SOLAR WATER DISINFECTION: FIELD TEST RESULTS AND IMPLEMENTATION CONCEPTS

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Abstract

Between 2006 and 2010, a simple solar water disinfection system called SoWaDis with almost no need for maintenance has been developed at the Institute for Solar Technology SPF in Rapperswil (Switzerland). Since 2009, several systems have been installed at various locations in Bangladesh, Mozambique and Tanzania. The device has been developed for remote areas with a maximum output capacity of the smallest unit in the range of 500 liters per day. The whole development covers three main working areas: A detailed study on thermal inactivation of pathogen microorganisms, the technical development of the device and field testing including the investigation of suitable implementation concepts that lead to a sustainable application.

In this paper, measurement data and experiences from almost two years operation time are presented and analyzed. It can be shown that the SoWaDis system fulfills the requirements for conditions in developing countries with a reliable long-term operation and almost no effort for maintenance. The correlation between irradiance and drinking water output from the systems in the field corresponded to the output expected from previous measurements at the laboratory at SPF in Rapperswil. Although the output fluctuations from day to day can be significant, also during rain seasons the monitored devices did not stop to produce drinking water over longer periods of time.

Currently, 11 systems are in operation in the three countries mentioned. They are operated with different concepts by different type of people: Some in schools or hospitals where staff members like teachers or health post chiefs are in charge, some by village water committees where the committee is responsible for the operation of the system and the distribution/selling of the drinking water and some by private operators (e.g. selling the water at a kiosk or restaurant). For all locations and concepts, social and economical aspects (responsibility, acceptance, involvement of local authorities, distribution of the water etc.) were at least as important as technological aspects.

1. Introduction

About two million people die worldwide each year due to lack of safe drinking water (WHO, 2000), and up to two billion people do not have access to safe drinking water which not only leads to diseases but also to constraints with regards to the economical and social development.

Starting in 2006, a research project has been carried out at the Institute for Solar Technology SPF in Rapperswil (Switzerland) to develop a simple, robust and affordable solar water disinfection system with almost no need for maintenance. Initially, the striking aim was to produce up to 500 liters of drinking water per day with initial system costs less than 500 USD. The whole development covers three main working areas:

- A detailed study on thermal inactivation of pathogen microorganisms,
- the technical development of the device and
- field testing including the investigation of suitable implementation concepts that lead to a sustainable application.

In chapter 2, the first two working areas are presented shortly as they have been published in detail before (cf. Konersmann and Frank, 2009; Konersmann and Frank, 2011). Emphasis is put on the description of field tests in chapter 3 where measurement data from almost two years operation time is presented and analyzed. In chapter 4, different implementation concepts and experiences with the operation of the devices under real (post field test) conditions are presented and discussed.

2. Technological development

Several methods and technologies exist to purify water (e.g. filters, UV treatment, thermal disinfection etc.) They all have specific advantages and disadvantages, not only technical, but also social and economical. Therefore, a catalogue of criteria was defined to assess different options for components and system assembly. This catalogue was developed with feedback from different experts coming from different fields, mainly solar technology, microbiology and development cooperation. The most important criteria were: Simple technology and little to no maintenance, no parasitic energy use, output capacity for small communities (100-1000 l/d), low initial costs, low treatment costs, high effectiveness. This implies many more aspects like a low vulnerability to scaling, high stagnation temperatures, corrosion, qualification for maintenance, a high expected service lifetime, high social acceptance (e.g. regarding the method of treatment, taste etc.), suitability for transportation, operation security, risk of theft, supply of peripheral parts, no need for additional energy sources (such as electricity), possibility for local production and distribution.

Before starting to investigate the technical specifications, an extensive microbiology study has been carried out in cooperation with Eawag in Switzerland which is among the world's leading aquatic research institutes (cf. Konersmann and Frank, 2011). The results confirmed that for the inactivation of all pathogenic microorganisms in water a temperature of 75°C with an exposure time of five minutes is sufficient (see also Konersmann and Frank, 2010).

As described in (Konersmann and Frank, 2009) a market survey on solar thermal water disinfection methods has been carried out. Based on that, a concept such as shown in Fig. 1 was investigated and further developed that meets the criteria as described above. The three main components (collector, thermostatic valve and heat-exchanger) have been investigated separately regarding their functionality and their cost/benefit ratios, and then the system behavior and performance has been investigated in detail both in the lab and in the field. To cope with the high complexity of requirements listed above (of which some are even contradictory), the defined criteria were weighted in order to assess the various possibilities for each of the three main components and finally for the overall system.

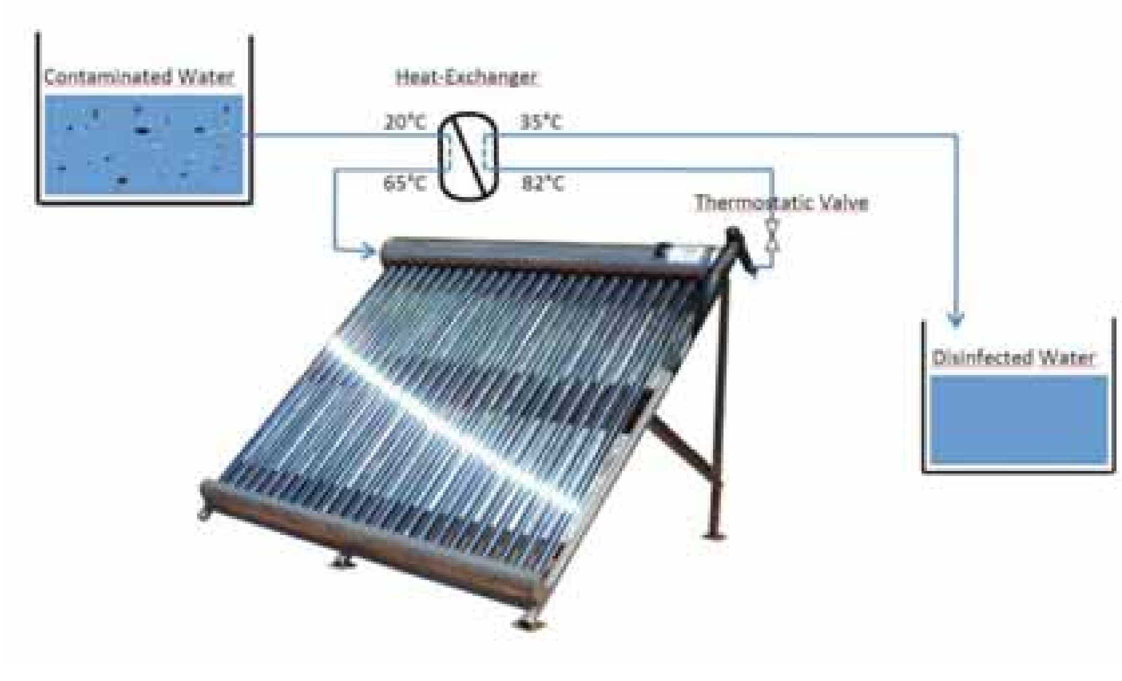

Fig. 1: Scheme of the solar thermal pasteurization plant with its main components heat-exchanger, collector and thermostatic valve (adapted from Konersmann and Frank, 2009). General functionality is indicated in the text box on the right.

As far as the **collector** is concerned, three different types (vacuum tubes, usual flat plate collectors and polymer collectors) have been looked at regarding the technical feasibility (especially clogging and cleaning) and costs. As the water is directly heated by the system and the flow is a sensible parameter of the gravity-driven system, the small pipe diameters of usual flap plate collectors and the effort for cleaning were mainly excluding flat plate collectors from the list. Based on literature (e.g. Burch, 1998), a self-developed polymer collector seemed to be a promising low cost solution for this low temperature application (cf. the section on microbiology). However, more detailed analysis showed that the suitable polymers which fulfill the requirements (such as temperature, UV-stability) would still have higher costs than those of directly flooded vacuum tubes. Furthermore, an important advantage of the vacuum tubes (which in this application are completely filled with water) is the large inner diameter so that the flow in the collector is not sensitive to clogging or scaling and allows a simple cleaning. The collectors of the systems operated in the field are of two kinds: Some with 24 tubes below a header tank which is horizontal (cf. Fig. 1) and a version with 48 tubes which are located on two sides of a header tank that is also tilted (a so-called “butterfly” collector, cf. Fig. 4).

In order to analyze the functionality and the efficiency of several **heat exchangers,** a test rig has been installed and experiments have been carried out. Not only low costs, but especially low maintenance and pressure drop were the main criteria for the assessment. Finally, a tube-in-tube concept with a comparably large diameter operated in counter-flow turned out to be the best option. Several versions have been developed and tested, with tubes made of copper, polymer or combinations. It could be shown that a polymer concept for a heat exchanger with almost the same heat exchange rate is not cheaper if all necessary parameters are met (again such as temperature resistance which is important as stagnation may occur in the collector if there is no water left in the first tank, so that steam may enter the heat exchanger) than a copper/copper version. Furthermore, an advantage of copper compared to polymer is the lower likelihood for recontamination. The final concept of the tube in tube heat-exchanger consists of two copper tubes with inner diameters of 22mm and 12mm, respectively, both with a wall-thickness of 1mm. Investigations have been carried out regarding the optimal dimensioning which is depending on the collector area with the aim of minimizing the cost/benefit ratio (see below).

The **thermostatic valve** was also investigated experimentally. To find an optimal solution that is opening and closing at the set temperature with a characteristic suitable for this application, ten products already available on the market have been analyzed. One of them was found to meet all technical criteria for the valve (set temperature of 82°C and a flow regulation leading to almost constant outlet temperatures for the right dimensioning of the system, cf. Fig. 8) while having a low price due to mass production. Other products were showing a less appropriate characteristic leading to a stop-and-go operation of the system which reduces the daily production. With the set temperature of 82°C and a mean flow time through the system in the range of several minutes, both the results of the microbiological study as well as further experiments with the system showed that a total inactivation according to the WHO standard can always be achieved.

With the single components described, the **system behavior** has been investigated thoroughly on the SPF test roof in Rapperswil/Switzerland using contaminated water. System parameters such as relative dimensioning (length of heat exchanger vs. size of collector-field), difference of height of water tanks (resulting volume flow through pressure difference) and the related start-stop characteristic of the valve were analyzed in detail on the system level. In Fig. 2 the daily produced amount of drinking water as a function of the daily irradiation are shown for different system configurations. The maximum daily production lies at around 600 liters per day for the system with 48 tubes and a 10 meter heat-exchanger and around 300 liters for the system with the 24 tubes and a 5 meter heat-exchanger. Fig. 3 shows the typical system behavior on a summer day in Rapperswil. The system has quite a large thermal mass containing about 100 liters of water in the tubes and in the header tank. Therefore the system’s operation only starts a few hours after the collector is exposed to irradiance. As shown in Fig. 2 and Fig. 7 an irradiation offset in the range of 2.5 to 3 kWh/d (depending on the climate) is needed to have a drinking water production of the system on that particular day. Furthermore Fig. 8 shows how the system starts producing when the temperature at “collector out” exceeds 82°C. The volume flow is variable according to the opening position of the valve, which again depends on the temperature. This way the operating temperatures are kept almost on constant optimal values for a steady state operation.

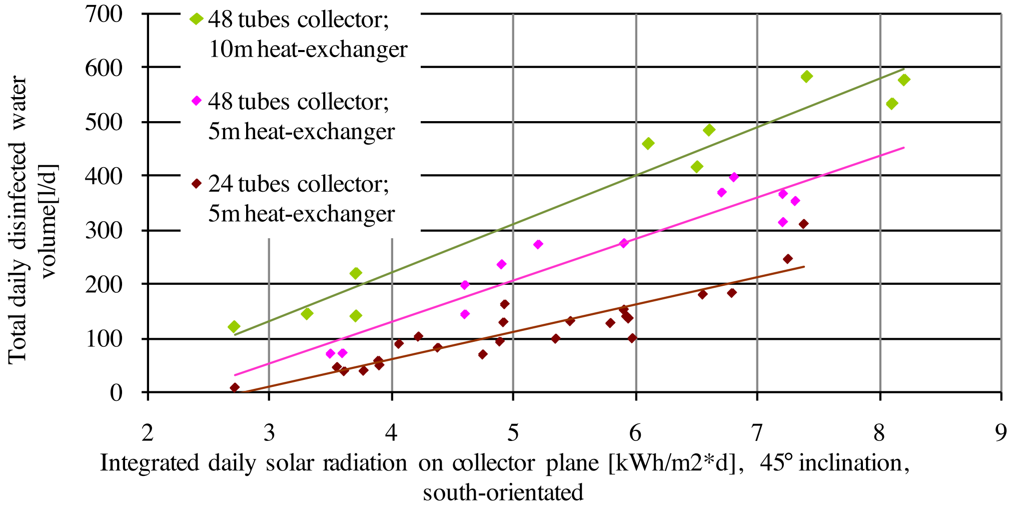

Fig. 2: Daily production of disinfected water for systems with different dimensioning (24- and 48-tube collector, different lengths of the heat-exchanger). Data measured on the testing roof at SPF in Rapperswil/Switzerland.

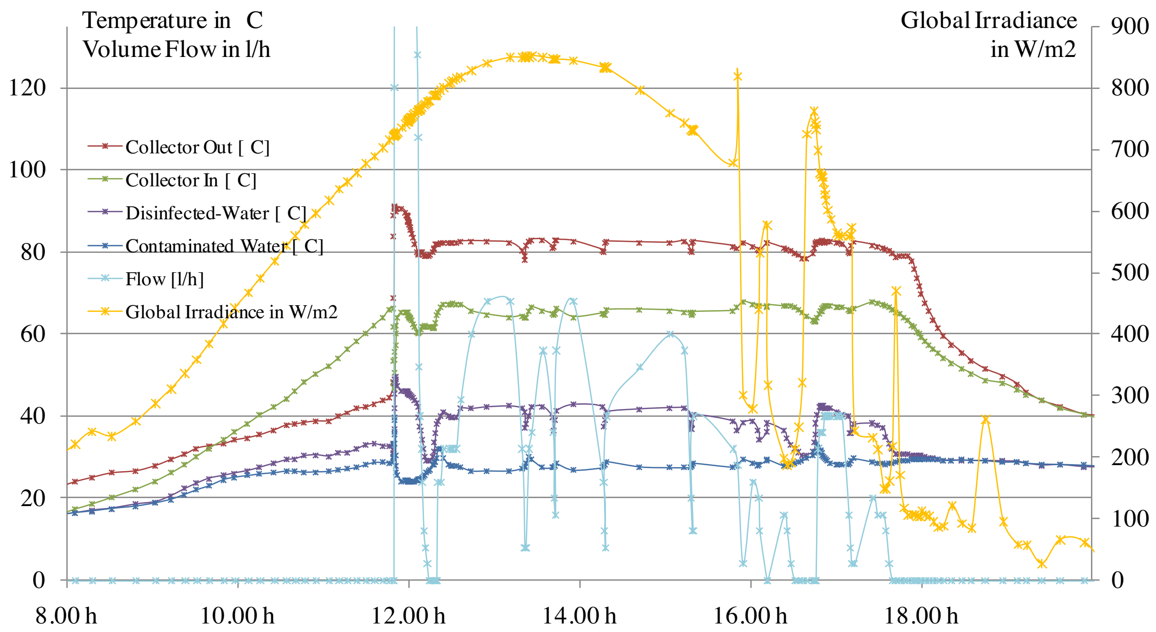

Fig. 3: Typical system behavior of the solar water disinfection device with 48 tubes and 10meter heat exchanger on a sunny day on the SPF testing-roof in Rapperswil (27.07.2009). The global irradiance (45° inclination, south-oriented, measured in collector plane), temperatures and the volume-flow are shown. The thermostatic valve regulates the flow in order that outlet collector temperature remains almost constant at optimum.

The long-term test in the testing facilities at SPF and also the experiences in the field (cf. section 0) showed that the system basically works without any maintenance. It is recommended that a coarse pre-filter (100micron) is used to restrain sediments from entering the system which has to be washed occasionally. The problem of scaling was also analyzed on a long-term-basis. The water used for the tests at SPF is rather calciferous with 33-36°fH. With water temperatures in the collector between 60°C and 100°C, scaling can be a serious problem to be considered regarding long-term operation. Also in many developing countries this can be an issue. However, due to the large diameters of the tubes neither scaling nor soiling led to an observable decrease in production or even a production stop. Yet, lime and dirt that may settle at the bottom of the tubes could easily be removed manually. As mentioned above, this was one of the main reasons for choosing a vacuum tube collector instead of a flat-plate collector with small diameters of the absorber-tubes.

3. Field Tests

By now the solar water disinfection (so-called “SoWaDis”) system has been operated in three different least developing countries over almost two years. In Table 1 an overview over the field tests is given. The aims of field testing and thus the choice of the locations and their conditions were twofold: To analyze the technical long-term-functionality and to find out about the acceptance and the sustainable operation (also economically) of these systems. By now three different types of locations/operation concepts are analyzed: schools, hospitals and water kiosks that are operated by private entrepreneurs.

Some of the SoWaDis systems have been monitored in detail. The measured data include global irradiance (on collector plane, 15° inclination, orientation north), volume flow and 4 temperatures (upper tank with contaminated water, collector inlet, collector outlet and inlet of clean water tank). The monitoring is a self-developed stand-alone concept with a logger in combination with a PV-panel, charge-controller and a car-battery (see Fig. 5).

Measurement data for the SoWaDis system at the university campus in Tanzania from March 2010 to April 2011 is presented in Fig. 6. For this period, data for less than 70 days is missing. As expected, the measured data show a correlation between irradiance and drinking water output that corresponds to the measurements conducted before at the laboratory at SPF in Rapperswil (see Fig. 2). The system installed is a collector with 48 evacuated tubes and a heat-exchanger of 6 meters in length (see Fig. 4). As it is shown in Fig. 6 the output fluctuations from day to day can vary significantly for the climate at the location in Tanzania, but even during rain seasons the monitored device did not stop to produce drinking water over longer periods of time. The annual average production of the system was about 200 liters per day, with a peak production of almost 600 liters per day. As mentioned above, an offset of about 2.5 kWh/d is needed to have a drinking water production of the system on that particular day at this location. Furthermore, the drinking water production stops if (a) for any reason there is no water available in the contaminated water tank or (b) when the safe water tank is completely filled (both tanks are equipped with a flow valve to avoid overflow).

Table 1: Overview of field tests of the SoWaDis system in three least developed countries.

	Mozambique	**Bangladesh**	**Tanzania**
Start	Oct. 2009	Oct. 2009	Mar. 2010
Partner	International NGO	Local NGO	Evangelic-Lutheran Church of Tanzania (ELCT)
# Systems installed	7	2	2
Environ-ment	Rural, remote (Macomia district)	Dense urban environment (Dhaka)	Rural / small village (Usambara mountain region)
Implemen-tation concept	- schools (public and private) - health posts - community operated water kiosk - privately operated by a foundation (the water is used for guests of a lodge, the staff and people from nearby villages)	Commercial: The water was filled in buckets and sold on the local market.	- University campus (owned and managed by the ELCT) in a rural area (see Fig. 4). The water is consumed free of charge by the students, the staff and the teachers. - The second system is operated as a water kiosk (see section “implementation”).

Fig. 4: The SoWaDis system installed at a university campus in Magamba/Tanzania.

Fig. 5: The technical monitoring system of the solar water disinfection plant is shown in the pictures above (from left to right): Temperature and radiation sensors, logging equipment powered by a car battery and a PV-panel (pictures previously published in Konersmann/Frank 2009).

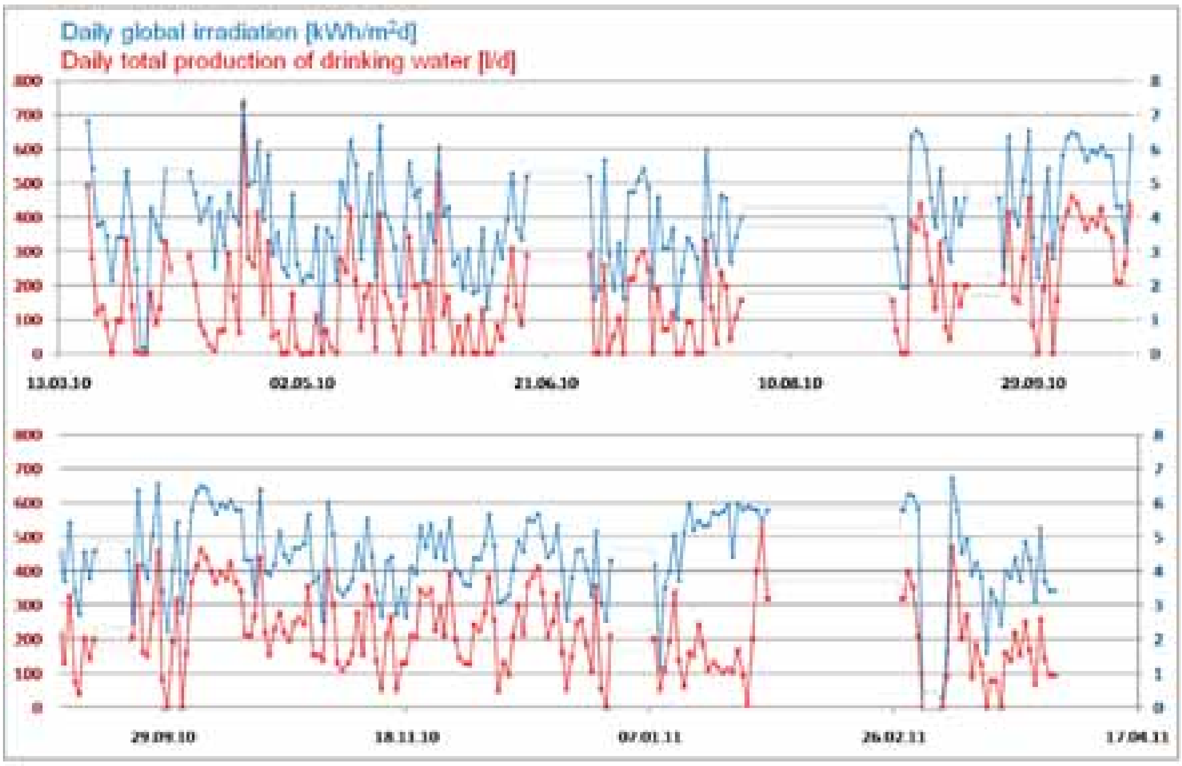

Fig. 6: Daily total production of drinking water and daily global irradiation at the SoWaDis system on a university campus campus in Magamba/Tanzania for one year, measured with the stand-alone monitoring system.

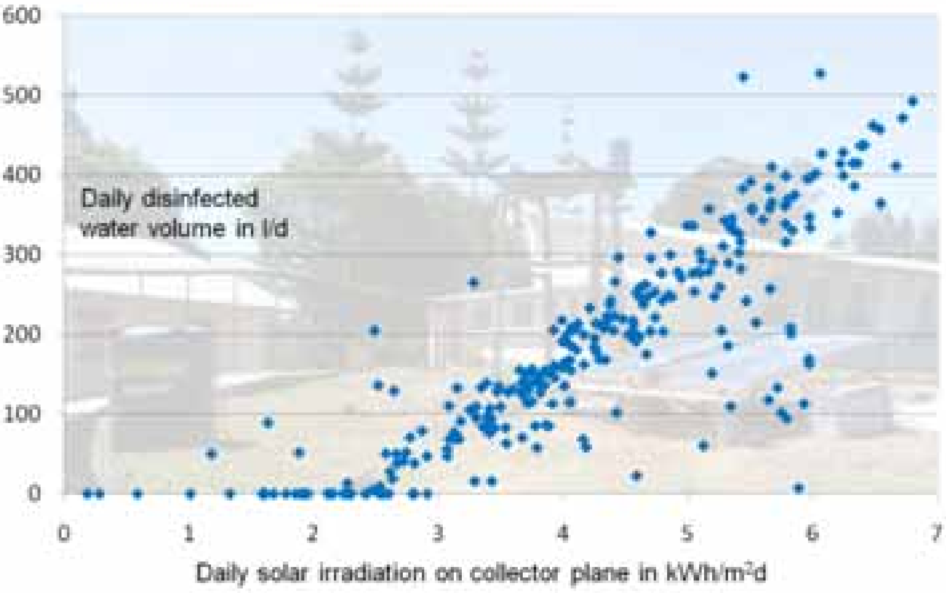

Fig. 7: Daily disinfected water volume as a function of the daily solar irradiation on the collector plane (15° inclination, orientation north).

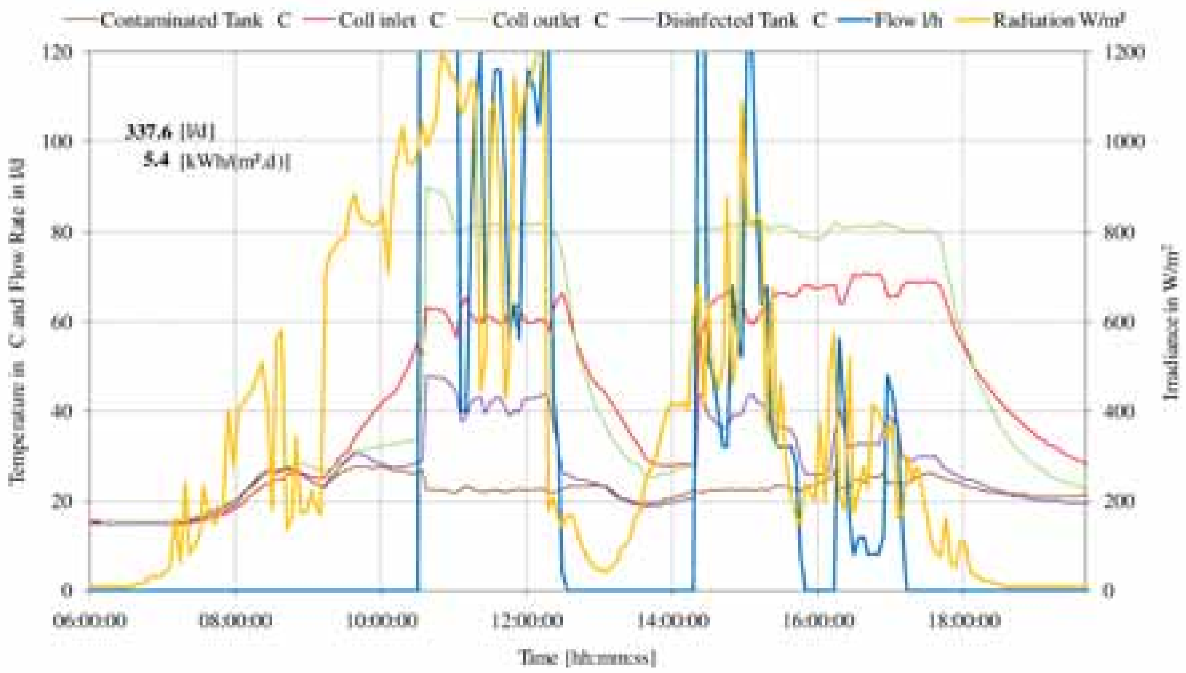

Fig. 8: Typical pattern of the operation of the SoWaDis system on March 27, 2010 at the university campus in Magamba/Tanzania. The measured data include global irradiation (on collector plane, 15° inclination, orientation north), volume flow and four temperatures (upper tank with contaminated water, collector inlet, collector outlet and inlet of clean water tank).

From the technical point of view the system proved to be working basically maintenance-free. Looking at the measurement data, only in January 2011 one week can be observed where the production is less than it should be due to the irradiation. The reason for this was a period when the water supply was instable. As the device is depending on the sunshine to produce drinking water, in fact the main challenge (that was also encountered in field tests at the other locations) is to have a constant water supply to the system. For most locations in developing countries, this is usually not the case. Most dots in Fig. 7 for which the daily disinfected water volume is lower than the line of best fit (for irradiations > 2.5 kWh/m²d) are results of a lack of water in the supply tank. One option to deal with this problem is to install a large tank that is filled while the water supply rate is higher than the current production rate (or mainly during the nights), e.g. 1000 liter that allow two days of production even for good weather conditions if the water supply is stopped. As far as the acceptance of water produced by the SoWaDis system at the university is concerned, by now all groups on the campus (such as students, teachers, staff, guests) consume water from the SoWaDis system on a daily basis. However, the acceptance may be a crucial factor for some locations and/or implementation concepts for several reasons, e.g. a remaining turbidity of the water (especially during rain seasons). In case of the university campus, the level of acceptance was induced by different factors, such as professors that acted as role-models and water quality tests that had been conducted repeatedly (the SoWaDis water even showed better results than bottled water that is locally available and rather expensive).

4. Implementation of the technology

A reliable technology with low costs and low maintenance is not yet assuring a long-lasting and effective use of the technology. Rural Water Supply Network (2010) describes that „thousands of people, who once benefited from a safe drinking water supply, now walk past broken hand pumps or taps and on to their traditional, dirty water point.“ Therefore, after having the system developed and operated almost two years in pilot-projects in three different least developing countries, the investigations were extended to find suitable ways for the deployment of the technology ensuring a sustainable operation. In this context the SwissWaterKiosk Foundation has been launched in spring 2011 (see www.swisswaterkiosk.org). The foundation aims to catalyze the SoWaDis projects in order to create fair access to safe water to people in developing countries. It is projected that in a first phase 70 systems will be installed until end of 2013.

The SwissWaterKiosk Foundation pursues three core objectives (in hierarchical order):

1. SwissWaterKiosk provides safe drinking water for people that otherwise have no access to drinking water. This is leading to an improvement of health standards, a reduced infant mortality rate, lower non-productive times of the consumers etc.
2. SwissWaterKiosk creates an economically sustainable operation after an initial funding for the set-up. With a (small) profit from selling the drinking water, a long-lasting operation and upkeep of the kiosk as well as a motivation to provide as much water as possible to the local people shall be achieved. The foundation especially supports the set-up of further kiosks in the same community and/or region with the help of local partners.
3. By this, not only the consumers of the water benefit but the economical situation in the community should improve (by creating new jobs and incomes with the water kiosks and education programs for water entrepreneurs etc.).

The foundations financing is multifaceted, e.g. by private donors, project funding, Corporate Social Responsibility programs etc. Apart from the water kiosk concept (operated by community or private entities and/or individuals) the SoWaDis-System is also implemented in schools and hospitals where usually no income is generated by the sale of water. In these cases the systems have to be financed completely by the foundation or the government or by implementing partners, in most cases non-governmental organizations.

In Table 2 and Fig. 9 an example of the financial operation of a water kiosk is presented that has been implemented in Tanzania in a rural village. The water could be sold at around 0.02 USD per liter so that the expenses for the operators (success-oriented) salary and for system amortization (here 7 years) can be covered. The water kiosk concept creates a strong sense of ownership and incentive for the operator since he or she can create an income by the operation of the water purification system. This is a good basis for the sustainable operation of the technology, which is one of the major challenges for most projects in the field of developing cooperation. However, the concept should not aim at the maximum economical benefit because the price for selling the water should remain so low that poor people can afford buying the drinking water. In general, the selling of water is being discussed highly controversially. In the case of the SwissWaterKiosk water is sold not in order to create profit for the foundation, but in order to guarantee the long-term operation. The revenues of the water sold in the shown case can only cover expenses needed for the operation and for the hardware, but they cannot cover the costs associated with the overhead to initiate and organize these projects. Based on field experiments with the SoWaDis implementation in Mozambique, Schiebold (2011) describes the main determinants for the successful operation of a water kiosk, concluding that enabling local micro-entrepreneurship is very important to create sustainable development in developing countries. A scheme for a possible implementation model is shown in Fig. 10. The basis for the successful implementation of the water kiosk (besides the availability of water in general) is the awareness of people regarding hygiene in water and sanitation. If people are not aware about the consequences of consuming water that is not safe to drink, there will be no willingness to pay. But even projects where safe water is offered for free can only work if there is a minimum level of awareness. Therefore, safe water projects usually have to involve a strong social marketing campaign. According to Heierli (2008) these campaigns should not only emphasize on rational arguments but also include lifestyle elements. From a technical point of view, one of the challenges of the water kiosk concept in combination with the SoWaDis technology might be the dependency on sunshine that could lead to a mismatch between demand and supply of drinking water at the kiosk.

Table 2: Overview of financial sustained operation model of the water kiosk concept.

	Costs for local operation of water kiosk		
a	Initial cost of system and peripherals	2000	$
b	System operator	60	$/month
c	System maintenance and controlling	30	$/month
	Assumptions		
d	Average output per system	200	l/d
e	System service lifetime	7	a
	Calculations		
f	Daily total costs of operation	4	$
g	Resulting water price	0.02	$/l
	Further Explanation		
a	Initial costs for material, production and transportation and peripherals such as water buckets, kiosk hut etc.		
b	Assumption of salary in Tanzania		
e	The lifetime in Europe is 20+ years, assumption for rough conditions		
f	Including the amortization of the initial system costs		

Fig. 9: In the left picture the SoWaDis system in the village of Lukozi/Tanzania is shown that was set up in August 2011. On the right hand side, the SwissWaterKiosk hut for selling the purified water is shown.

Fig. 10: Schematic diagram how a financially sustainable operation of SoWaDis could be implemented.

5. Summary and Outlook

The technical development of a water disinfection device (so-called „SoWaDis") has been presented. Both by experiments on the laboratory test roof in Rapperswil (Switzerland) as well as by extensive field testing and monitoring in Bangladesh, Mozambique and Tanzania it was shown that the system fulfills the requirements to be reliable, robust, user-friendly (simple and socially accepted technology, very low operation and maintenance effort) and effective. With a proven record of success, the SoWaDis system is a suitable solution for the implementation in schools and hospitals where the system is under the responsibility of the staff and causing almost no extra-work. Beyond that, a water kiosk concept is presented that is meant to amplify the deployment and the long-lasting sustainability of the technology. In total, three out of eleven systems that have been installed so far are now operated with a commercial water kiosk approach, and though there is no long-term experience yet the evaluation of the sites will show in the near future if a financially self-sustained operation of the system can be achieved.

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