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Utilization of a solar PV mini-grid powered cold storage to reduce fishery spoilage - A Tanzanian case

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ABSTRACT

Access to electricity is important for the development of rural areas in Sub-Saharan Africa. One area where better electricity access could contribute to development is reduction of spoilage of food. This article aims to understand how access to electricity can affect the spoilage of fish and the economical possibility to implement a communal cold storage unit connected to a solar PV mini-grid, as well as what technical requirements this would put on the mini-grid operation. The study is based on a case on the island Ukara in Lake Victoria, Tanzania. A techno-economic analysis is performed simulating a walk-in cold storage room connected to a solar PV mini-grid. The article also includes a qualitative analysis with a causal loop diagram illustrating the interlinkages between the system variables to identify the effects of electrification on the spoilage of fish. The findings indicate that it is economically feasible to implement a communal cold storage unit if an investor makes the initial investment and allows the fishers a pay-back period of at least one year and if a profit wants to be made more than 50 kg fish should be sold a day. Another finding is that the capacity of the mini-grid may need to increase to be able to cover the demand during periods of low solar PV generation. The cost for the mini-grid company becomes higher with the cooling unit during the high season of fishery, this is since the rain seasons correlate with this, and the solar radiation is low. The mini-grid operation cost is around 2.4 $/day higher with the cooling unit connected to the grid, it may be higher if the mini-grid owners decide to run the diesel generator instead to invest in higher capacity batteries and solar PV. The causal loop diagram indicates that access to electricity can be an important solution to reduce the spoilage of fish by enabling the use of cold storage. Moreover, electricity access allows the fishermen to use electricity for value addition of the fish, as the refrigerated fish have higher price than fresh fish. The spoilage has become zero when the fish is refrigerated.

Introduction

In 2018, roughly 600 million people in Sub-Saharan Africa lacked access to electricity. The rate of electrification in Africa outpaced the population growth for the first time between 2014 and 2018. There is however still a challenge to provide electricity to a rapidly increasing population (International Energy Agency, 2019).

A majority of the people lacking access to electricity lives in rural off-grid areas, where off-grid mini-grid systems may increase access to electricity (Hartvigsson et al., 2021). Renewable energy supplied by off-grid technologies is increasing in rural areas in Sub-Saharan Africa, where Tanzania is one of the leading countries for mini-grid deployment in the region, where particularly solar PV mini-grid deployment has increased rapidly (Odarno et al., 2017). Several studies conclude that linking implementation of mini-grids to business activities is important for rural development (Candelise et al., 2021; Katre et al., 2019; Pueyo & DeMartino, 2018).

Other studies have focused particularly on solar PV; Pueyo and DeMartino (2018) and Ogeya et al. (2021) investigated the usage and influence of solar PV mini-grids on businesses. Both studies concluded that solar PV mini-grids did not give the intended effects and that the electricity consumption remained low and the profit of businesses did not increase since the demand for the products and services produced remained low. Pueyo and DeMartino (2018) concluded that one reason for the continued low consumption is that 85 % of costumers comes from the area, and their main income is from agriculture. Since the profits from agriculture are low in general, they have limited economic resources and cannot afford the products and services produced. As a solution, Pueyo and DeMartino (2018) suggests that the mini-grids should be used more within agriculture to improve the profit of the sector. This

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could be done by utilizing the mini-grid electricity for refrigeration to increase the life of agricultural products, improve yields through irrigation and increase the access to markets by using energy to transport goods.

Food security is a major problem in Sub-Saharan Africa, and while the agricultural and fish sector stands for almost 20 % of total GDP in the region in 2020 (World Bank, 2020), the countries suffer from large post-harvest losses (PHL) (Affognon et al., 2015). Post-harvest losses are generally referred to as the losses that occurs in the field, during storage and processing, and transportation until it reaches the final costumer (Abass et al., 2014).

In a meta-analysis it was evaluated that an average of 27.3 % of fish was spoiled in Sub-Saharan Africa, where the majority of these losses were related to storage (Affognon et al., 2015). Additionally, several studies have reported that fishers sell their fish soon after catch at low prices due to lack of storage capability and economic pressure (Abass et al., 2014; Brander et al., 2021; Prodhan et al., 2022).

The lack of proper storage technologies can be seen for both crops and fish (Abass et al., 2014; Chan et al., 2019). Some of the main causes of PHL in fish are the high temperatures, delay before marketing and lack of storage facilities (Assefa et al., 2018; Prodhan et al., 2022). In the Lake Victoria Region some common preservation practices are hot smoking, deep-frying and sun-drying, which all leads to a decrease of nutrients and proteins, as well as to a lot of waste (Kabahenda et al., 2009). Improvements of the cold chain for fish are therefore needed to improve food security and contribute to income generation (Assefa et al., 2018; Chan et al., 2019; Ibengwe & Kristófersson, 2012; Prodhan et al., 2022).

Access to electricity through mini-grids could thus be part of a solution since it makes cold storage possible thereby reducing post-harvest losses and, hence, improving food security (Chan et al., 2019; Dasappa, 2011; Kabahenda et al., 2009). Few studies have investigated how storage that utilizes electricity, such as cold storage, can contribute to decreasing post-harvest losses in rural areas. A techno-economic study performed by Sadi and Arabkoohsar (2020) investigated different types of solar cells to power cold storage units to reduce PHL in India. The study assessed which type of solar cell was the best option both from an energy and economical point of view. The study concluded that by enabling access to electricity and cold storage, large amounts of food that would otherwise have been wasted could be stored with minimal waste being generated. Thus, farmers can provide more food for more people without expansion of the agricultural capacity. Sadi and Arabkoohsar (2020) also states that this problem is not limited to India, and that it is important to promote access to electricity and cold storage in similar countries with hot and humid climates to prevent PHL. Another case study, performed in Nigeria by Lamidi et al. (2019), focused on estimation of the economic profitability of using a biogas facility to power a cold storage and drying unit for different types of crops. By performing a techno-economic analysis, they suggest that it would have a positive effect on reduction of post-harvest losses.

However, there is still a lack of knowledge in the literature of how access to electricity in rural areas is interlinked with reduced post-harvest losses, particularly for fisheries where the losses of fish are high due to the lack of cooling opportunities (Assefa et al., 2018). There is also an information gap regarding what challenges fishers have in implementing cold storage as a possible solution to decrease the spoilage of fish.

Thus, this study aims to evaluate how electrification through mini-grids can contribute to reduced spoilage within the fishing industry in rural areas where access to electricity is limited, by enabling a joint cold storage room. Three specific research questions are addressed: 1. Would the implementation of a joint cold storage system utilizing electricity from solar PV mini-grids be economically beneficial for smallholder fishers? 2. What requirements would a connection of a cold storage system put on the operation of the mini-grid? 3. How does the access to electricity through mini-grids result in a decrease in spoilage of fish?

The study is based on a case in Tanzania, the village Bwisya on the island Ukara in Lake Victoria, where a solar PV mini-grid is investigated.

Method

The study combines various methods. A literature review was conducted followed by a field study (in Tanzania between March and April in 2022 (8 weeks)) focusing on gathering case specific information and information missing in the literature. Interviews were held with different stakeholders such as mini-grid companies, NGO's, as well as with local fishers from the island Ukara in Lake Victoria, Tanzania. The interviews were semi-structured with open-ended questions and were later transcribed and analyzed with Grounded Theory, an approach used to identify themes and contexts within different types of text (Luna-Reyes & Andersen, 2003). The data gathered in the literature review and through the field study were used for a techno-economic simulation of a cold storage room as well as for a qualitative analysis trough a causal loop diagram. The methodology is further presented in Sections 2.1 and 2.2. The methodological approach of the study is outlined in Fig. 1.

Techno-economic analysis

The techno-economic analysis is used to assess whether it is economically beneficial for the fishers to invest in a walk-in cooling room and how it is interacting with the operation of the mini-grid. It is based on a simulation of a cold storage room that is connected to a solar PV mini-grid to analyze the economic benefits for fishermen to invest in a communal cold storage room and what requirements this puts on the mini-grid operator. An overview of the calculations and methodology is shown in Fig. 2.

The first part of the calculations is the modeling of the cooling unit.

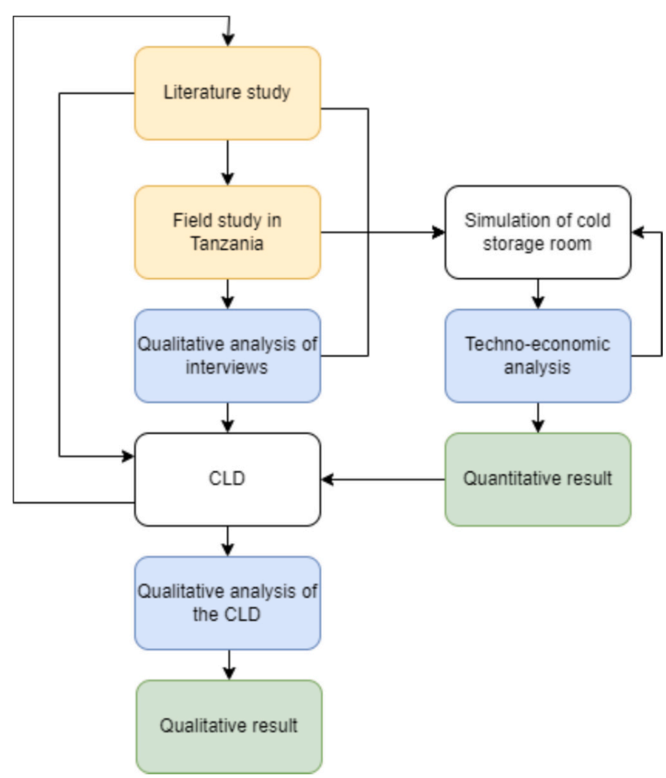

Fig. 1. Overview of the methodology. The yellow box represents the collection of information and data, the blue boxes are analysis steps, the white boxes are modeling, and the green boxes represent the results. CLD stands for causal loop diagram. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

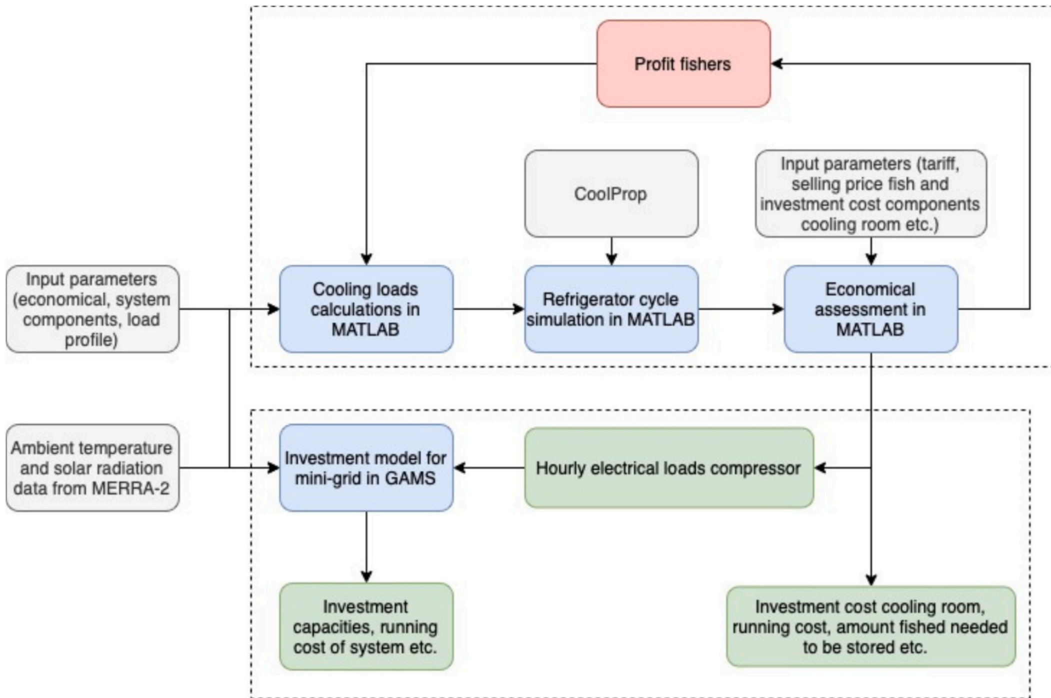

Fig. 2. The methodology for the techno-economic analysis. The gray boxes represent input parameters, the blue boxes the modeling, the green results and the red is an iteration that stops when a condition is fulfilled, e.g. profit for fishers. The dashed boxes show the system boundaries for the two system: the cooling unit (the upper box) and the mini-grid (the lower box). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This is done through an iteration where the cooling loads and refrigeration cycle are calculated and an economical assessment is made. The profit of the fisher is the stopping criteria of the iteration. The input parameters are shown in Fig. 2. When the profit in the iteration reaches the set criteria, the economical assessment of that iteration is used to create an investment model of the mini- grid.

Simulation of the cold storage unit

The aim of the simulation of the cold storage unit is to evaluate if it is economically beneficial for fishers to invest in a cooling unit and what compressor work the cooling unit has to do during one day with a resolution of one hour. The simulation consists of three different steps modeled in MATLAB.

First, the cooling loads are calculated for each hour. This is done by using ambient temperatures for Bwisya, taken from Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) though the web-page www.renewables.ninja where the calculations are based on the work of Pfenninger and Staffell (2016) and Staffell and Pfenninger (2016). The cooling unit is assumed to be a walk-in cooling room with a variable-frequency vapor compressor and the dimensions: 2.4 × 1.7 m × 2.5 m, and insulation according to Kabeel et al. (2016). The total cooling load is calculated though summation of the largest losses according to Hmida et al. (2019), to which 15 % is added to account for unknown heat gains (Uddin et al., 2022), as:

$$Q_{tot} = 1.15^{*}\left(Q_{wall} + Q_{bottom} + Q_{roof} + Q_{fish} + Q_{inf} + Q_{junction}\right) \quad (1)$$

where Q_{wall}, Q_{roof} and Q_{bottom} are the losses through the walls, the roof and the ground, respectively. Q_{fish} is the loss from cooling down the fish, Q_{inf} is the loss from the infiltration of air due to the door opening, and $Q_{junction}$ is the loss from the wall junctions, assumed to be 12 % of the thermal losses of the walls.

The second step is the refrigeration cycle simulations. This is done by using CoolProp, a library for refrigerants, to get the chemical characteristics of the cooling agent R134a. R134a was assumed to be the cooling agent as it is a common refrigerant (Uddin et al., 2022). In the refrigerator cycle there are four main components: condenser, capillary tube, evaporator and compressor (Meng et al., 2016). However, it is assumed that the compressor work is the only component that is contributing to the electricity usage since the contribution of the other components are not significant compared to that of the compressor. The compressor work is calculated by:

$$W_{compressor} = \frac{m_{ref}(h_{2a} - h_1)}{\eta_{mec}} \quad (2)$$

where m_{ref} is the mass of the refrigerant, h_1 is the enthalpy of saturated vapor before the compressor, h_{2a} is the actual enthalpy of the superheated vapor after the compressor, and η_{mec} is the mechanical efficiency of the compressor.

Finally in the third step, an economic assessment was done based on the investment cost of the cooling room unit and the running cost. The running cost depends on the tariff for productive usage, the amount of fish caught and the selling price of fish. Thus, to evaluate the amount of fish that is needed for payback of the cold room during one year, an iteration of the amount of fish that needs to be caught for the different cases was done. One year was chosen since this is the pay-back time ELICO Foundation often applies for their projects (Head of Programmes and Operations, ELICO Foundation, 2022). It was assumed that all the fish stored in the cooling unit was sold.

The investment of the cold room mostly depends on the four main components: compressor, capillary tube, condenser and evaporator (Sanaye & Malekmohammadi, 2004) where the investment cost of the compressor in ($) is calculated as (Roy & Mandal, 2019):

$$CAPEX_{compressor} = 10167.5^{*}W_{compressor}^{0.46} \quad (3)$$

The investment cost for the capillary tube (in $) is calculated according to Roy and Mandal (2019):

$$\mathrm{CAPEX}_{\mathrm{capillary}} = 114.5^{*}\dot{\mathrm{m}}_{\mathrm{R134a}} \quad (4)$$

The investment cost for the four components is summarized to get the total investment cost of the cold room as:

$$CAPEX_{cold} = CAPEX_{capillary} + 3*CAPEX_{compressor} \tag{5}$$

The investment cost of the evaporator and condenser is assumed to be the same as for the compressor (Sanaye & Malekmohammadi, 2004). The running cost of the cold storage unit for one day is calculated using Eq. (6):

$$OPEX_{cold} = \sum_{1}^{23} \frac{W_{compressor}(t) + W_{compressor}(t+1)}{2} * Tariff \tag{6}$$

where $OPEX_{cold}$ is the OPEX for the cold storage room in $. The summation gives the total electricity usage from the cooling room for one day, where the compressor work is calculated by using Eqs. (1) and (2). The amount of fish needed to be sold to get a certain profit for the fishers is calculated by the following inequality:

$$Profit_{fishers} \leq \frac{CAPEX_{cold}}{365} + OPEX_{cold} - P_{fish}*F \tag{7}$$

where $Profit_{fishers}$ is the profit for fishers in $, k is the fish price in $/kg, *Tariff* is the tariff level in $ and F is the amount of fish needed to be sold to get that certain profit in kg and is the variable that will be iterated. The iteration will start by guessing a value of F, then the Eqs. (1) to (7) is iterated until the statement in Eq. (7) is fulfilled.

Investment model of the mini-grid

With the compressor work from the simulation of the cooling unit, an investment model is used to understand how the electrical consumption from the compressor influences the operation of the mini-grid, illustrated in Fig. 2. The investment model is calculated using GAMS. It considers the possibility to invest in more capacities in solar PV:s, batteries, and diesel generators. It also includes the running cost of the diesel generator. The optimal solution of the system is obtained by minimizing the running cost of the mini-grid in one day by including the annualized daily investment cost of the three technologies and the running cost of the diesel generator.

The objective function of the model is to minimize the investment and running cost of the mini-grid in Bwisya C_{tot} for the system with and without the cooling room load as:

$$\begin{aligned} C_{tot} =& CAPEX_{bat,an}*Cap_{bat,invest} + (CAPEX_{PV,an} + OPEX_{PV})*Cap_{PV,invest} \\ &+ CAPEX_{diesel,an}*Cap_{diesel,invest} + OPEX_{diesel} \end{aligned} \tag{8}$$

where $CAPEX_{i,an}$ is the annualized CAPEX of the solar PV per day, battery and diesel generator, respectively, in $/kW*year. $OPEX_{PV}$ is the operational expenses of the solar PV in $/kW day for the new solar PV installed. $OPEX_{diesel}$ is the operation expenses of the diesel generator in $/day. The annualized capital investment is consider instead of capital recovery investment, since that payment method is used for the mini-grid in Ukara (Executive Director, ELICO Foundation, 2022; Team, 2020). $CAPEX_{i,an}$ is calculated as:

$$\text{CAPEX}_{i,an} = \frac{CAPEX_i*AF_i}{365} \tag{9}$$

where the $CAPEX_i$ is the capital expenses of the component *i*. *AF* is the annuity factor for unit i and is the present value of a cash flow. The annuity factor is calculated by

$$AF_i = \frac{r}{1-(1+r)^{-N_i}} \tag{10}$$

where r is the discount rate and N_i is the component lifetime in years. The $OPEX_{diesel}$ is calculated with equation

$$OPEX_{diesel} = \sum_{1}^{t} Gen_{diesel}(t)*(OPEX_{men} + OPEX_{diesel,running}) \tag{11}$$

where the $Gen_{diesel}(t)$ is the power production from the diesel generation at time t in kW, the $OPEX_{men}$ is the operational expenses for maintenance of the diesel generator in $/kWh and the $OPEX_{diesel,running}$ is the expenses for buying and transporting the diesel in $/kWh.

The $SoC_{initial}$ is the initial storage level of the battery when the model starts running, the unit is in kWh. The battery level is modeled according to Soroudi (2017). The storage level of the battery must be the same as when the model started, for example at time 24 (Soroudi, 2017), which gives the equation

$$SoC(t=24)*SoC_{initial} \tag{12}$$

The levelized cost of electricity (LCOE) is calculated as (Ahmad et al., 2023):

$$COE = \frac{\sum i\left(\frac{CAPEX_i}{N_i} + OPEX_i\right)*Cap_i*(1+r)^{-N_i}}{\sum_{1}^{23} E_t*(1+r)^{-N_i}} \tag{13}$$

where the LCOE has the unit dollar/kWh and E_t is the energy consumption in kW/day. The energy consumption is the summation of the load for the mini-grid and the energy consumption from the cold room. Table 1 is presenting values for some of the parameters used in the model together with the corresponding source.

Causal loop diagram

Rural electrification affects several parts of the community, such as education, health, agriculture and enterprises, but it is also affected by the same factors in return (Hartvigsson et al., 2020). Due to these interlinkages between variables, Hartvigsson et al. (2020) suggests a framework where conceptual system dynamics are used to aid in tackling complexity and problem formulation. The purpose of the analysis is to understand how access to electricity can be used to reduce the spoilage in fish.

For this study a causal loop diagram (CLD), according to the framework presented by Hartvigsson et al. (2020), is used to analyze the dynamics of the system. Through a literature review, an initial CLD is built for basic understanding of the system. As more information is gathered through the field study and the techno-economic analysis, the initial CLD is re-evaluated and the scope narrowed, producing the final CLD. Vensim® was used to make the conceptual model of the system.

The final CLD is analyzed by analysis of the systems behavior

Table 1
The values for some of the parameters used in the model and the corresponding source.

Parameter	Value	Unit	Source
η^{ch}	95	%	Soroudi (2017)
η^{dis}	90	%	Soroudi (2017)
$Cap_{PV,ex}$	60	kW	Head of Operations, JUMEME (2022)
$Cap_{bat,ex}$	60	kWh	Head of Operations, JUMEME (2022)
$Cap_{diesel,ex}$	42	kW	Head of Operations, JUMEME (2022)
$CAPEX_{diesel}$	450	$/kW	Wilson (2018)
$OPEX_{diesel,running}$	3.85	$/kWh	Local technician, JUMEME (2022)
$OPEX_{diesel,men}$	0.04	$/kWh	Uddin et al. (2022)
$CAPEX_{PV}$	2145	$/kW	Abid et al. (2021)
$OPEX_{PV}$	$\frac{10}{365}$	$/kW*day	Tsai et al. (2020)
$CAPEX_{bat}$	129.2	$/kWh	Wilson (2018)
DOD	80	%	Huneke et al. (2012)
N_{diesel}	13	years	Wilson (2018)
N_{bat}	5	years	Head of Operations, JUMEME (2022)
N_{PV}	25	years	Tsai et al. (2020)

through identification of balancing- and reinforcing loops in the system. Whether the loop is balancing or reinforcing is determined by identifying the polarity of the loop. The polarity of the loop was identified by assuming a small change in one of the variables and tracing the effect as it propagates around the loop (Sterman, 2000).

Case, data and assumptions

The case that this study is based on is presented below, together with data from the interviews and assumptions made in the simulations. The methodology described above is applied to two different simulation cases which are specified in Section 3.3.

Case

The evaluated mini-grid in this study operates in the village Bwisya, located on the island Ukara in Lake Victoria. It has a population of around 6000 people (Pueyo et al., 2020). Further, it has primary and secondary schools, local government offices, and mobile phones and television signals. There are also daily ferry connections between Bwisya and the larger island Ukerewe from which another ferry continues to Mwanza, the second largest city in Tanzania.

Since April 2016, JUMEME Rural Power Supply Ltd. operates a solar hybrid mini-grid in the village. The solar hybrid mini-grid has an capacity of 102 kW where 60 kW is solar PV capacity and 42 kW is allocated to the diesel generator. It was mainly financed by a European Union grant (Pueyo et al., 2020). The installation capacity has increased from the first installation. The old diesel generator of 35 kW was replaced with a 42 kW generator in 2020. The initial battery with a capacity of was 60 kWh was replaced in 2021 when the battery life-time was reached with a battery of only 40 kWh (Head of Operations, JUMEME, 2022).

When a customer wants to use electricity from the mini-grid, they pay for a certain bundle, depending on the amount of electricity they want to use. JUMEME have three different tariff levels that depend on the type of consumer and bundle: household (HH), commercial usage (CU) and productive usage (PU) (Cluster manager, JUMEME, 2022). These bundles and the tariffs for different time periods in Bwisya from the start are presented in Table 2. The PU has the highest electricity consumption since they use it for larger machines for business purposes, such as milling and carpentry.

In 2020, the energy minister of Tanzania made a statement that all the mini- grid operators had to charge 100 TZS per kWh for households, the same price as the subsidized main grid (Chair person TAREA, 2022). This is the first tariff change seen in Table 2. This new regulation led to lower tariffs, which in turn resulted in decreased services since it was no longer profitable for JUMEME to run the diesel generator in Bwisya. The reliability of the mini-grid thus decreased and the provision of electricity changed from 18–24 h a day to 9–13 h per day (Head of Operations, JUMEME, 2022; Local technician, JUMEME, 2022). In addition, in 2021 the batteries connected to the mini-grid needed to be replaced, but due to the decrease in revenue since 2020, JUMEME took batteries from another mini-grid. The capacity of the batteries was therefore reduced to 40 kWh (Head of Operations, JUMEME, 2022).

Due to the decreased services of the mini-grid, JUMEME agreed with the community in Bwisya to increase the tariffs in 2021, the second tariff change in Table 2, in an attempt to get a more reliable power supply. However, there was a limit put on the amount of electricity the costumers were allowed to purchase since the mini-grid could not satisfy the demand without causing an even higher unreliability (Cluster manager, JUMEME, 2022). The increase in tariffs were however not accepted by the Tanzanian government and JUMEME had to go back to the low tariffs again (Former cluster manager, JUMEME, 2022).

The mini-grid in Bwisya is connected to two villages (Former cluster manager, JUMEME, 2022), where 16 % of the costumers are productive users operating heavy-load devices such as milling machines (Pueyo et al., 2020).

The interviewed fishermen in Bwisya have been provided with small solar powered fridges, not connected to the mini-grid, to store fish. These fridges were provided by ELICO Foundation at a subsidized cost. The prices of fish changes between seasons because of the varying amount of fish caught. During the rainy season the amount of fish caught is high resulting in low revenues per unit sold fish. When the amount of fish is scarce during the dry season the prices rise again. Table 3 shows the amount of fish caught as well as price differences before and after the fishermen started using the cold storages. Table 4 presents the answers from the fishermen when they were asked how much waste they experienced without and with the solar powered fridges.

Data and assumptions

The price of the fish in the simulation was set according to Table 3 "With fridge", which is 6000 TZS/kg fish. The tariff level for the productive usage was set to 40,000 TZS/kWh as this is the price that JUMEME most likely will go back to without the restriction from the government (see Table 2). It is assumed that an external party, like an NGO as ELICO Foundation, invests in the construction of a cold storage unit and that the fishermen utilizing the unit are allowed a payback time of one year. An interest rate of 7 % for the investment was considered (Focus economics, 2022).

The load profile is generated by using a tool produced by Reber et al. (2018), which generates an hourly load profile specifically for the Sub-Saharan Africa region. It is assumed that the percentage between low, medium and large income households are divided equally. The rest of the input data is provided by Head of Operations, JUMEME (2022) where the given costumer amount is presented in Table 5. The average daily electricity usage used was 87 kWh (Head of Operations, JUMEME,

Table 2
The tariff levels for the three different costumer groups (Households (HH), commercial users (CU) and productive users (PU)) for the mini-grid in Bwisya for different time periods. The usage constraints are also included.

Time period	Costumer	Price [TZS/kWh]	Limitation [kWh/week]
2017	HH	3500	–
–	CU	2500	–
2020	PU	750 (+10,000 TZS Month)	–
2020	HH	100	–
–	CU	100	–
2021	PU	356	–
2021	HH	2000	1
–	CU	4000	2
	CU	10,000	5
2021	PU	40,000	50
2021	HH	100	1
–	CU	610	5
2022	PU	17,560	50

Table 3
The amount of caught fish in different seasons and the change in price before and after being able to store the fish for the interviewed fishermen in Bwisya.

Fisher interview		Amount of fish caught [kg/day]	Price [TZS/kg]	
1	Dry season	1	Before fridge	3 000
	Rain period	30	With fridge	6 000
2	Dry season	8	Before fridge	3 000
	Rain period	30	With fridge	6 000
3	Dry period	–	Before fridge	3 000
	Rain period	40	With fridge	6 000

Table 4
The spoilage of fish for the three interviewed fishermen and what the difference is without and with the solar powered fridge.

Fisher interview	
1	No waste with the freezer, before it could be around 2–3 kg of fish
2	Not experienced any waste with the freezer, a little waste before
3	With the freezer there is no waste. But with the electricity runs out the waste can be up to 10 kg of fish

Table 5
The costumers information given by Head of Operations, JUMEME (2022).

Costumer	Amount
Households	225
Milling	5
Schools	2
Clinics	2
Small shops	24

2022). This data is used to fit the hourly load profile generated from Reber et al. (2018).

Simulation cases

The simulation of the mini-grid system was made for two simulation cases to understand the dynamics of the system. The factors that differs between the two simulation cases are profit for the fishers and solar radiation.

The first simulation case was evaluated for the high and low season for fishery, corresponding to the two seasons in fishery according to the interviews. The high season of fishery is during the rainy season. Thus, the lowest solar radiation was assumed. The low season is during the dry period, when a day with high solar radiation was assumed. In the first simulation case, the fishers got no profit as to evaluate the seasonal differences. This comparison is made for a case when the cooling room is only loaded during the morning at 6 am and cooled down to 4 °C at 5 pm.

The second simulation case evaluates how the profit from the fisheries influences the system. This simulation case only considers the high season when the solar PV production is low. Two types of scenarios of loading the fish where simulated, in the first scenario the fishermen loads the cooling room during the morning at 6 am and in the second scenario the fish is loaded both during the night and the morning at 0 am and 6 am. In both scenarios the fish is cooled down to 4 °C by 5 pm.

The solar radiation variation for the two simulation cases is presented in Appendix Figs. A.2 and A.3. The temperature variation is presented in Appendix Fig. A.1. The solar radiation and temperature data are from MERRA-2 released by NASA's Global Modeling and Assimilation Office. MERRA-2 has been validated to have good quality for temperature and solar radiation by Hearty et al. (2018); Ahmad and Zeeshan (2022); and Gupta et al. (2020).

Result

Techno-economic analysis

The techno-economic assessment for the first simulation case is calculated for both the dry and rainy season for an investment cost payback time of one year. Table 6 presents the results based on the Eqs. (5)–(7). The numbers presented is the investment cost ($CAPEX_{cold}$), the running cost ($OPEX_{cold}$), and amount of fish needed to be sold per day (F) to cover the running cost and the investment cost, as well as the energy consumption of the cooling unit which is the total electricity usage for the compressor for one day.

Table 6
The table shows the results of the techno-economic assessment for the first simulation case for the investment of a cooling room and the amount of fish needed to be sold to cover the running costs and the investment cost with a payback time of one year. This is presented for the dry and rainy season.

	Dry season	Rainy season
Fish needed to be sold [kg/day]	55	47
Energy consumption [kWh/day]	5.6	4.6
Running cost [$/day]	96	80
Investment cost [$]	17,000	15,000

According to the results, shown in Table 6, the investment cost of the cooling unit will be 2000 $ higher if it is based on the conditions during the dry season. This is correlated with the need for a bigger compressor to handle the higher ambient temperature, see Fig. A.4 in Appendix. This is also the reason the energy consumption of the cooling room is higher during the dry season, 1 kWh higher per day than during the rainy season. This implies that the amount of fish needed to be sold in the rainy season is smaller. The amount of caught fish of 47 kg corresponds to about 1.5 fishers catch per day based on the amount of caught fish per fishermen, see Table 3, which is around 30 kg per fisher during the rainy season. This means that two fishers need to collaborate to be able to reach that amount. While for the dry season, where the fishers need to catch 55 kg per day, it is difficult to obtain since the fisher often only catches 1 kg each since this is the low season in fishery.

Moreover, the requirements for the mini-grid according to the modeled system in the first simulation case, with and without the cooling unit connected, are presented in Table 7. It is calculated using the investment model described by Eqs. (8)–(12).

The modeled system presented in Table 7 shows that there is no need for the mini-grid operators to invest in extra capacities or run the diesel generator during the dry season since the capacities are the same as the initial system in Bwisya. However, for the rainy season the model simulations show that investments are needed both with and without the cooling unit. According to the model, it is more profitable for the for mini-grid operator to invest in solar PV and battery capacity rather than running the diesel generator. The existing mini-grid in Bwisya has the diesel generator running when the solar PV generation is low, which explains why the electricity is still provided during the rainy season. According to Table 7, an additional 12 kW solar PV capacity is required to cover the load during rainy season, with the cold room another 4 kW is required. 2 kWh extra capacity of batteries is required for the rainy season since the solar PV generation is lower, and with the cooling room another 4 kWh is required. This makes the cost for the mini-grid company 2.4 $/day higher when the cooling unit is connected. The LCOE is lower during the dry season, thanks to the mini-grid's lower capacity. If the diesel generator is running, the LCOE increases considerably, and the LOCE would be approximately doubled during the rainy season with a cold room if the mini-grid would operate with today's capacity.

The result of the second simulation case for the two different scenarios of loading of fish in the cooling room is presented in Table 8 with

Table 7
The table presents the modeled system and the running cost of the mini-grid according to the first simulation case where there is no profit for the fishers. The table also shows how the system differs with and without the cooling unit connected to the mini-grid.

	Dry season		Rain season	
	Without	With	Without	With
PV capacity [kW]	60	60	72	76
Battery capacity [kWh]	60	60	62	66
Diesel capacity [kW]	42	42	42	42
Diesel generation [kWh]	0	0	0	0
C_{tot} [$/day]	0	0	6.8	9.2
LCOE [$/kWh]	0.26	0.26	0.31	0.31

different profits for the fishers for the rain season when the solar PV generation is at its lowest.

The amount of fish needed to be sold to get a specific profit is not affected by when the fish is loaded, see Table 8. The amount of fish needed to be caught for a profit of 500 $ is 250 kg, which corresponds to the catch from approximately eight fishers per day. The cost for the operation of the mini-grid is increasing when the profit is higher, which is correlated to a higher energy requirement coming from the higher amount of fish stored. This can be seen in the Figs. A.5 and A.6 in the Appendix. As can be seen in Table 8 there is no significant differences in the capacity needed for the mini-grid to compensate for the loading of fish once or twice per day, indicating that the load profiles of the two scenarios does not differentiate enough from each other to affect the load of the mini-grid. This is also reflected by the lack of variation of the LCOE between the scenarios.

Causal loop diagram

The following section will present a qualitative analysis that will give insight to the interlinkages between the access to electricity and the decreased spoilage in fish. It conceptualizes the system that the techno-economic analysis in Section 4.1 is based on, and the conclusions in the previous section are added to the qualitative results. The causalities between the different variables in the system are presented by a causal loop diagram (CLD) in Fig. 3. Table B in the Appendix explains all the relationships in the CLD shown in Fig. 3.

The *Electricity access* provides opportunity to use cold storage (*Cold storage opportunities* in Fig. 3) as a preservation method (Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022; Mramba & Mkude, 2021; Nuru et al., 2021). However, an important aspect to consider is the *Reliability* of the electricity since there is a high risk of the fish going bad during a blackout (Former cluster manager, JUMEME, 2022). If the electricity is reliable enough and the fishers have the opportunity to utilize cold storage they will most likely do so due to the increased *Access to markets*, decreased *Spoilage in fish* and *Pressure to Sell*; all leading to an increase in *Income* and the possibility to expand business further (Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022; Former cluster manager, JUMEME, 2022). In recent years, however, the *Reliability* of electricity in Bwisya has decreased, and in an interview with the local technician from JUMEME he said that the costumers had started to harass and threaten him because of the blackouts (*Technician harassment* in Fig. 3).

An important aspect in the system is the awareness of the mini-grid investor about the community that the mini-grid will be installed in (Executive Director, ELICO Foundation, 2022). Most of the people in rural areas are not aware of the benefits of electricity, so it is important to show the people what electricity can be used for. Increase in the *Costumer awareness* therefore leads to an increase in *Productive usage of electricity* which is the usage of a larger amount of electricity in a business, for example refrigeration of fish, milling or carpeting.

Table 8
The table shows the result from the second simulation case with different levels of profit per day. This is done for the rainy season.

	Loading morning			Loading night & morning		
Profit levels for fishers [$/day]	0	300	500	0	300	500
Fish needed to be sold [kg/day]	47	170	250	48	170	250
PV capacity [kW]	76	77	77	76	77	77
Battery capacity [kWh]	66	66	67	66	67	67
Diesel capacity [kW]	42	42	42	42	42	42
Diesel generation [kWh]	0	0	0	0	0	0
C_{tot} [$/day]	9.2	9.5	9.7	9.2	9.6	9.8
LCOE [$/kWh]	0.31	0.31	0.31	0.31	0.31	0.31

Moreover, *Electricity access* allows the fishermen to use electricity for *Value addition* of the fish by, for example, refrigeration and drying of the fish (Das & Behera, 2020; Executive Director, ELICO Foundation, 2022; Head of Programmes and Operations, ELICO Foundation, 2022). Using electric equipment to dry the fish reduces spoilage, since fish would otherwise lie on the ground to sun dry and expose it to both sand and birds (Das & Behera, 2020; Gyan et al., 2020; Kabahenda et al., 2009). Furthermore, drying fish using solar powered drying facilities increases the quality of the product and thus increases the price, and therefore the *Income* and thus the *Ability to pay* (Head of Programmes and Operations, ELICO Foundation, 2022). If the *Ability to pay* is increased, this would also lead to an increased amount of *Productive usage of electricity* (Executive Director, ELICO Foundation, 2022; Jumeme costumer 2, 2022). Several studies also suggest that better *Education* can lead to a decrease in *Spoilage of fish* (Acharjee et al., 2021; Gyan et al., 2020).

Based on the techno-economic analysis in Section 4.1 there is a positive causality between *Financial assistance* and *Cold storage opportunities* due to the high investment cost of a cold storage unit. It is therefore necessary for an investor to invest in the technology so that the fishermen can pay back the cost over a set period. The techno-economic analysis also supports the positive relationships between *Productive usage of electricity* and *Mini-grid capacity* as well as *Mini-grid capacity* and *Mini-grid investment cost*. According to the cluster manager at JUMEME, there is a positive causality between the *Tariff* and the *Profit from mini-grid*, i.e. if the tariffs increase, so does the profit, unless the tariffs are too low for there to be any profit at all (Cluster manager, JUMEME, 2022). Based on the interviews and literature study performed, there is no indication that the *Profit from mini-grid* and *Mini-grid investor awareness* are correlated.

Fig. 3 shows that there are several feedback loops in the system. When the opportunity to use cold storage increases it will cause more fishermen to utilize the cold storage since this technology has many benefits. As more cold storage is used it leads to decreased pressure to sell the fish since it can be preserved for a longer time, hence making it possible to increase the income by charging a higher price. It also directly decreases the spoilage of fish and makes it possible for fishermen to expand their business into new markets farther away, which also leads to reduced spoilage since more fish can be sold, thus increasing the income. Since the majority of people in these rural areas are poor, the possibility to earn a higher income has a large effect on their ability to pay, thus increasing the possibility to expand their business by buying more cold storage. These effects that *Cold storage opportunities* have on the income and spoilage of fish are described by the reinforcing feedback loops *R1*, *R2* and *R3*. However, the cost for the utilization of the cold storage decreases the ability to pay and in turn the possibility to use the cold storage. This is represented by the balancing feedback loop *B1*.

The utilization of cold storage is also balanced by the demand described by *B2* since the demand for cold storage will eventually become saturated. For the case in Bwisya it may however take a while for the demand to be saturated due to the low capacities that the fishermen have today (Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022). All the interviewed fishermen expressed that they wanted to expand their business but that required more storage space. The demand of cold storage is also limited by the quantity of fish caught; here it is important to make sure that the fish population does not decrease over time due to over-fishing. The balance between *Fish caught* and *Fish population* is described by *B3*.

An increase in *Productive usage of electricity* for the use of, for example a cold storage room, may also require an increase in the *Mini-grid capacity* which was shown in the techno-economic analysis. The techno-economic analysis also showed that this will lead to investment costs for the mini-grid which, according to the CLD in Fig. 3, will lead to an increase of the *Tariffs*. Higher *Tariffs* in turn cause lower consumption of electricity due to the limited ability to pay. This is described by feedback loop *B4*.

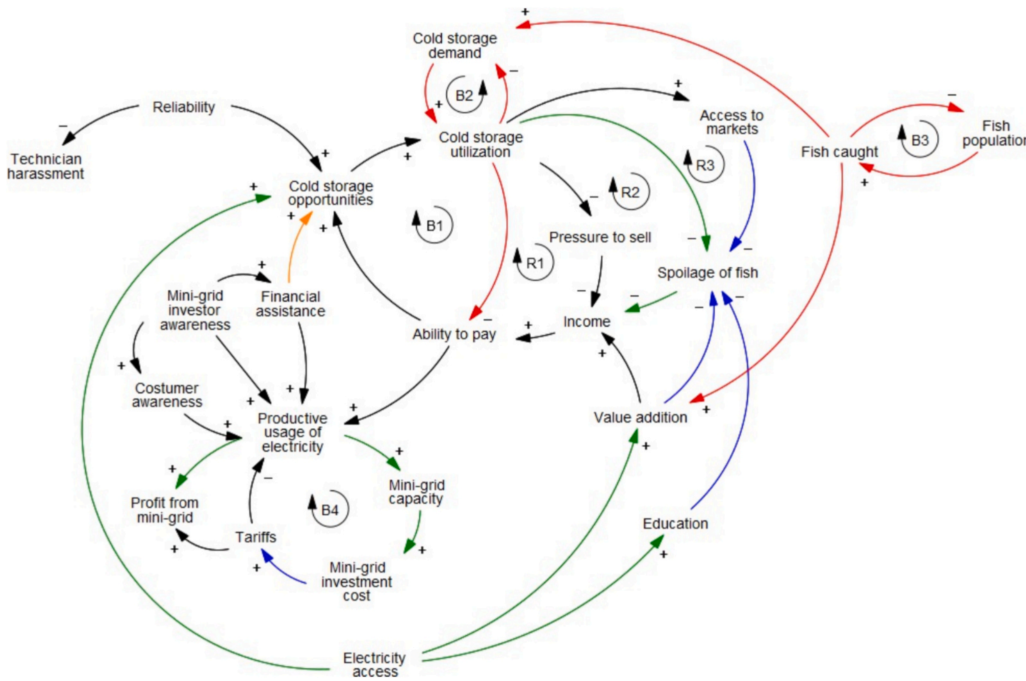

Fig. 3. Causal loop diagram of the system related to the ability to use cold storage to preserve fish. It consists of three reinforcing feedback loops and four balancing feedback loops. The black arrows represent information from interviews, blue arrows represent information from the literature study, the green arrows are information that is confirmed by more than one source, the red arrows are based on assumptions and the orange arrow represents results from the techno-economic analysis. See Appendix B for a summary of the feedback loops and a complete list of the references for the causalities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The three reinforcing feedback loops of the system, *R1*, *R2* and *R3*, positively correlate the opportunity and utilization of cold-storage to an increase in income and, therefore, ability to pay. The balancing feedback loops *B1* and *B2* shows that the system is balanced as the utilization of cold storage comes with a cost for the fishermen, as well as a saturated demand. For the case in Bwisya, it may however take a while for the demand to be saturated due to the low capacities that the fishermen have today (Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022). The system is also balanced by the feedback loop *B4*, since the increase in tariffs, due to increase in the mini-grid capacity, puts a limit to the system for how much productive usage of electricity the fishermen can afford.

Discussion

The results from the techno-economic analysis indicate that if an investor makes the initial investment of a cold storage unit connected to a mini-grid, it can be economically feasible for the fishermen to pay back the investment within one year if they collaborate. Moreover, the causal loop diagram (CLD), Fig. 3, points to the importance of awareness of the mini-grid operator, as well as the investor, regarding challenges related to electricity utilization in rural areas. The CLD shows that, for the productive usage of electricity to increase, the mini-grid operator needs to educate their customers about the advantages of electricity usage. In addition, it can be seen in the CLD that by utilizing a cold storage, the income will most likely increase. An increase in income indicates that it is economically beneficial to make this investment and, according to the techno-economic analysis, it can be possible to cover the investment cost over a pay-back time of only one year. Such a short pay-back time might increase the willingness to invest.

The techno-economic analysis also shows that, even with higher tariffs than the current ones, it is economically possible for the fishermen to utilize the cold storage unit. Thus, investment is less sensitive to changes in the tariff level. During the rainy season, at least two fishermen must cooperate to cover the costs, as the required catch of fish is high. However, it can be more difficult during the dry season when the catch is scarce, and this needs to be considered by the investor. However, even though the system in this study focuses on fish, the variables described in the CLD in Fig. 3 can also be applied to the agricultural sector, as the mechanisms behind food waste are similar. Therefore, it could be a possibility for both farmers and fishers to utilize the cold storage, but at different times of the year.

A profit of 500$ per day, as assumed in the second simulation case, is high for businesses in rural areas, but it needs to be considered that there are several fishermen that split the profit. In addition, the fishermen may have other cost to cover such as fishing nets or salaries if there are people working on the boat.

The implementation of a cold storage room would significantly increase the productive usage of electricity by the fishermen according to the techno-economic analysis. It also shows that the mini-grid operators need to invest in more solar PV and battery capacity to be able to power the cold storage room, specifically during the rainy season when there is low solar PV generation, while for the case when the solar PV generation was high in the dry season, the capacity did not need to be increased since the solar PV produced enough electricity to satisfy the demand. Moreover, it is more economically beneficial to invest in more solar PV and batteries than to run the diesel generator when the solar PV generation is low. This may, however, be because the model is only running for one day. If the model was run over a year, the results might be different since the solar PV generation varies during the year. The investment cost for extra capacity might however be too high for the mini-grid operators to cover, which may be the reason why they choose to run the diesel generator since that cost is easier to cover in the short-term.

By implementing a cold storage unit, the spoilage of fish can be reduced, as shown in Table 4. The importance of access to electricity to reduce this spoilage in several ways is illustrated in the CLD in Fig. 3. First, access to electricity provides an opportunity to use cold storage that directly leads to a reduction in spoilage, but also through increased access to markets. Secondly, it also gives the possibility to use electric equipment to reduce the spoilage through value addition. Thirdly, it has also been shown that electricity results in a higher quality of education and in several studies have concluded that better education leads to reduced spoilage (Acharjee et al., 2021; Gyan et al., 2020).

This shows the importance of electricity in fishing communities in rural areas to reduce the spoilage of fish, but as can be seen in Fig. 3, this also results in a higher income. In these rural areas a higher income would lead to a higher economic status and significant improvement in standards of living (Fishermen 1, 2022; Lukuyu et al., 2019). This also implies possibilities for continued business growth and increased quality of life.

Furthermore, reduced spoilage of fish can be part of the solution to reduce food insecurity in Africa (Chan et al., 2019), since less food will be wasted. However, the fish industry is not the only food sector in Africa suffering from high losses, this is also a problem within the agricultural sector where several types of crops would benefit from cold storage (Sadi & Arabkoohsar, 2020; Affognon et al., 2015). Due to differences in system setup, conditions assumed, and products stored, it is not possible to make any direct comparisons between the studies.

As previously mentioned, electricity does not only provide the possibility to use cold storage. It can also be used to add value to the fish, as well as other agricultural products. It can be used to power machines for drying fish and milling machines to make flour. Value addition is an important part of a business since the price of the products increase, leading to higher income. When the income increases, the entrepreneur will have more opportunities to further expand the business and increase the usage of electricity in their business even more. Business development within agriculture and fisheries can thus help to reduce poverty and food insecurity (Chan et al., 2019; Ibengwe & Kristófersson, 2012).

The CLD, by showing the complexity of the system, indicates that stakeholder collaboration would be essential for the successful implementation of the studied system. Too often policies and actions are targeting one particular issue, but in order for electrification to be contributing to development successfully, focus should not only be at the supply of electricity but also how electricity can be used to provide economic and social development in different contexts.

The study findings are based on one particular case in Tanzania. This constrains the possibility to draw general conclusions based on the study. Both mini-grid operations and fishing practices are context-specific, but the studied dynamics and aspects are certainly valid also beyond the case since conditions are similar over large areas of SSA. Another limitation is that the simulations performed were utilizing simulated weather data for two days only; one in the rainy season and one in the dry season and the load profile is assumed to be the same for the seasons. If the simulation would have been based on annual data including wider solar PV generation fluctuations, this could have affected the results. Further, investment cost assumptions are based on the literature, implying that the real market costs may be higher than the ones calculated, and the cost for transportation of the cold storage room, which may be significant due to the remote location of Bwisya, was not considered.

More research is needed within the field to increase knowledge about the correlation between cold storage, access to electricity and decreased spoilage in the fishery sector. Simulations with other weather data, load profiles and varying interest rates would increase the robustness of the results. It would also be beneficial to further investigate the possibility to use the cold storage room for crops during the dry seasons when the fish catch is scarce. Further research could also include long-term monitoring of systems, alternative funding mechanisms, or cross-industry applications of the causal loop diagram framework.

Conclusions

This study concludes that the implementation of a joint cold storage room can be economically possible for small-scale fishers in Tanzania if the initial investment is made by an investor and the investment is payed back within at least one year. The calculations are based on cooling room investment cost assumptions, but it still seems to a robust outcome that it is economically feasible for the fishermen to pay back the investment. The results suggest that the amount of fish caught during the high season is enough to cover the running costs and the investment costs if it is paid back over at least one year. A solution to cover the costs during the low season would be to use the cold storage room to preserve crops that easily perish in the hot climate, since the same variables and mechanisms, presented in the causal loop diagram, can be applied to agriculture as well, or if some of the profit from the high season can be saved.

The connection of a cold storage unit to a solar PV mini-grid would require extra investments from the mini-grid operator to be able to cover the demand during periods where the electricity production is low. The model indicates that in the long run, it is more beneficial for the mini-grid operator to invest in a higher capacity of solar PVs and batteries instead of running the diesel generator when the electricity production is low.

It can also be concluded that access to electricity has a significant effect on the reduction of spoilage of fish. Electricity makes it possible to utilize cold storage to preserve the fish for several days, directly decreasing the loss and the pressure to sell instantly. Cold storage in turn also provides the opportunity to transport the fish over longer distances to utilize different markets with varying prices.

Making sure that the mini-grid customers are aware of the benefits of electricity is also an important aspect to promote productive usage of electricity, and this requires knowledge and awareness of both the mini-grid operator and the investor. For the implementation of a cold-storage system as proposed in this study, the engagement of different stakeholders is therefore of high importance for it to succeed.

These conclusions show the importance of electricity access in rural areas for small-scale fishermen to reduce the spoilage of fish and that, with the help from an investor to make the initial investment in a larger cold storage unit, it is economically possible for the fishermen to pay back the investment within a relatively short time.

CRediT authorship contribution statement

Ofelia Carlsson: Visualization, Methodology, Formal analysis, Data curation, Conceptualization, Writing – original draft. **Madeleine Johansson:** Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – original draft. **Erik O. Ahlgren:** Supervision, Methodology, Funding acquisition, Conceptualization, Writing – review & editing.

Declaration of competing interest

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.

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Appendix A. Cooling loads

The cooling loads in the cooling room depend on the ambient temperature, the fluctuations for Bwisya in 2019 can be seen in Fig. A.1.

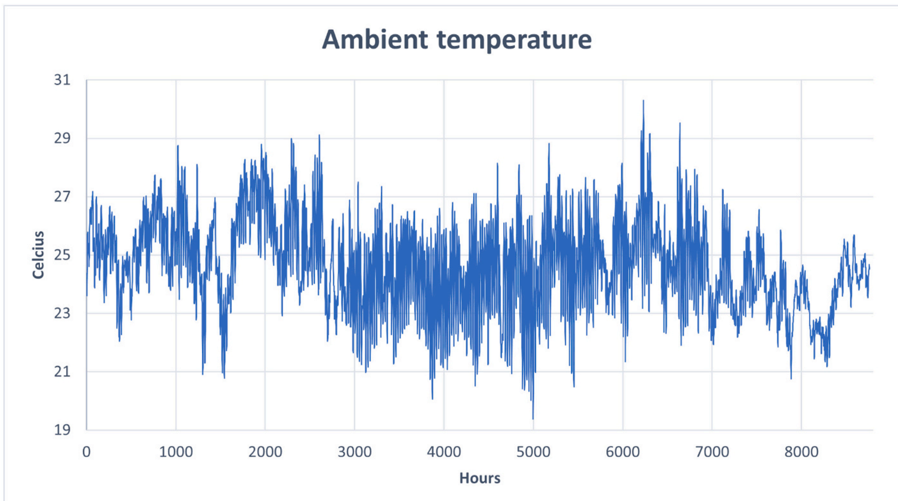

Fig. A.1. Ambient temperature in Bwisya for 2019.

Figs. A.2 and A.3 presents the electricity generation over 24 h at the days when the production was at its highest and lowest, respectively. These graphs are used in the techno-economic analysis as best and worst case.

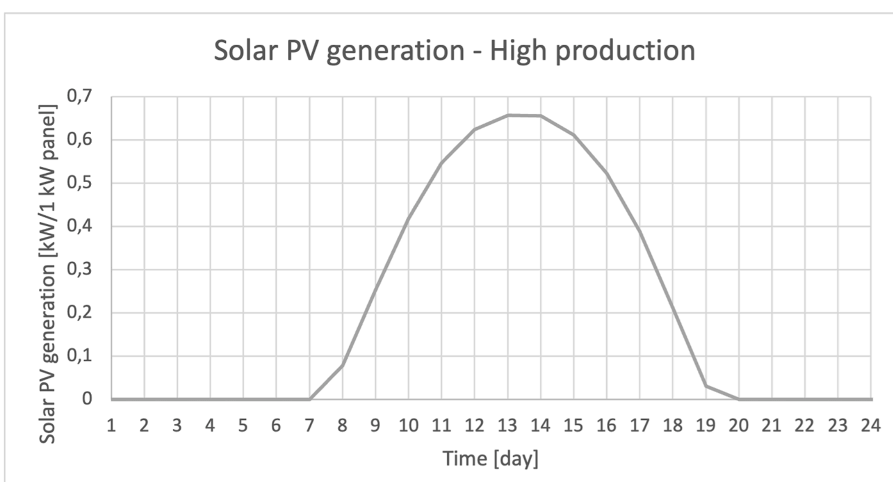

Fig. A.2. Solar PV generation over 24 h when the production was at the highest in Bwisya in 2019 for a 1 kW solar PV panel.

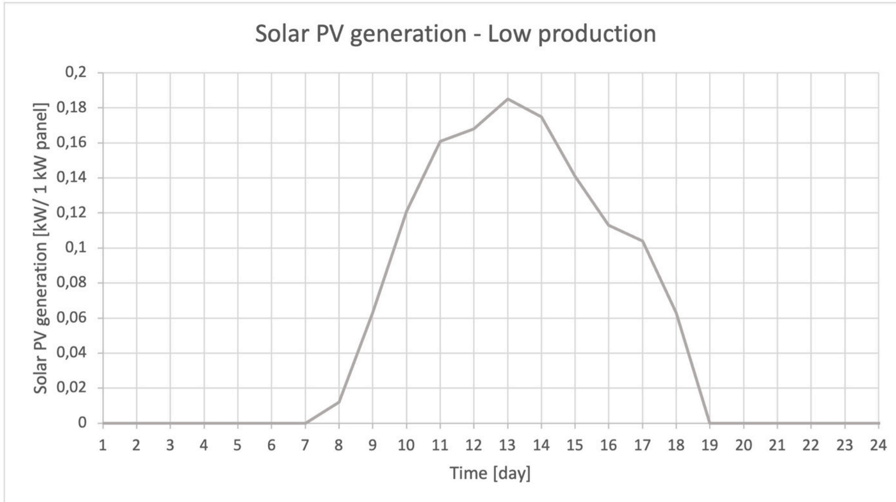

Fig. A.3. Solar PV generation over 24 h when the production was at the lowest in Bwisya in 2019 for a 1 kW solar PV panel.

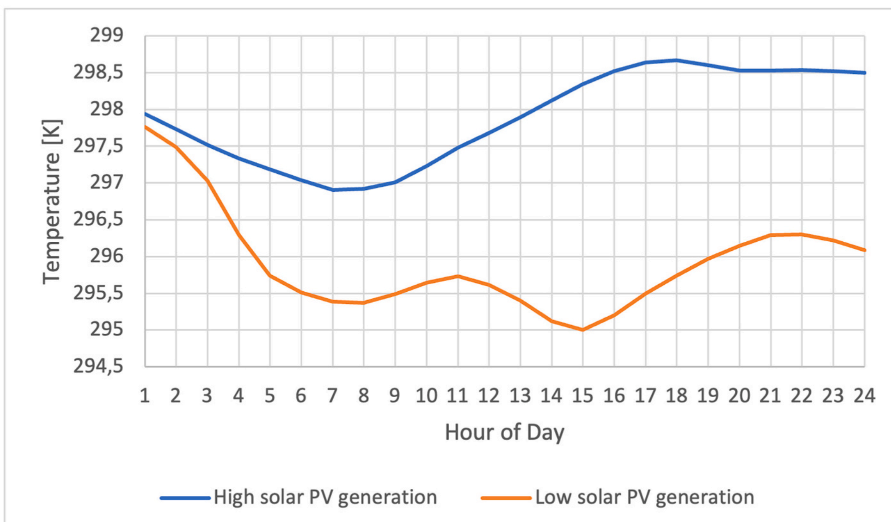

Fig. A.4. How the temperature changes during the day for the different solar PV generation cases.

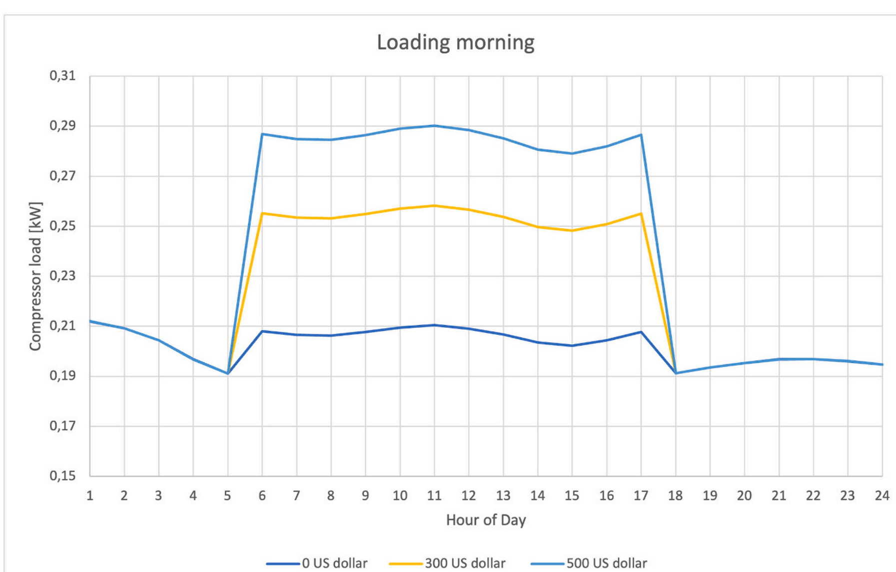

Fig. A.5. The compressor load when loading the cooling room with fish in the morning.

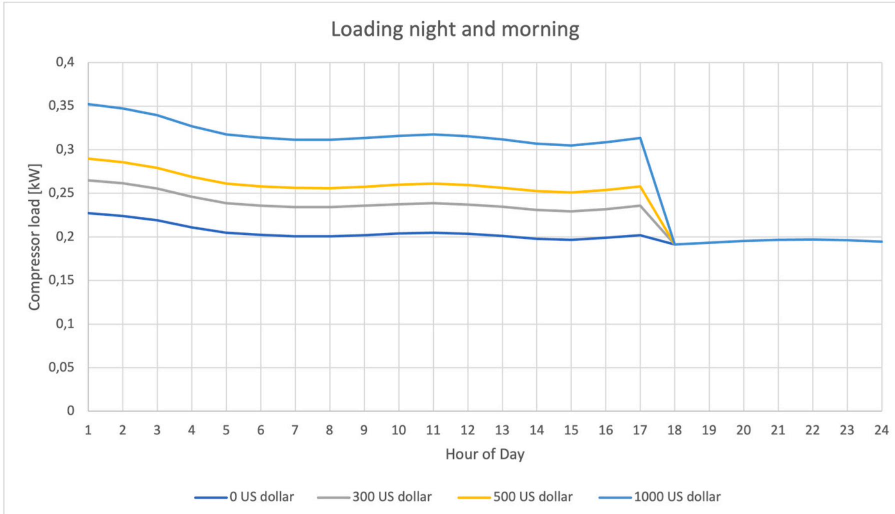

Fig. A.6. The compressor load when loading the cooling room with fish in the night and morning.

Table A.1
Monthly precipitation in Bwisya in 2019 (www.renewables.ninja).

Month	Precipitation [mm/month]
January	81
February	129
March	133
April	159
May	85
June	14
July	18
August	31
September	98
October	180
November	255
December	145

Appendix B. Causal loop diagram causalities and sources

Table B.1
The causal relationships, their description and sources for the causal loop diagram in Fig. 3.

Causal relationship	Description and source
Reliability → Cold storage opportunities (+)	Reliability of electricity is a necessity to be able to have cold storage (Fishermen 3, 2022; Former cluster manager, JUMEME, 2022)
Cold storage opportunities → Cold storage utilization (+)	If people have the opportunity to use cold storage they utilize it (Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022; Former cluster manager, JUMEME, 2022)
Cold storage demand → Cold storage utilization (+)	If there is a demand, cold storage will be utilized
Cold storage utilization → Cold storage demand (−)	If cold storage is utilized, the demand decreases
Fish caught → Cold storage demand (+)	The more fish that is caught, the more demand for CS
Fish caught → Fish population (−)	When fish is caught the fish population decreases
Fish population → Fish caught (+)	If the population increases more fish is caught
Cold storage utilization → Ability to pay (−)	Logical assumption, when money is invested in cold storage the ability to pay decreases
Ability to pay → Cold storage opportunities (+)	When the income is increased, they can expand their business by investing in more cold storage (Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022)
Cold storage utilization → Access to markets (+)	Being able to store the fish gave them opportunity to sell in other markets (Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022)
Access to markets → Spoilage in fish (−)	Long distances to markets may cause higher losses if there are not enough buyers to buy the fresh fish (Assefa et al., 2018)
Cold storage utilization → Spoilage in fish (−)	An improved cold chain would lead to decreased spoilage (Chan et al., 2019; Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022; Prodhan et al., 2022)
Cold storage utilization → Pressure to sell (−)	They had to sell the fish quickly when they were not being able to store it (Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022)

(continued on next page)

Table B.1 (*continued*)

Causal relationship	Description and source
Pressure to sell → Income (−)	When being able to store and not pressured to sell, they could increase the price (Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022)
Spoilage in fish → Income (−)	Being able to store what would otherwise have been wasted has increased the income (Fishermen 1, 2022; Fishermen 2, 2022; Gyan et al., 2020; Lukuyu et al., 2019)
Income → Ability to pay (+)	An increase in income increases financial opportunities (Jumeme costumer 2, 2022)
Electricity access → Cold storage opportunities (+)	Access to electricity gives the opportunity to use refrigerators or producing iceblocks to cool the fish (Fishermen 1, 2022; Fishermen 2, 2022; Fishermen 3, 2022; Mramba & Mkude, 2021; Nuru et al., 2021)
Electricity access → Value addition (+)	Refrigeration, drying, milling etc. by using electric equipment (Das & Behera, 2020; Executive Director, ELICO Foundation, 2022; Head of Programmes and Operations, ELICO Foundation, 2022)
Fish caught → Value addition (+)	The more fish that is caught, the more fish van be processed
Value addition → Income (+)	Drying fish using solar powered drying facilities increases the quality of the product and thus increases the price (Head of Programmes and Operations, ELICO Foundation, 2022)
Value addition → Spoilage in fish (−)	Improved drying of fish decreases spoilage (Gyan et al., 2020; Kabahenda et al., 2009)
Electricity access → Education (+)	Improved studying conditions for students and teachers when connected to electricity (Director and Founder, ENSOL (T) LTD, 2022; Site manager Power Corner, Engie, 2022; Nuru et al., 2021; Uamusse et al., 2019)
Education → Spoilage in fish (−)	Improved education has showed to decrease the losses of fish (Acharjee et al., 2021; Gyan et al., 2020)
Ability to pay → Productive usage of electricity (+)	The ability to pay positively influences the productive usage of electricity (Executive Director, ELICO Foundation, 2022; Jumeme costumer 2, 2022)
Costumer awareness → Productive use of electricity (+)	When costumers are aware of what electricity can do, they can use it for more productive uses (Chair person TAREA, 2022; Executive Director, ELICO Foundation, 2022)
Mini-grid investor awareness → Costumer awareness (+)	Mini-grid investors/operators need to be aware that they need to educate and create awareness for their customers. Investor awareness positively affects the costumer awareness (Executive Director, ELICO Foundation, 2022)
Mini-grid investor awareness → Financial assistance (+)	If the investor are aware of the needs in the community they can provide financial assistance (Executive Director, ELICO Foundation, 2022)
Financial assistance → Productive use of electricity (+)	Financial assistance helps more people to use electricity for productive uses (Cluster manager, JUMEME, 2022; Executive Director, ELICO Foundation, 2022; Jumeme costumer 3, 2022)
Mini-grid investor awareness → Productive use of electricity (+)	Investor awareness positively effects the productive uses since the investor know it will be profitable for them to promote productive uses (Executive Director, ELICO Foundation, 2022)
Productive use of electricity → Profit from mini-grid (+)	Productive users stand for majority of the profit from the mini-grid (Executive Director, ELICO Foundation, 2022; Hartvigsson et al., 2021; Pueyo et al., 2020)
Tariffs → Profit from mini-grid (+)	If the tariffs increase so does the profit, unless the tariffs are too low for there to be any profit at all (Cluster manager, JUMEME, 2022)
Financial assistance → Cold storage opportunities (+)	Techno-economic analysis
Productive use of electricity → Mini-grid capacity (+)	If productive usage of electricity increases the capacity needs to increase based on the techno-economic study
Mini-grid capacity → Mini-grid investment cost (+)	Increasing the capacity results in higher investment cost (Director and Founder, ENSOL (T) LTD, 2022; Abada et al., 2021; Hartvigsson & Ahlgren, 2018)
Mini-grid investment cost → Tariffs (+)	The tariffs are partly based on the investment cost of the mini-grid (Abada et al., 2021; Zomers, 2003)
Tariffs → Productive usage of electricity (−)	If the tariffs are high the usage decreases because it is expensive (Head of Operations, JUMEME, 2022; Jumeme costumer 2, 2022)
Reliability → Technician harassment (−)	Costumers blamed the local technician for the blackouts and threatened him (Local technician, JUMEME, 2022)

Table B.2
Description of the feedback loops for the causal loop diagram in Fig. 3.

Feedback loop	Description
R1	Cold storage utilization → Pressure to sell → Income → Ability to pay → Cold storage opportunities
R2	Cold storage utilization → Spoilage in fish → Income → Ability to pay → Cold storage opportunities
R3	Cold storage utilization → Access to markets → Spoilage in fish → Income → Ability to pay → Cold storage opportunities
B1	Cold storage utilization → Ability to pay → Cold storage opportunities
B2	Cold storage demand → Cold storage utilization
B3	Fish caught → Fish population
B4	Productive use of electricity → Mini-grid capacity → Mini-grid investment cost → Tariffs

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