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Integrated solar home system

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Abstract

To date, many traditional Solar Home Systems (SHS) have consisted of separate components which required assembly by trained individuals and were also more susceptible to failure and maintenance. As a result, many SHSs in remote areas have not fulfilled their desired lifecycles or simply have not functioned at all. Thankfully, a solution to these problems has arrived—the newly developed Integrated Solar Home System (I-SHS). Within this new system all components such as the support structure, foundation, PV modules, charge controller, DC–AC converter and wiring are pre-assembled by the manufacturer. Benefits of the new system are ease of assembly and maintenance combined with an associated reduction in cost and failure—critical aspects to consider for remote and impoverished regions. Additionally, electrical yield was increased by 9% by a significant reduction of operating cell temperature. This was achieved by an integrated water tank, serving as a cooling unit and also providing the system's foundation. This measure is neither expensive nor energy intensive, improves output of the system in an unproblematic way and allows for use of the heated water.

Keywords: Performance; Solar Home System; Rural Electrification; BOS; Cost reduction

1. Introduction

More than 20 million people in Brazil (approx. 42% of the rural population) do not have access to electricity. Grid line extension is a rather costly option because distances are long and average consumption is low. According to Messenger and Ventre [5] installation of each kilometer of a simple 115 V line extension costs in the vicinity of 50,000 €—depending on the region and the environment. In addition,

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costs for surveillance and maintenance are considerable due to exposure of grid lines to hostile conditions (e.g. vandalism, thunderstorms, vegetation, flooding).

Conversely, a means to supply remote areas with electrical energy are Solar Home Systems (SHS). Apart from ecological advantages, in many cases this option is also the most economic way to electrify rural areas - especially when consumption is low and grid extension is long. But even this most economic option often has a price that is too high for the wide spread use of traditional SHS. According to a recent report by Kister [1] about 60% of the traditional SHS installed in Brazil by the PRODEEM program (rural electrification by PV) are no longer working or never worked at all. Reasons include a shortage of trained staff which resulted in inadequate installations and improperly maintained systems. Another reason for the high failure rate of the systems was on the load side because traditional SHSs were installed with DC outputs only (which have the advantage that the user is not able to connect to common and typically inefficient electro-domestic equipment such as filament light bulbs). On the other hand it is rather difficult to find replacements for such supplies in retail outlets. Furthermore, DC equipment (e.g. fluorescent lamps) is more expensive than AC equipment. System components could be manipulated by the user in an undesired manner (e.g., bypassing of the charge controller). The newly developed I-SHS minimizes or eliminates these problems.

2. The I-SHS

2.1. Composition of the system

Fig. 1 shows the basic layout of the system: The PV generator consists of two parallel-connected frameless 30 W_P modules. Located in the foundation structure are a maintenance-free lead acid battery (12 V, 105 Ah) and a 200 W sine wave inverter

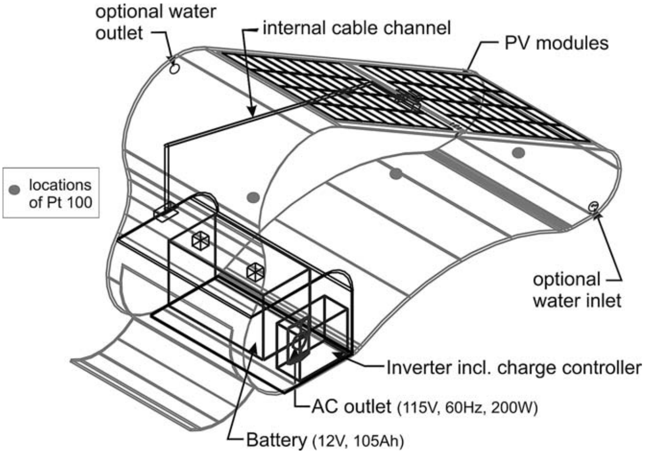

Fig. 1. Structure and components of the Integrated Solar Home System (I-SHS).

(115 V 60 Hz) with an integrated charge controller (6 A). A water tank cools all components. The output leads to a regular AC plug. Additionally, five Pt-100 temperature sensors have been integrated into the prototype. Through computer based measurements—utilizing a 16-channel-USB-DAC card and LabView® software—the temperature profile has been improved through design changes to achieve optimal cooling in a future prototype. Ambient temperature, irradiance and the electrical parameters (V ,I, P) are also monitored (see Fig. 1 and Fig. 2).

All components are contained in a waterproof epoxy fiberglass tank. The prototype is 1.37 m long, 0.76 m high and 0.5 m deep and has a volume of 0.3 m^3 (see Fig. 3). A module elevation angle of 30° was chosen to achieve a good yield even in winter in most parts of Brazil. The tank has a volume of almost 300 l, which results in a weight of at least 300 kg, when full.

2.2. Temperature dependence

The electrical power generation of a solar cell depends on its operation temperature. While the short circuit current (I_{sc}) increases slightly with increasing temperature, the open circuit voltage (V_{oc}) decreases significantly (about −2.3 mV for each K) with increasing temperature, leading to an electrical yield reduction of −0.4 % K^{-1} to −0.5 % K^{-1} for mono- and multi-crystalline silicon solar cells which are used in most SHS applications. Fig. 4 shows the *I–V*-characteristics for a typical multi-crystalline silicon solar cell at different temperatures together with the operation points for maximum power generation.

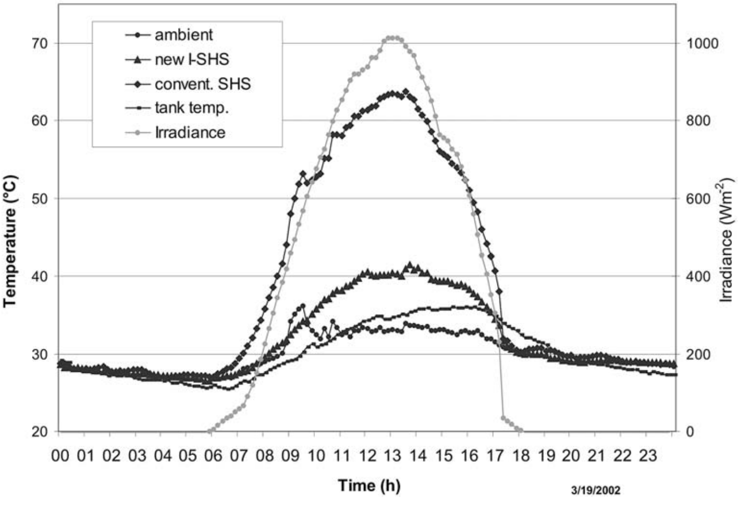

Fig. 2. Temperature measurements of the I-SHS during a clear day (see ‘Irradiance’): The lower module temperature (‘new I-SHS’) and water temperature in upper part of the container (‘tank temp.’), in comparison to a conventional SHS and ambient temperature.

Fig. 3. The Integrated Solar Home System (I-SHS) prototype during tests in Copacabana, Rio de Janeiro, Brazil. Design by ‘Escola de Belas Artes’, UFRJ, Rio de Janeiro.

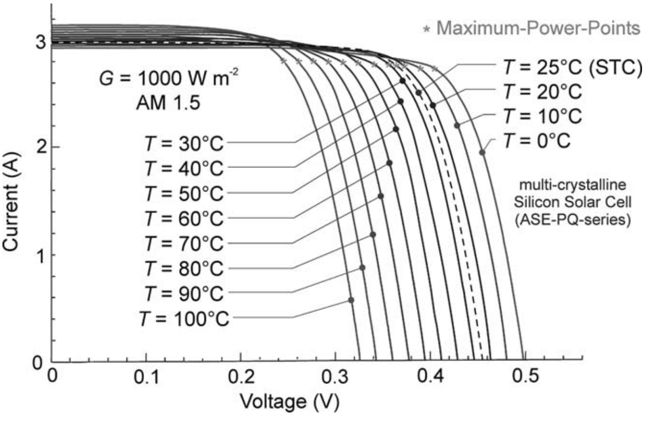

Fig. 4. *I–V* characteristics at different temperatures of a typical multi-crystalline Silicon solar cell.

2.3. Temperature reduction

While efficiency and electrical yield is decreasing with increasing operation temperature, the idea to keep the system at low temperatures is quite evident. The energy consumption of an active cooling system would not be compensated by the gain in increased energy generation, at least for small systems. Operation temperatures were kept at low levels by mounting the module on a water filled tank. This allows for an effective reduction of operating cell temperatures without spending any energy for refrigeration. The water virtually soaks up the heat flow generated by the module.

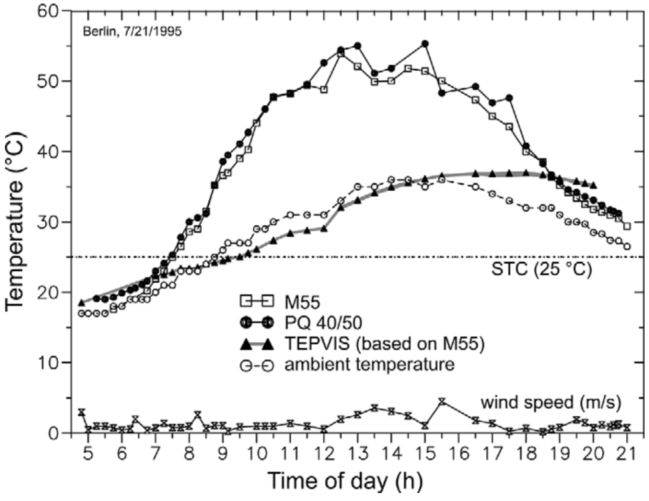

Fig. 5. TEPVIS (Thermal Enhanced PV with Integrated Standing)— proof-of-principle prototype based on a M55 by SSI, now Shell Solar (Berlin, 1995).

Due to the high thermal capacity of the incorporated water, the temperature increases gradually (see also results in Fig. 5 and Fig. 6).

The principle was proven and validated with different prototypes in Europe and in Africa built over previous years (e.g., Krauter [2], Krauter [3], Krauter et al. [4]).

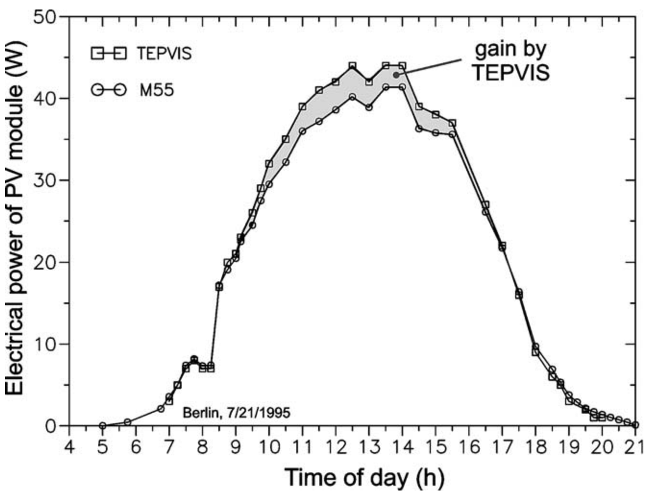

Fig. 6. Temperatures of TEPVIS in comparison to conventional PV modules (PQ 10/40 and M 55) and ambient temperatures for a clear day in Berlin.

2.4. History

The first cooling device which followed the ‘cooling by an extended heat capacity’ concept was built in 1992. The tank was integrated into the original framing of a M55 PV module by SSI (former Siemens Solar Industries, now Shell Solar) with a volume of 12 l, so it could be used with conventional mounting. This prototype provided a 2.6% increase in daily electrical energy yield. Subsequent tests, which utilized latent heat storage material (sodium sulphate), showed significantly better results but caused severe corrosion.

The second prototype built in 1994 had a much larger water tank which served also as the module’s foundation, stand and mounting structure (TEPVIS—Thermal Enhanced PV module with Integrated Standing). It was tested with a M55 in Berlin (see Fig. 5–7) which showed an energy gain of up to 12%, and with PQ 10/40 devices in Bulawayo, Zimbabwe (see Fig. 8–10) which proved an increase of 9.5%. The gain in Zimbabwe was lower due to reduced water circulation and more stratification (the upper part of the tank got considerably warmer than the lower one). The inclination of the module plane in Zimbabwe was much lower (20°, according to the latitude of Bulawayo), thus reducing the thermo-siphon effect (see also Fig. 9). The device in Berlin was also equipped with an additional plate inside the tank, in parallel to the module at a distance of 12 cm, forming a kind of chimney and thus enhancing circulation (‘Onneken’s seperator’). Nevertheless, the PV conversion

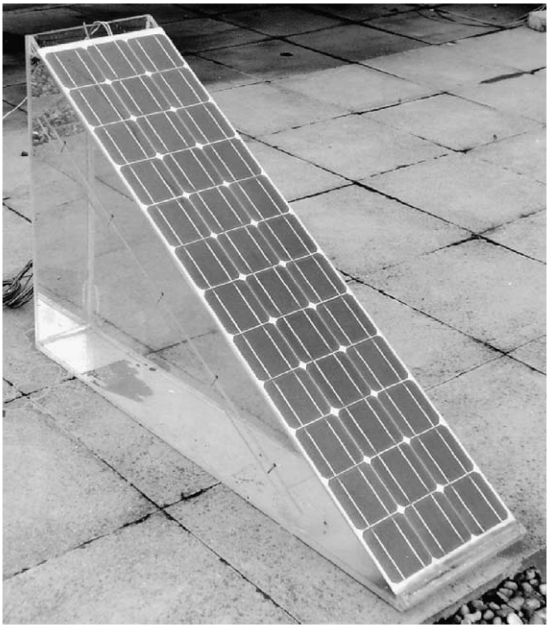

Fig. 7. PV power output of TEPVIS in comparison to a conventional M55 with conventional mounting. The gain in electrical yield is 11.6%.

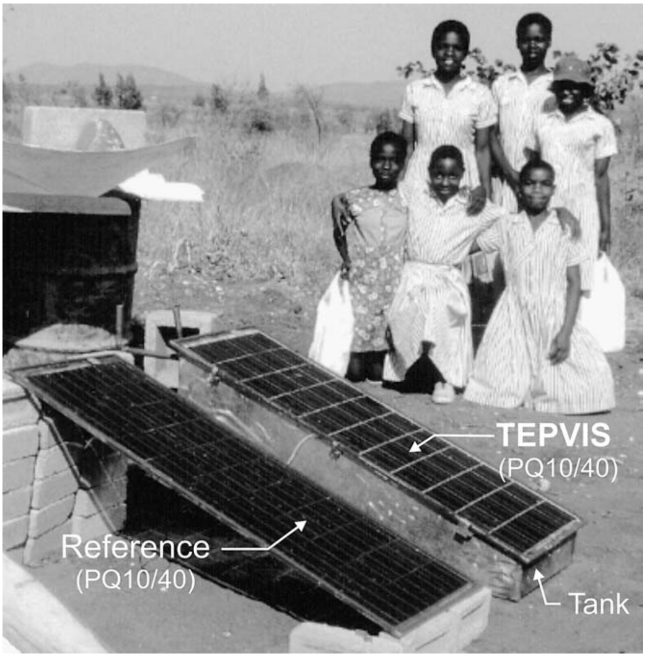

Fig. 8. Comparative measurement of a TEPVIS with a steel tank and a multi-crystalline standard reference PV module (PQ 10/40) during 1995 in Zimbabwe.

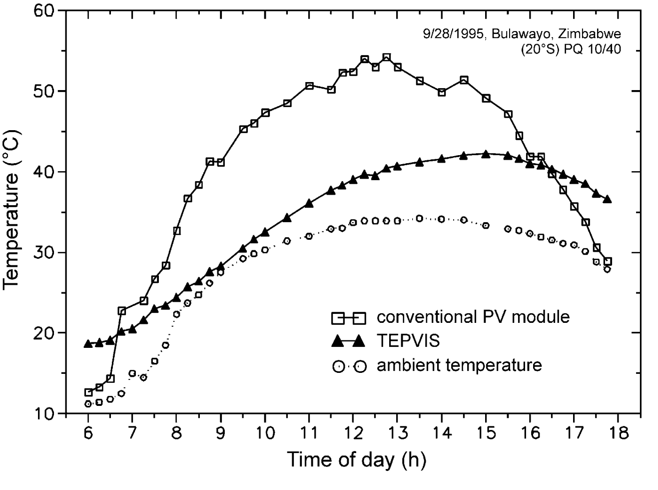

Fig. 9. Comparison of module temperatures for a conventional multi-crystalline PV module (PQ 10/40) with TEPVIS with for a clear day in Bulawayo, Zimbabwe.

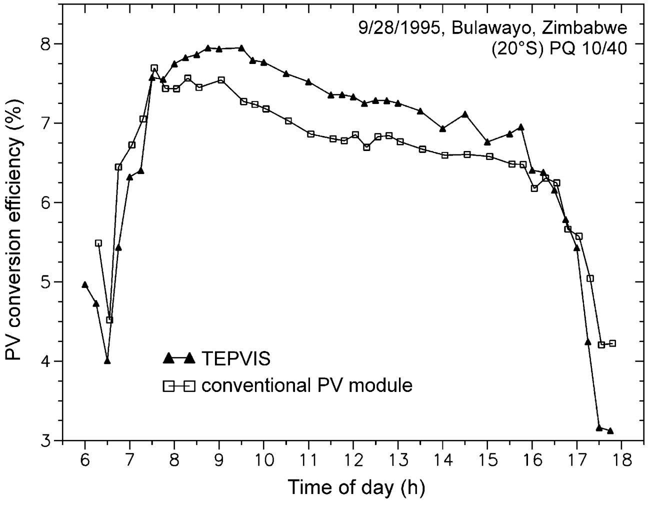

Fig. 10. Comparison of PV conversion efficiencies for a conventional multi-crystalline PV module (PQ 10/40) with TEPVIS with for a clear day in Bulawayo, Zimbabwe.

efficiency of the cooled module was considerably above the reference module during at least 95% of the day (see Fig. 10).

To eliminate possible measurement errors which may have been caused by the differing electrical properties of the systems, all modules (reference and cooled ones) were interchanged and retested. The modules had been operated continuously at the Maximum Power Point (MPP) by manual tracking of an ohmic load together with power metering.

The application for the new I-SHS was carried during the first quarter of 2002.

2.5. Measurement system

Fig. 11 shows the configuration of the measurement equipment. The sensor signals (temperatures of modules, water and ambient, global irradiance (see also Fig. 3), module current and voltage, loads) are amplified, then digitalized by a 16 bit analog-to-digital converter (ADC) and are averaged over a period of 10 minutes. The A–D sample rate is quite low (one measurement every second). Visualization and submission of the data on the Internet is done via the LabView® interface by National Instruments.

3. Results

The tank acts as an efficient cooler for the PV modules. The aluminum back of the frameless PV modules allows for good heat transfer to water stored in the tank. The water, with its high thermal capacity, limits solar cell temperatures to a range in proximity to that of ambient temperatures (see Figs. 2 and 12).

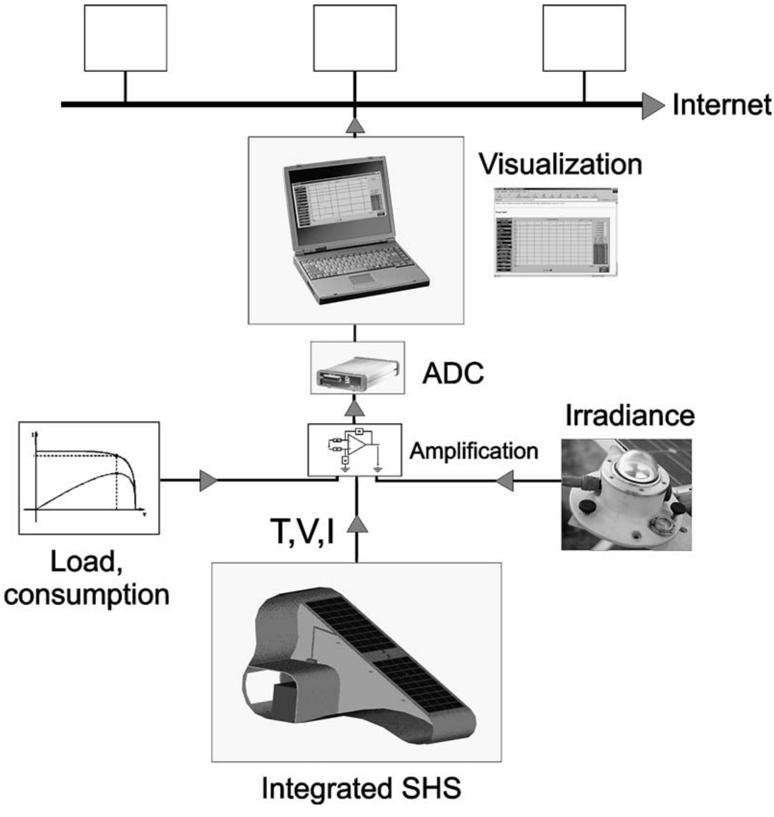

Fig. 11. Scheme of measurement and data-acquisition system and for the Integrated SHS.

The increase of cell temperature relative to ambient temperature was measured for several days in Rio de Janeiro during March 2002 and is shown in Fig. 12 as a function of irradiance in comparison to the equivalent values for a conventional SHS (e.g. Messenger and Ventre [5], Krauter [7], Krauter and Schmid [8]). Despite a relatively wide spread in values, mainly due to wind speed variations, the following linear approximations can be extracted:

$$T_{\text{comv. SHS}} - T_{\text{ambient}} = 0.03 \cdot G\,(\text{W m}^{-2})^{-1}\,\text{K} \tag{1}$$

$$T_{\text{I-SHS upper}} - T_{\text{ambient}} = 0.012 \cdot G\,(\text{W m}^{-2})^{-1}\,\text{K} \tag{2}$$

$$T_{\text{I-SHS lower}} - T_{\text{ambient}} = 0.058 \cdot G\,(\text{W m}^{-2})^{-1}\,\text{K} \tag{3}$$

G stands for global irradiance, T_{SHS} for module operation temperature of a conventional SHS (‘Reference Case’) as measured (see Krauter [7], Krauter and Schmid [8]) or given in literature (e.g. Messenger and Ventre [5], Krauter [6]). $T_{\text{I-SHSupper}}$ stands for the temperature of the upper module and $T_{\text{I-SHSlower}}$ for the lower module in the I-SHS. All temperatures are given in Kelvin (K) or degree Celsius (°C).

In previous experiments, a reduction in cell temperatures during operating time

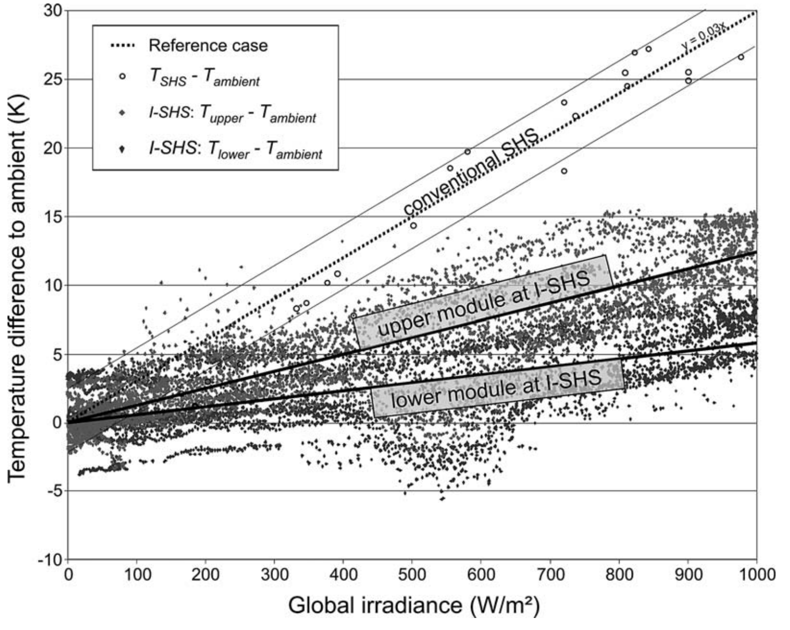

Fig. 12. Differences between module temperature and ambient temperature in comparison to the reference case (conventional SHS) plotted as a function of irradiance.

increases electrical yield by up to 12% (Krauter [3], and Krauter et al. [4]), see also section 2.4. Due to the stratification observed, the I-SHS showed just a 9% gain. Forcing circulation in the tank would certainly result in higher electrical yields; on the other hand, stratification serves very well for an optional thermal use of the system. The hot water generated is sufficient for the consumption of a small household in Brazil if the problem of Legionella bacteria is solved. The upper module can also be replaced by a thermal absorber and would boost hot water generation. A new model of the I-SHS with an increased tank volume in the upper part of the device for hot water storage is under construction and will suit even better for that purpose.

4. Manufacturing

For testing purposes a single prototype was manufactured. Mass production of the I-SHSs (e.g. by recycled PE or PP) would be fast and inexpensive with large scale production costs at less than 50 €. Material problems related to UV stability and the drying of the plastic seem to be solved - manufacturers of similar tanks (used as floating docks for boats) give guarantees of 10 years.

4.1. Prototype

The prototype's form was shaped from a block of expanded polystyrene (EPS). Subsequently the container-tank, consisting of six parts, was laminated using a fiberglass and epoxy resin. To allow for modifications the modules are mounted in a detachable manner. A cable tube passing through the tank was installed to simplify maintenance (e.g. replacement of cables). Additionally, possible non-exchangeable integration of the PV modules within the tank-container would provide improved heat transfer and performance by lowering the thermal resistance between the modules and the water. Construction time for the prototype was less than a week. Material costs for the prototype have been 420 € and are listed in Table 1.

4.2. Balance of system costs (BOS)

Since the foundation, support structure and mounting equipment are no longer required, significant reductions in installation costs and 'turn-key' system costs are achieved. Together with improved aspects of maintenance and higher energy yields, PV electricity is becoming more available. Once the I-SHS has been placed at an appropriate site, it has just to be filled with water and is immediately ready to supply power to any AC device from its standard plug. The weight of the tank-container, without inverter and battery, is about 7 kg, making transportation easy. When filled with water the container has a weight of more than 300 kg, thus making the system stable enough to withstand any storm without additional fixings.

5. Conclusion

Once placed at an appropriate site the I-SHS is immediately ready to supply small AC loads (illumination, air-fan, radio etc.). Additionally it is capable of supplying the hot water needed for a small household. Several systems can be combined to fulfill higher power needs without a redesign of the system. Without having higher costs than conventional SHSs, and featuring favorable BOS and the generation of more energy, the I-SHS is an efficient means to successfully electrify remote areas.

Table 1
Costs of materials for a prototype structure of the I-SHS

Material	Number, value	Unit	Cost p. u. (€)	Total cost (€)
Styrofoam	1	m^3	45	45
Fiberglass	30	m	5	150
Epoxy resin	5	kg	30	150
Glass bubbles	1	l	25	25
Other materials	1		50	50
Sum				420

Summary of benefits of the I-SHS:

- Ease of installation
- Significant reduction of system costs
- Increased efficiency via low cell temperature operation
- Increased reliability via pre-manufactured and pre-tested units
- Standard AC output (‘plug and play’)
- Optional use of hot water as a by-product.

Acknowledgements

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