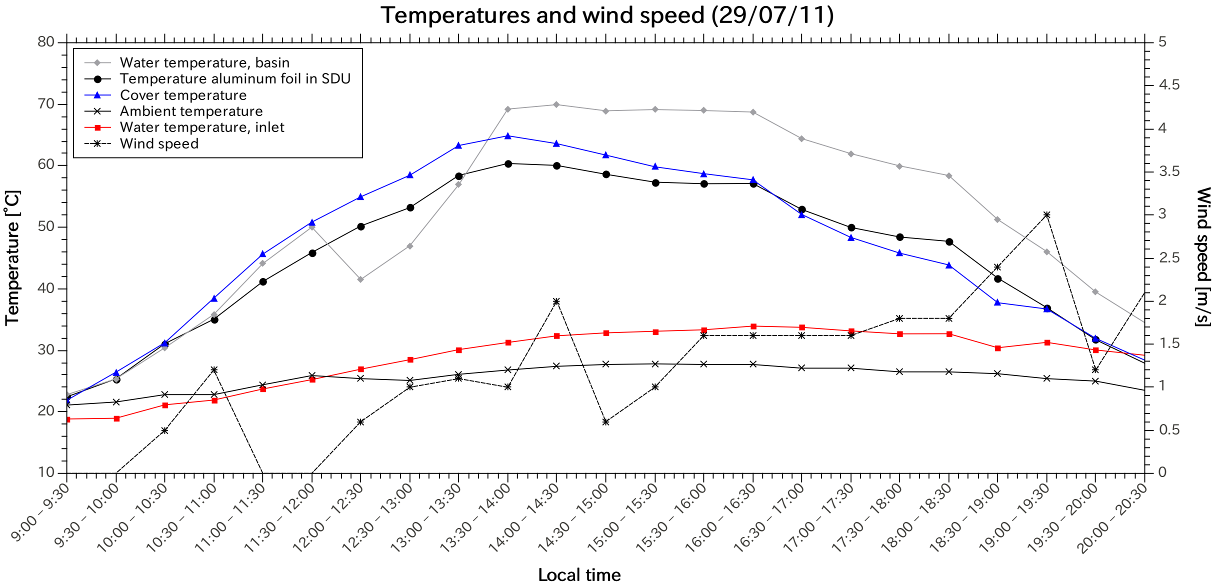


Figure B.21. Temperature and wind speed curves for 29/07/2011.

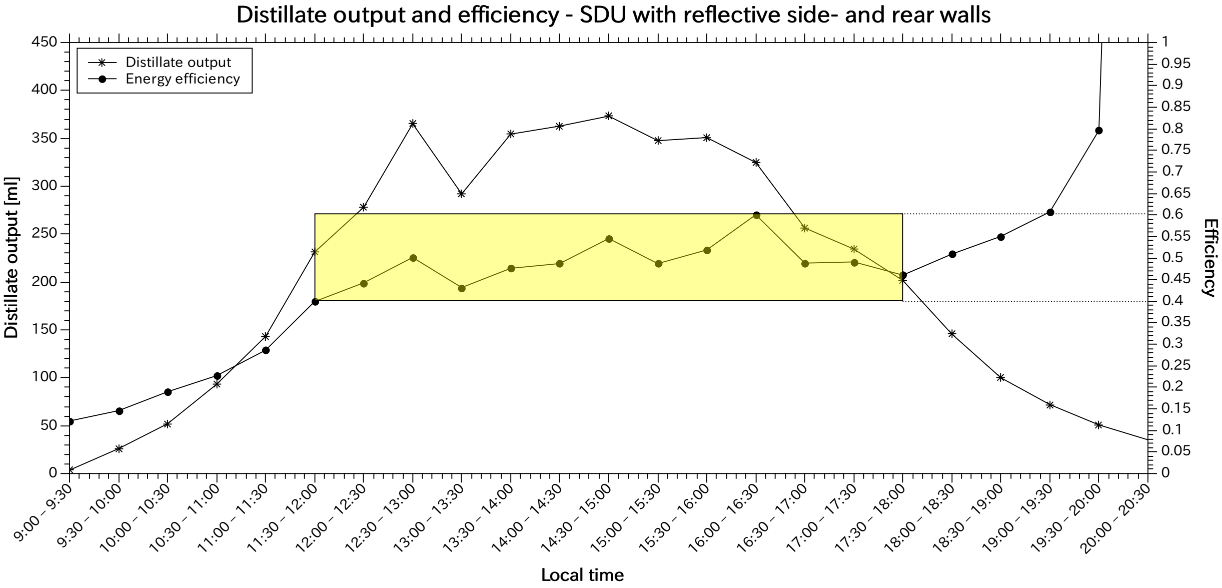


Figure B.22. Distillate output and energy efficiency for the SDU with reflective side- and rear walls.

C. Physical values

Table C.1. Values of enthalpy of vaporisation for water at standard ambient pressure (1013 hPa) (adapted from Keenan et al., 1978).

Temperature [°C]	**ΔH_{vap} [kJ/kg]**
0.01	2501.3
5	2489.6
10	2477.7
15	2465.9
20	2454.1
25	2442.3
30	2430.5
35	2418.6
40	2406.7
45	2394.8
50	2382.7
55	2370.7
60	2358.5
65	2346.2
70	2333.8
75	2321.4
80	2308.8
85	2296
90	2283.2
95	2270.2

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