Development and Analysis of an Off-grid Solar Food Processing System in Kenya

Alexander Morgenstern[1], Dilara Maria Subasi[2], Norbert Pfanner[3], Nils Reiners[4], Felix Stortz[5], Johannes Wüllner[6], Md Nasimul Islam Maruf[7]
Fraunhofer Institute for Solar Energy Systems ISE
Freiburg, Germany
[1]alexander.morgenstern@ise.fraunhofer.de, [2]dilara.subasi@ise.fraunhofer.de, [3]norbert.pfanner@ise.fraunhofer.de,
[4]nils.reiners@ise.fraunhofer.de, [5]felix.stortz@ise.fraunhofer.de, [6]johannes.wuellner@ise.fraunhofer.de,
[7]md.nasimul.islam.maruf@ise.fraunhofer.de

Abstract— **The agricultural sector, including fisheries, is one of the main economic drivers in Kenya, which employs two million people to accelerate the rural community development in the country. These fisheries contribute to food security, livelihood security, poverty reduction, and rural development. However, there are high post-harvest losses due to inefficient and inadequate cooling and drying practices, poor processing and transportation techniques, badly insulated and designed storage containers, and weak handling and mismanagement. These losses impede economic development and cause health problems, which can be minimized by a blend of technical, policy support, and societal solutions. This paper focuses on the technical part of the solution, where we propose an off-grid hybrid food processing system for Kenyan fisheries. Following a feasibility analysis, we implemented a working prototype composed of two main parts: (i) solar PV and battery-based ice machines for cooling, and (ii) solar thermal collector and heat storage-based dryers for drying the fish. Besides, an energy management system is installed to monitor and control the different components in the system. Based on simulation results, a PV system of 15 kW and a lithium-ion battery of 14.4 kWh are selected for powering a 5.6 kW ice machine. Economic analysis of the cooling system shows that a capital expenditure of 85,052 € is needed for the cooling system, which can be further reduced by 40% to make it more economically feasible. The annual operation and maintenance cost is calculated to be 3,410 €. Sensitivity analysis shows that the payback period can be as low as six years when subsidies finance the system. Life cycle analysis shows that the PV-battery-based system can provide better environmental benefits (0.06 kg CO_2/kWhe) compared to grid-powered (0.23 kg CO_2/kWhe) or diesel-generator powered (1.14 kg CO_2/kWhe) systems.**

Keywords: solar food processing; PV-battery system; fish refrigeration; solar dryer; off-grid cooling; life cycle analysis

I. INTRODUCTION

One of the economic main drivers in Kenya is the agricultural sector including forestry and fisheries. It serves the development of the rural communities by providing a variety of jobs like fishers, traders, processors, suppliers and merchants of fish accessory [1]. In the year 2016 marine fisheries had about 27,000 fishers, including 13,000 artisanal fishers [2]. According to the Kenyan marine fisheries and socio-Economic Development Project of the World Bank, 80% of the total marine products are caught in coastal waters and reefs, while only 20% is from offshore fishing [3]. In the year 2016, the production of rural marine fisheries was 24,000 metric tons; if the whole sector is taken into account, including inland capture, marine capture and aquaculture the production was about 150,000 metric tons [1].

According to the technical report of the Food and Agriculture Organization (FAO) [4], the periodic causes of fish losses have been reported as poor handling and inadequate cooling; lack of ice and poor cooling practices, poor processing and transportation techniques and conditions; badly insulated and designed storage containers and mismanaging of fish post-harvest. The causes of fish loss can be summarized in two categories: (1) non-availability of adequate equipment and infrastructure for drying and cooling fish, and (2) the remoteness of fisher communities from the markets, means of transportation and fish type are fish loss influencing factors as well. The losses are also linked to the socio-economic context and other factors. Other factors can be listed as: losses due to heat, insects and invasion occur mainly during storage, mold growth arises during rainy seasons due to higher humidity and insufficient training/caution leads to fragmentations during stacking, loading and off-loading fish on the vehicle. Different kind of post-harvest fish losses exists, such as, physical loss, quality loss and market force loss. Physical fish loss is defined as thrown away (due to spoilage, over smoking, contamination, discard of bycatch etc.) or eaten by animals. Quality loss is described as fish which has undergone physical or chemical changes and is sold for a lower price than the actual value. Market force loss occurs due to demand and supply situations in the market, leading to a selling price below expectations at time of production [5].

One may conclude that the reduction of fish loss may be accomplished by a combination of progress in technical, infrastructural and policy support, as well as awareness, market access and knowledge. This paper focuses on the technical part of the solution, where we propose an off-grid hybrid food processing system for Kenyan fisheries. Following a feasibility analysis, we implemented a working prototype composed of two main parts: (i) solar PV and battery-based ice machines for cooling, and (ii) solar thermal collector and heat storage-based dryers for drying the fish. In addition, an energy management system is installed to monitor and control the different components in the system.

II. SYSTEM DESIGN

A. Technology Selection

Different types of ice can be used for cooling purposes like tube ice, block ice or flake ice. The recommended cooling practice for fish is to pack them in layers with ice having regular small pieces or flakes to provide the most efficient cooling. Therefore, flake ice for fish cooling was selected for the project. Figure 1 illustrates the ice production process.

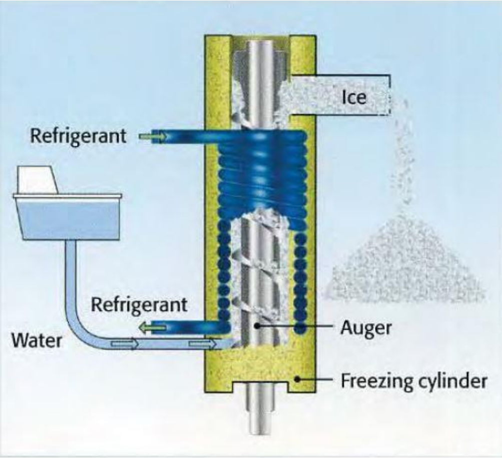


Figure 1. Illustration of the ice production process [6]

B. Design of the Ice Production System

Due to the unavailability of grid connection and the high environmental burden caused by fossil fuel powered generators, it was decided to run the system with a PV-battery system. Figure 2 illustrates the solar powered ice production system. As seen the system is mainly composed of PV panels, PV inverters, a battery, battery inverters and a flake ice machine.

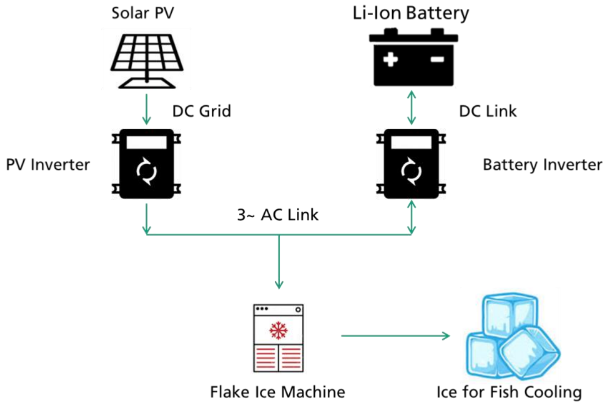


Figure 2. Schematic of the PV powered ice production system

C. System Sizing

A simulation was done to determine the necessary size for the PV system, battery system and ice machine. Components with different sizes and prices were chosen and simulated to find the most suitable one in terms of economics and ice productivity. During this process, five different batteries, two different PV systems and two different sizes of ice machines (3.54 kW and 5.3 kW) were considered. The financial limit was initially set at 74,600 €, indicated by the red horizontal line, i.e., the maximum available capital expenditure (CAPEX).

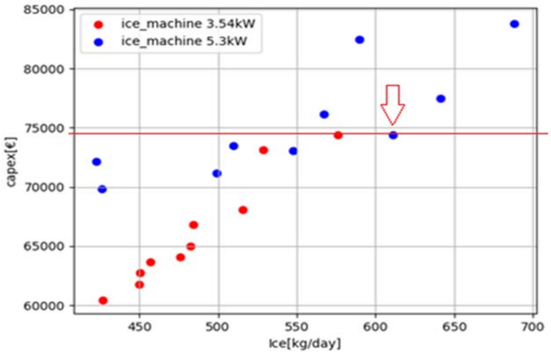


Figure 3. Initial investment vs. the average daily ice production

Finally, the system was chosen to have the following capacities (indicated by the red arrow in Figure 3):

TABLE 1. System selection

Component	Capacity
PV System	15 kW
Battery System	14.4 kWh
Ice Machine	5.6 kW*
Max Capacity (24 hours)	1500 kg

*The tropical version of the ice machine consumes 5.6 kW

III. RESULTS

The system was simulated to check the feasibility in accordance with the available PV power potential in Kenya. The system is planned to be set up in the Mwazaro town, and the climate data used to simulate the system was taken from the Meteonorm climate database and from the MERRA-2 satellite provided by NASA.

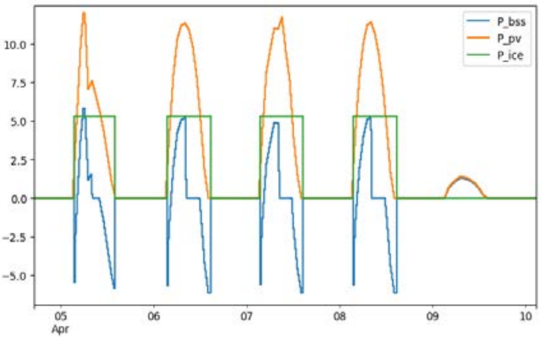


Figure 4. Example of daily power plots. Orange: PV power production, Blue: Battery power charge/discharge, Green: Ice machine power consumption.

Figure 4 shows that during daytime the PV system produces enough energy to run solely the ice machine and recharges the battery. The battery supports the system in the mornings to start-up the ice machine and in the evenings to keep it running longer. Night operations are avoided to decrease the investment.

Figure 5 shows the expected daily ice production vs the PV energy production, sorted from low to high. The ice production mostly higher than 600 kg/day. However, lower PV production will result in lower ice production.

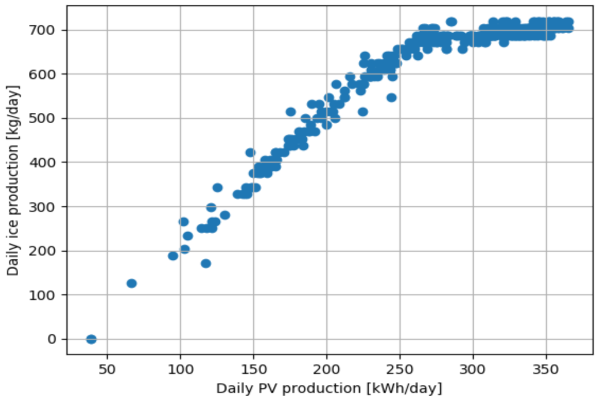


Figure 5. Expected daily ice production vs. daily PV energy production

Figure 6 shows that the yearly average for ice production is 610 kg/day. According to the graph the ice production decreases between April – June (rainy season), and October – February (higher cloud coverage).

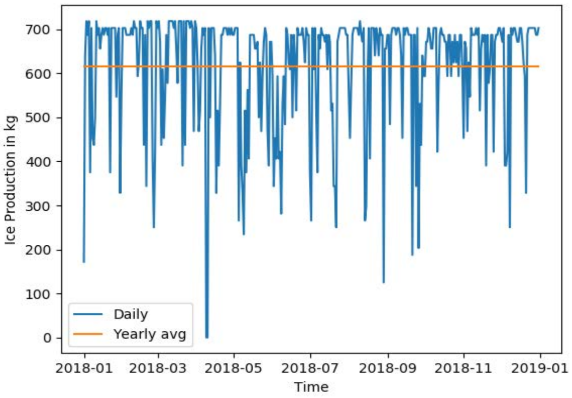


Figure 6. Daily sums and yearly averages for ice production

IV. ECONOMIC ANALYSIS

To calculate the feasibility of this project a net present value (NPV) analysis was conducted.

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+r)^t} \ [€]$$

Where NCF_t is the net cash flow generated in year t, n is the expected lifetime of the system and r is the discount rate. To get an initial selling price a levelized cost of ice (LCOI) was calculated.

$$LCOI = \frac{\Sigma \, of \ Discounted \ \ Cash \ Flow \ Over \ Life \ time}{\Sigma \, of \ Produced \ \ Ice \ Over \ Life \ Time} = \frac{\sum_{t=0}^{n} [\frac{I_t+M_t}{(1+r)^t}]}{\sum_{t=0}^{n} [\frac{Produced \ \ Ice}{(1+r)^t}]} \ [€ / \text{kg Ice}]$$

Where I_t is the investment expenditures of the system in year t in euros, M_t is the operation and maintenance (O&M) cost of the system in year t in euros, r is the discount rate and n is the expected lifetime of the system in years. The LCOI includes all the cost margins of the value chain manufacturing, shipping, installation, O&M and battery replacement. Table 2 shows the system CAPEX and operational expenditure (OPEX).

TABLE 2. System Cost

CAPEX		**Annual OPEX**	
Battery	18,582 €	Battery O&M	280 €
PV System	29,703 €	PV O&M	600 €
Ice Machine	24,030 €	Staff Wage	1,190 €
Container	2,737 €	Water Costs	1,340 €
Shipping	10,000 €	-	-
Total	**85,052 €**	**Total**	**3,410 €**

With the calculated LCOI of 0.051 € for 1 kg ice, the NPV exceeds zero in the 19th year. Sensitivity analysis of NPV against different CAPEX in Figure 7 shows that, the shortest payback period of six years is achieved when the PV-battery system is financed by subsidies.

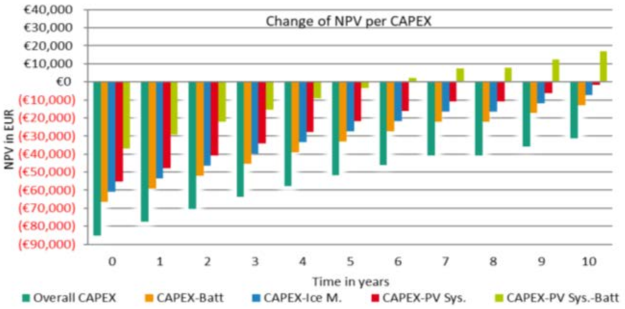


Figure 7. Change in NPV regarding different CAPEX costs

Further sensitivity analysis of NPV with varying ice selling prices shows that even the highest assumed selling price of 0.09 €/kg has a long payback period. Scaling down the system cost is a plausible solution to decrease the ice selling price, which can be achieved by using a smaller ice machine or excluding the battery. Without the battery, the system cost can be reduced by 40%.

TABLE 3. System Compilation

System Compilation	**CAPEX [€]**
Current system	85,052
PV-Battery with smaller ice machine	≈ 78,550
PV-ice machine system w/o battery	≈ 50,000

V. IMPLEMENTATION

Finally, the project was implemented along with a solar dryer-based drying system, as shown in Figure 8 and 9.

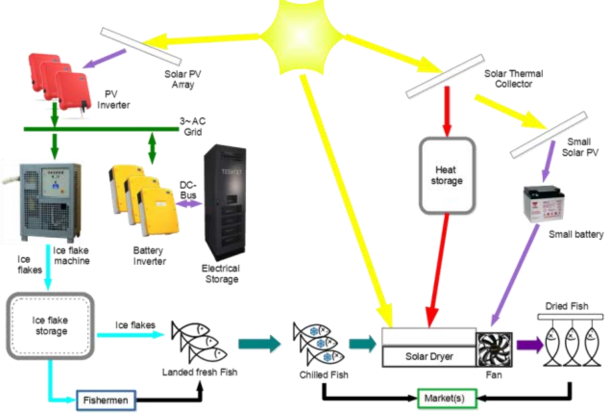
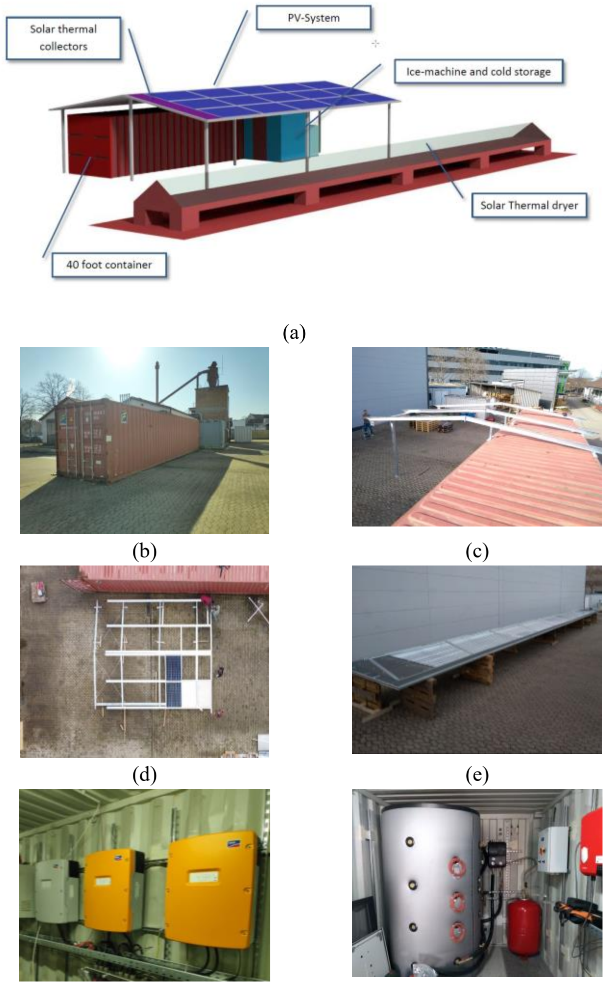


Figure 8. Final design of the overall system



(a)

(b) (c)

(d) (e)

(f) (g)

Figure 9. Construction of the prototype (a) conceptual design of the infrastructures (b) container (c) container with roof setup (d) PV setup on the roof (e) solar tunnel dryer (f) components inside the container (g) heat storage

The final system is composed of 15 kWp PV, due to the higher starting currents of the ice machine a 19.2 kWh Li-Battery which allows a higher maximum starting power, 12 m² flat plate collectors, and 2000 liter heat storage. For energy management, the OpenEMS is set up as shown in Figure 10.

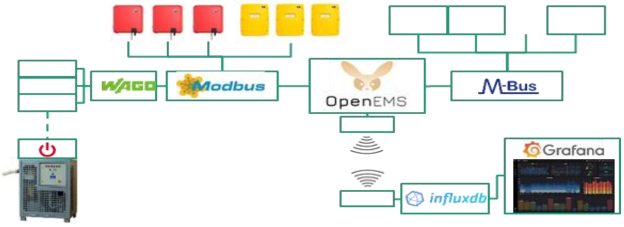


Figure 10. Overview of the energy management system

VI. LIFE CYCLE ANALYSIS

A life cycle analysis (LCA) was conducted to assess the CO_2 footprints of three different energy supply systems: (1) Pure diesel generator system, (2) grid connected system, (3) PV+Battery system. The results are summarized in Table 4.

TABLE 4. Total life cycle impacts in kg CO_2-eq/kg produced ice

System	kg CO_2/kWh$_e$	kg CO_2/kg ice	kg CO_2/15 year lifespan
Pure Diesel Generator	1.14	0.11	376,485.27
Grid Connected System	0.23	0.02	78,445.35
PV+Battery System	0.06	0.01	43,350.15

The pure diesel generator system has the highest, and the PV-battery system has the lowest CO_2 footprint.

VII. CONCLUSION

To summarize, the LCA shows that the PV-Battery system has more environmental benefits than any of the other systems examined. However, the economic considerations of the system should take subsidies and scaled down of investment costs into consideration to realize a feasible product in the future.

ACKNOWLEDGMENT

The authors want to thank Federal Ministry of Food and Agriculture of Germany, and the SolCoolDry project partners: Innotech (Germany), KIRDI (Kenya), KMFRI (Kenya), and TUM (Kenya).

REFERENCES

[1] Kenya/AFRICA- P163980- Kenya Marine Fisheries and Socio-Economic Development Project (MAFIDEV) - Procurement Plan (English). Washington, D.C. : World Bank Group. http://documents.worldbank.org/curated/en/307341514410256316/Kenya-AFRICA-P163980-Kenya-Marine-Fisheries-and-Socio-Economic-Development-Project-MAFIDEV-Procurement-PlanUNEP-Nairobi Convention and WIOMSA, The Regional State of the Coast Report: Western Indian Ocean, Nairobi, Kenya, 546 pp. 2015.

[2] H.N. Gartaula, Practices of participation in coastal area management: Experience from Kenya. Ocean & Coastal Management 2008, 51, 528–535.

[3] FAO, High food prices and food insecurity: Threats and opportunities. The state of food insecurity in the world, Vol. 9.2008, FAO, Rome 2008.

[4] G. Akande, Y. Diei-Ouadi, Post-harvest losses in small-scale fisheries: Case studies in five sub-Saharan African countries. FAO fisheries and aquaculture technical paper, Vol. 550, Food and Agriculture Organization of the United Nations, Rome 2010.

[5] Compact Machines-Remote-Ice Maker: Standard and Tropical Execution. Available at: https://www.hosbv.com/data/specifications/12798_Standard%20Englisch.pdf Accessed on: 03 March 2022.