ISEC 2024 – 3rd International Sustainable Energy Conference
Solar Thermal and Energy Efficiency for Sub-Saharan Africa's Industry and Commerce
https://doi.org/10.52825/isec.v1i.1219

Published: 19 Apr. 2024

Life Cycle Assessment of Thermosyphon and PV Hot Water Systems Under the Same Operating Conditions in a Side-by-Side Experimental Setup in Namibia: Initial Results and Data Comparison With Existing Similar Installations

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Abstract. The global demand for hot water is increasing, driving a shift towards solar technologies. Namibia, aligning with emission reduction goals, plans to replace electric boilers with solar thermal and PV2Heat systems, emphasizing cost efficiency. This study focuses on providing eco-performance data for solar hot water systems, specifically thermosiphon and PV systems. Three systems in a container at the NUST Science and Technology Park are being compared, with commissioning scheduled for 2024. Preliminary eco-performance data will be derived from initial monitoring, followed by a comprehensive life cycle assessment (LCA). The study envisions a straightforward process in generating input data for the LCA, including performance data. Determining the levelized cost of electricity (LCOE) for economic comparison is a key aspect. While leveraging existing data from previous works, it acknowledges the limitations in estimating expected eco-performance indicators. The study aims for a direct LCA and eco-performance comparison between solar thermal and photovoltaic-based systems, contributing to Namibia's sustainable energy strategy.

Keywords: Solar Hot Water Systems, Eco-Performance, Life Cycle Assessment

1. Introduction

The demand for hot water is increasing worldwide. Many countries have set targets to promote a higher proportion of energy production through solar technologies. A global energy strategy is crucial to meet the growing energy demand, minimize the environmental impact and reduce dependence on fossil fuels. The use of solar thermal energy for water heating is a promising and sustainable option. Two technologies are particularly promising for the so-called Sunbelt region (between the 20th and 40th parallel in the northern and southern hemisphere), where Namibia is located [1]. These technologies are solar thermal thermosiphon systems and electric hot water systems powered by photovoltaics (PV2Heat). They are expected to play the largest role in the solar hot water market in this region in 2030.

Namibia is focusing strongly on reducing its greenhouse gas emissions in line with its Intended Nationally Determined Contributions (NDCs) to mitigate climate change. The reduction potential for 2030 is estimated at up to 91 % [2]. The strategy for achieving the target in the energy sector is to replace conventional electric boilers with the above-mentioned solar thermal systems and PV2Heat systems with a particular focus on cost efficiency for the sustainable use of these systems for the end consumer. The aim of the present work is to accompany this strategy with eco-performance indicators, as to date there is hardly any meaningful data, literature and comprehensive comparative studies on thermosiphon and PV hot water systems for household applications under real environmental conditions, especially for Namibia.

2. Experimental & Modelling

In the comparative study mentioned in the introduction, which serves as the basis for the life cycle assessment, 3 different hot water systems are examined.

They each consist of a 200-liter tank and collectors/PV modules with 1.2-1.6 kW equivalent rated thermal output/kW peak:

- System 1: Indirect thermosyphon system with a flat-plate collector;
- System 2: Indirect thermosyphon system with evacuated heat pipe collector and
- System 3: PV-to-heat (PV2Heat) system.

The overall aim of the systems under investigation is to carry out a direct comparison of small systems for solar hot water generation, including energy monitoring and determination of the heat generation costs. The three systems are installed in a 12 m long shipping container, with the monitoring system, the controls and the storage tank of the PV2Heat system housed in the container. Figure 1 illustrates the structure of the container. The container will be installed in the NUST Science and Technology Park.

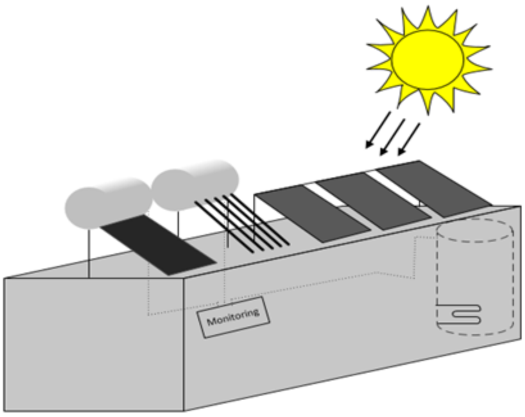

Figure 1. *Experimental setup of the side by side comparison of thermosyphon and PV hot water systems*

The project is currently in the detailed planning phase and the first components are being shipped to the site. Commissioning of the plant is planned for the beginning of 2024. The technical details will be presented in a separate paper. The life cycle assessment parameters will be determined on the basis of the detailed planning and, if sufficient initial monitoring data is available, preliminary eco-performance data will also be derived.

As the monitoring phase of the project extends beyond the period of this study, comparative data from previous studies [3–8] will also be used.to create a preliminary comparative database and to estimate the expected eco-performance indicators. A comprehensive and final life cycle assessment and determination of the eco-performance indicators is planned in a follow-up study after the monitoring phase has been completed.

3. Results & Discussion

For the preparation of the LCA, it is expected that the generation of the associated input data, such as the performance data for the derivation of the eco-performance data, which are obtained by monitoring the metrological data and the technical data of the system, will not present any hurdles. Based on the costs for the components of the system, the LCOE can be determined, which can serve as an economic indicator for the comparison and also flow into a detailed economic and ecological performance value generation derived from the life cycle analysis (LCA) of the system. As the current work cannot take into account the entire monitoring period, existing data from previous work on similar systems is also used.

However, as the previous work lacks an absolute basis for comparison, as is the case in the current project, and no data is available for all three hot water systems currently being investigated, these generated parameters only represent an initial basis for estimating the expected eco-performance indicators. An important finding of this work and the planned follow-up work after completion of the entire monitoring phase will be the direct comparison of the LCA and eco-performance indicators from the two solar thermal systems in direct comparison with the system based on photovoltaic.

Based on previously generated measurement data from the SOLTRAIN program, data from 2016 of similarly configured systems were utilized for an initial LCA screening. Figure 2 illustrates, through a highly simplified product life cycle diagram (derived from the works of Ashby [9]), the product phases initially considered for the screening.

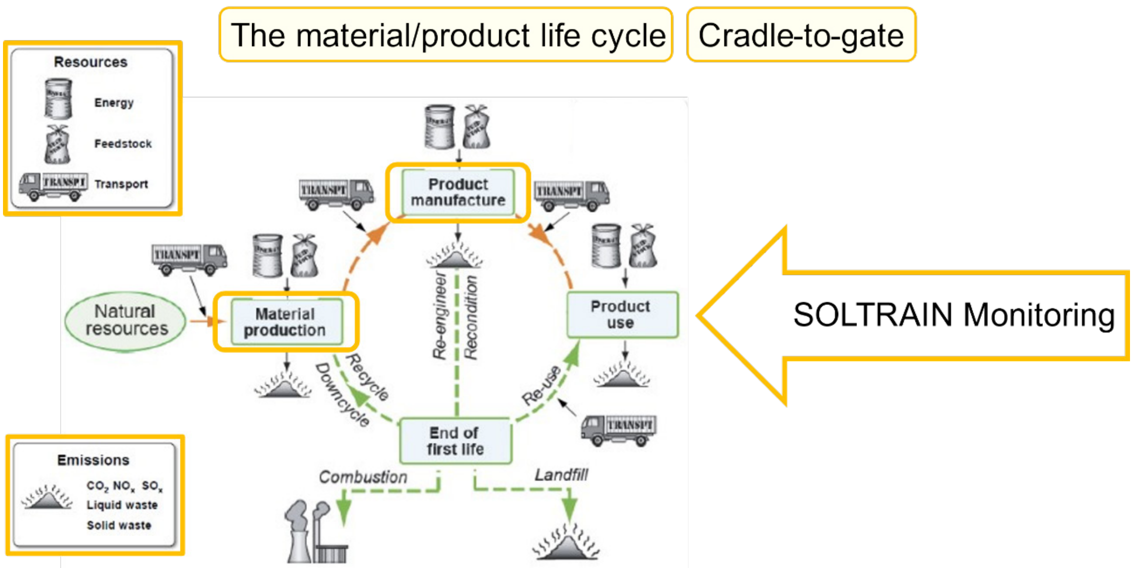

Figure 2. *Product life cycle & system boundaries*

This entails a classic cradle-to-gate analysis with respect to the applied system boundaries. For the assessment of the use phase, data from SOLTRIAN monitoring were utilized. In the context of a comprehensive LCA examination, the system maintenance and the necessary consumables and operating materials for it would need to be considered for the use phase. However, since these were not documented in the records of the data monitoring and the purpose of the analysis is to serve as an initial screening, these data are not taken into account. Their inclusion is naturally planned for the evaluation of the side-by-side study.

Figure 3 depicts the schematic structure of the monitoring concept applied for generating the historical data from 2016. This concept will also be employed in an expanded, adapted form in the current side-by-side study.

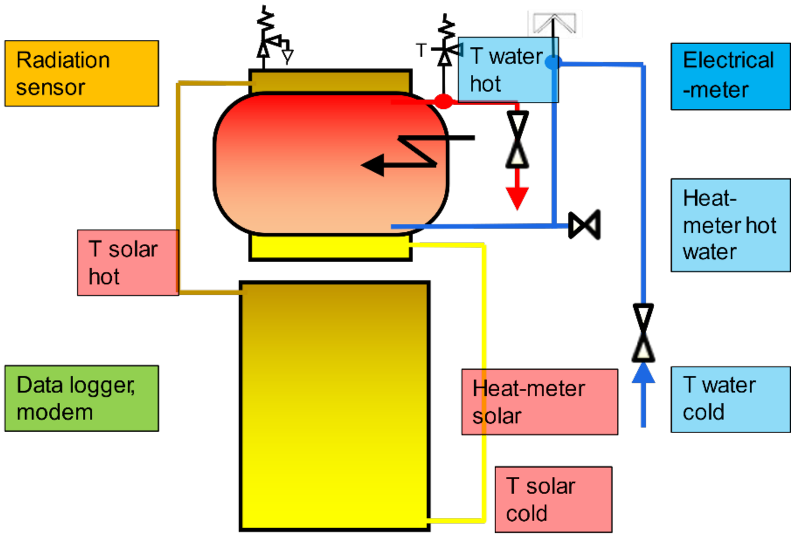

Figure 3. *Monitoring concept SOLTRAIN*

Figure 4 illustrates the positioning of the measured SOLTRAIN demonstration systems. This comprises four houses, each equipped with a thermosiphon system featuring 2 m² of collector area and a 150-liter storage tank. Additionally, one house incorporates doubled collector area of 4 m² and doubled storage volume, while a demonstration unit is equipped with a 300-liter tank directly heated by 6 PV modules.

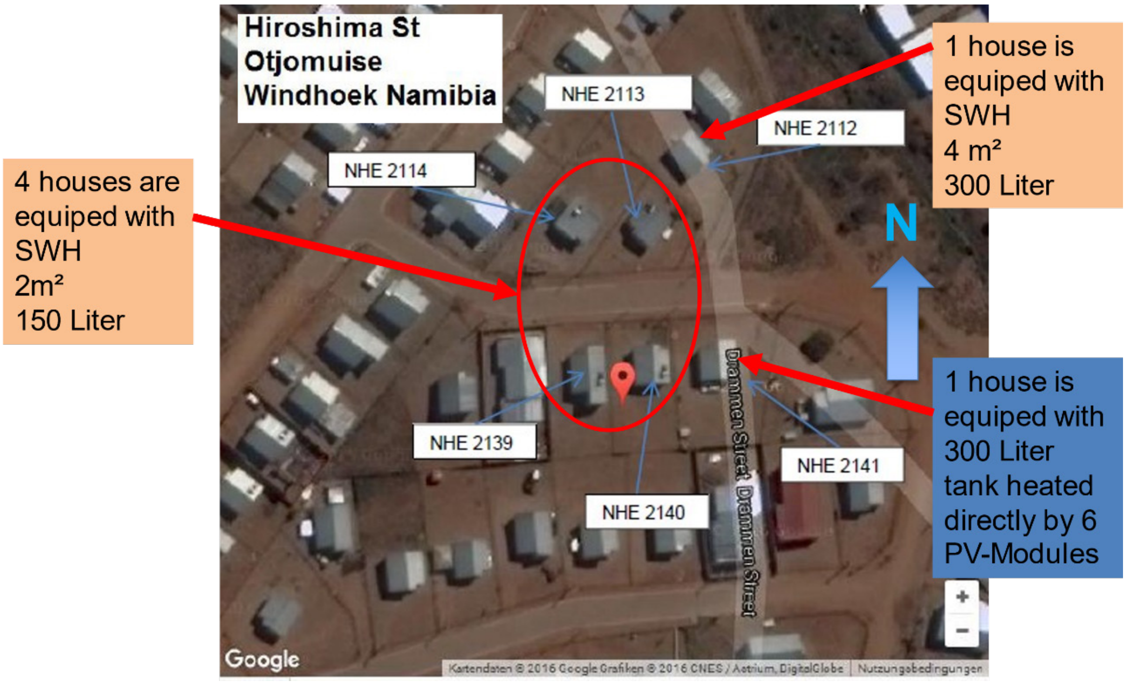

Figure 4. *Monitoring concept SOLTRAIN – location of the demonstration systems*

For the initial screening, the 2 m² system with the 150-liter storage was primarily considered. The LC inventory data modeling was initially approximated using manufacturer datasheets. In refining the data model for the side-by-side study, efforts are aimed at improving the quality of these data by incorporating more precise information where available. Figure 5 illustrates the annual monitoring data trend for the year 2016 for the NHE 2140 system. From the measurement data, a solar fraction of 95% and a solar yield of 752 kWh/m² were derived.

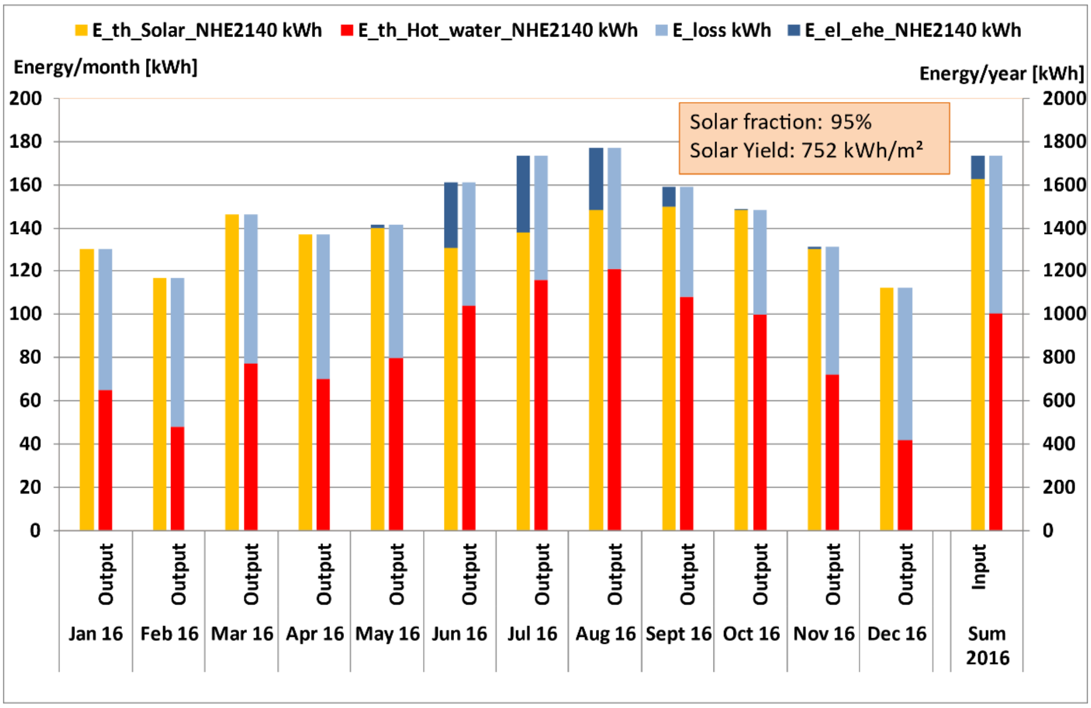

Figure 5. *Monitoring data for the NE2140 system in 2016*

The solar yields for the 2 m² systems ranged between 130 and 150 kWh per month. For further computation of eco-performance indicators, as outlined in Table 1 below, the mean value of 140 kWh per month was utilized for the screening. From the measurement data, it can be deduced that the 2 m² collector area / 150-liter storage can generate a total thermal output of 1.5 MWh per year. This metric was employed for calculating the energetic PayBack Times (EPBT) of the system. For determining the GHG reduction potential and the Carbon Payback Time (CPBT), a rough initial approximation of the system was computed according to the EPA [10] calculation model. It is noted that for the detailed determination of these metrics for the side-by-side system, this approximation is very coarse, and the electricity mix of Namibia, primarily covered by imports from South Africa, should be applied to the future measurement period's appropriate data. Figure 6 and Table 1 illustrate that the majority share of energy and carbon footprints, at 94%, lies within the materials used for production. For the production processes themselves, the relative share stands at 6% each. Also depicted is the End of Life (EOL) potential, which stands at 1% for energy and 2% for CO_2.

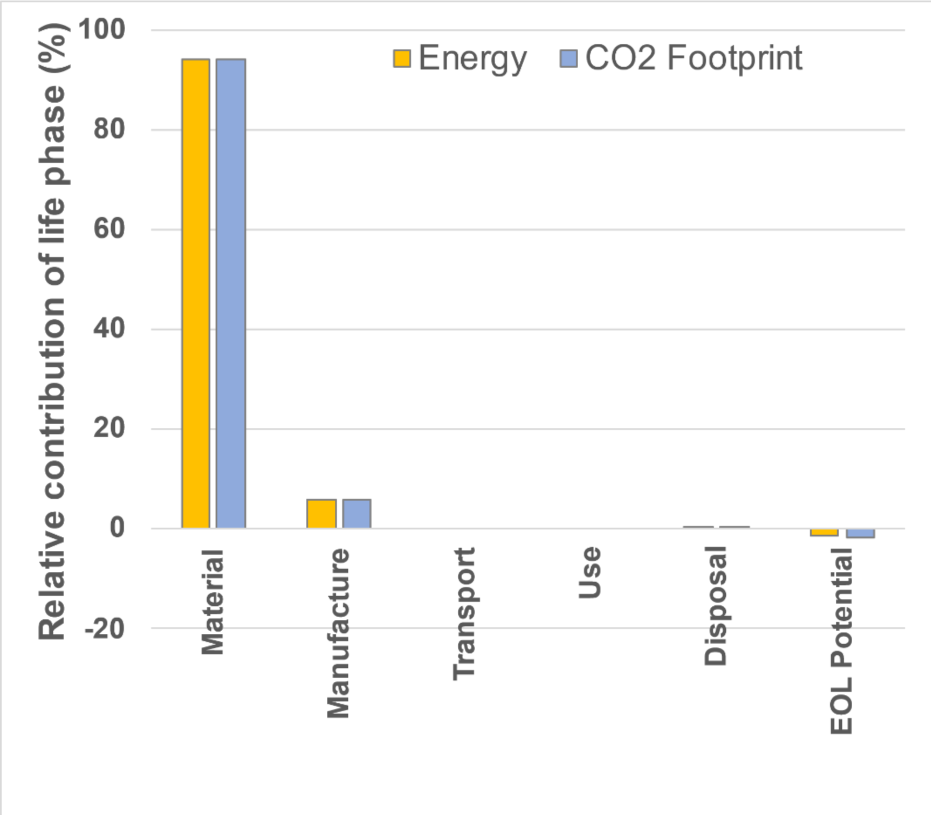

Figure 6. *First simplified LCA Screening with Monitoring Results from SOLTRAIN Demonstration Systems NHE houses in 2016*

Table 1. *First simplified LCA Screening with Monitoring Results from SOLTRAIN Demonstration Systems NHE houses in 2016*

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	8834	94	590	94
Manufacture	533	6	40	6
Transport	*0*	*0*	*0*	*0*
Use	*0*	*0*	*0*	*0*
Disposal	1	0	0	0
Total (for first life)	**9368**	**100**	**630**	**100**
End of life potential	-139		-10	

EPBT	**1,5**	**years**	
GHG Reduction Potential			**1.050 kg / year ***
CPBT			**0,6 years**

* following EPA GHG calculation

Data availability statement

The data generated or analyzed during this study are available upon request. Please contact the corresponding author for access to the data. Please note that the research is currently ongoing, and a follow-up Data in Brief article is planned to provide a detailed overview of the data collected and analyzed in this and follow-up studies.

Author contributions

Harald Kicker: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft, Gernot M. Wallner: Conceptualization, Funding acquisition, Project administration, Writing – review & editing, Supervision, Daniel Tschopp: Validation, Writing – review & editing, Project administration, Rudi Moschik: Conceptualization, Data curation, Wolfgang Gruber-Glatzl: Project administration, Joseph Shigwedha: Conceptualization, Data curation, Helvi Ileka: Conceptualization, Data curation, Project administration, Fenni Shidhika: Project administration.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The work presented in this study and its subsequent iterations is conducted within the framework of IEA Task 69, utilizing system and measurement data generated within the SOLTRAIN project. We extend our gratitude to our partners at the Namibia Energy Institute (NEI), AEE INTEC, and GREENoneTec.

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