POLITECNICO DI MILANO

Facoltà di Ingegneria Industriale e dell'Informazione

Corso di Laurea Magistrale in
Ingegneria Energetica

Solar cooling for food preservation: technology review and design of a stand-alone system for fish preservation in Mozambique

Relatore: Prof. Mario MOTTA

Co-relatori: Ing. Lorenzo PISTOCCHINI
Ing. Gabriele CASSETTI

Tesi di Laurea di:

Martina FRANGI Matr. 800986
Carlotta MARAFFIO Matr. 804994

Anno Accademico 2014 – 2015

Ringraziamenti

Un ringraziamento particolare va a Gabriele e Lorenzo per averci seguito passo dopo passo nel nostro lavoro e averci dato la forza e la voglia per concludere il nostro percorso universitario.
Ringraziamo il prof Mario Motta per aver accettato il nostro lavoro di tesi.

Un ringraziamento da lontano va a Flavia e Marco per aver cercato di restringere le distanze fra due mondi così lontani e diversi, grazie ai quali parte di questo lavoro è stato possibile.

Grazie anche a Caroline e Matteo per l'aiuto datoci nei momenti più critici.

Carlotta ringrazia…

La mia piccola ma fantastica famiglia che mi ha dato l'opportunità e la forza di portare a termine i miei studi e che mi ha saputo sopportare sempre e comunque

Ringrazio soprattutto i miei compagni d'avventura Ele, Duffy, Leo, Meli, Mosca e Tom che sono riusciti a rendere questi anni di studio meravigliosi…

Un ringraziamento va anche a…
…Giulia, per avermi fatto prendere il percorso giusto
…alle chiavennasche, per avermi sempre supportato nei momenti difficili
…e va beh, anche a Paolo

Martina ringrazia…

I miei genitori e mia sorella Carlotta che mi sono stati vicini (a volte anche troppo) nel percorso universitario e soprattutto nell'ultimo periodo e che hanno sempre creduto in me, anche quando io stessa non ci credevo.
Un ringraziamento va anche a zia Elena e zio Mauro e ad Alessia ed Eleonora, poiché so che spesso sono stata nei loro pensieri.
Grazie anche a te nonno per darmi un esempio di forza tutti i giorni.

Un immenso grazie va alle Polletecniche Celeste, Flavia, Lucia e Sara perché in loro ho trovato, oltre che un supporto negli ardui studi al Politecnico, anche e soprattutto delle vere amiche capaci di trasformare una monotona giornata in un tripudio di gioia e divertimento.

Index

Index....3
Abstract....i
Sommario....iii
Estratto in lingua italiana....v
1. Introduction....1
2. State of the art of refrigeration technology....5
2.1 Introduction to refrigeration technology....5
2.1.1 Vapor compression cycle....5
2.1.2 Sorption cycles....8
2.1.3 Evaporative cooling....17
2.2 Review of existent technologies for stand-alone systems....17
2.2.1. Icemakers....18
2.2.2. Refrigerators....36
2.3 Refrigerators and icemakers: different technologies for different needs....54
3. Case Study....59
3.1. Context description....59
3.1.1. Mozambique....59
3.1.2. Focus on the context of the action....63
3.2. Problem identification....69
3.3. Strategy definition....71
4. Solution design....73
4.1 Demand evaluation....73
4.1.1 Fish preservation needs of farmers and merchants....73
4.1.2 Fish preservation conditions....75
4.1.3 Determination of ice request....77
4.2 System definition....80
4.2.1 Selection of suitable technology....80

4.2.2 System components 83
4.2.3 Different system configurations 93
4.2.4 Simulation modeling 101
4.3 Results 114
4.3.1 Simulation results and discussion 115
4.3.2 Decision-making process to select the appropriate configuration 123
4.3.3 Model validation 132
4.3.4 Economic analysis 134
4.3.5 System evaluation 141
5. Conclusions 143
APPENDIX A 145
APPENDIX B 153
APPENDIX C 155
Bibliography 157

Abstract

Food loss and waste is a critical problem that affects the wide world. In developing countries, it concerns the first stages of food supply chain, in particular harvest and conservation. Regarding the latter, an adequate conservation system is hardly present, since refrigeration techniques rely on access to reliable and affordable source of energy (either electricity or diesel), often lacking in rural areas. A great deal of effort has been directed to develop alternative technologies to reduce perishable food losses, as stand-alone cooling systems powered by solar energy.

The present thesis consists of the design and the feasibility study of a solar cooling system for food preservation. Specifically, the work concerns a particular case study represented by the problematic fresh fish preservation in the Mozambican province of Zambezia, where CeLIM, an Italian non-governmental organization, is operating to improve fishermen and merchants conditions. The installation of a system that allows an adequate conservation would help CeLIM in a partial realization of its project.

A review of existing prototypes aims to illustrate some interesting cooling systems developed for food preservation in rural contexts.

The analysis of the context of interest, consisting of the individuation of the stakeholders and their needs, brings to identify the problem and to define objectives and strategy. From the analysis emerges that icemaker is the technology that better meets the local needs. On the other hand, the prototypes review leads to define photovoltaic modules as the most appropriate energy source for the specific case. Because the area under study does not have grid connection, a battery bank is necessary to guarantee a reliable system. The operation of different types of system configurations is simulated with a Matlab code, developed by Authors in order to select the suitable system to propose to CeLIM. In particular, systems using electric storage and thermal storage with different operation modes are considered. A decision making process leads to define the most appropriate solution, represented by the freezing storage, as it represents a good compromise between an affordable technology and a system that guarantees standard preservation conditions.

Keywords: Food preservation, Ice, Matlab, Stand-alone photovoltaic system, rural context, Mozambique

Sommario

Le perdite e gli sprechi alimentari rappresentano un problema critico di interesse globale. Nei paesi in via di sviluppo questo problema riguarda le prime fasi della filiera alimentare, in particolare la raccolta e la conservazione del cibo. Per quanto riguarda quest'ultima, difficilmente sono presenti sistemi di conservazione adeguati, poiché il loro funzionamento si basa sulla disponibilità di fonti energetiche affidabili ed economiche (quali elettricità e diesel), spesso assenti nelle aree rurali. Per trovare una soluzione alle elevate perdite alimentari sono stati fatti diversi tentativi che consistono principalmente nello sviluppo di tecnologie alternative, come sistemi di refrigerazione stand-alone alimentati da fonte solare.

Il presente lavoro di tesi si propone di dimensionare e condurre uno studio di fattibilità di un sistema di refrigerazione alimentato ad energia solare per la conservazione del cibo. In particolare, questo studio riguarda lo specifico caso di conservazione del pesce fresco nella provincia mozambicana della Zambezia dove CeLIM, un'organizzazione italiana non governativa, opera per migliorare le condizioni di vita di pescatori e commercianti che svolgono le loro attività nei pressi del fiume Zambezi. L'installazione di un sistema che permetta una corretta conservazione del pescato potrebbe aiutare CeLIM nel portare a termine una parte del suo progetto.

Una review dei prototipi esistenti è stata condotta allo scopo di presentare i sistemi di refrigerazione più interessanti sviluppati per la conservazione del cibo in contesti rurali.

L'analisi del contesto, consistente nell'individuazione dei principali beneficiari e dei loro bisogni, permette di identificare il problema e di definire obiettivi e strategia dell'azione. Da questa analisi emerge come le macchine del ghiaccio siano la soluzione tecnologica che meglio soddisfa le necessità di pescatori e commercianti, mentre la review sui prototipi permette di individuare nel fotovoltaico la fonte energetica più adatta al caso d'interesse. Poiché la zona in questione non presenta alcuna connessione alla rete elettrica, per garantire un sistema affidabile è necessario accoppiare al fotovoltaico un sistema di accumulo elettrico. Attraverso un codice Matlab, sviluppato dagli Autori, è stato simulato il funzionamento di differenti configurazioni del sistema al fine di individuare quella più adatta alla specifica richiesta diCeLIM. In particolare, sono stati considerati due sistemi, uno caratterizzato da accumulo elettrico ed un altro da accumulo termico, e le loro differenti modalità di funzionamento. Tramite un processo decisionale è possibile definire come la tecnologia più appropriata la macchina del ghiaccio alimentata a fotovoltaico che permette di conservare il ghiaccio in un freezer; questa infatti riesce a soddisfare due esigenze, avere un sistema economicamente accessibile e garantire condizioni di conservazione che rispettano i livelli standard.

Parole chiave: conservazione del cibo, ghiaccio, Matlab, impianto fotovoltaico stand-alone, aree rurali, Mozambico

Estratto in lingua italiana

Introduzione

La problematica delle perdite e degli sprechi alimentari è rilevante a livello mondiale e ha un forte impatto sulla sicurezza alimentare delle fasce più povere della popolazione, sulla qualità del cibo, sullo sviluppo economico e sull'ambiente.

In particolare la problematica degli sprechi è caratteristica dei paesi sviluppati ed è imputabile al comportamento poco attento dei consumatori. Diversamente, nei paesi in via di sviluppo, si presenta la problematica della perdita di cibo, che avviene nel momento in cui l'inadeguata catena alimentare degrada la qualità del cibo fino a renderlo non più adatto al consumo. Le fasi particolarmente affette da questo problema sono le prime della catena alimentare, quali la raccolta e la conservazione del cibo, a causa dei limiti tecnici ed economici delle tecniche utilizzate in tali aree.

Poiché le perdite di cibo nelle prime fasi della catena alimentare influiscono non solo sulla sicurezza alimentare e sulla qualità del cibo ma anche sul suo valore economico, appare evidente come la riduzione di tali perdite, causate dalle inadeguate tecniche di raccolta e conservazione, possa migliorare gli standard di vita nei paesi in via di sviluppo.

Il presente lavoro di tesi si focalizza sulla problematica delle perdite di cibo nei paesi in via di sviluppo ed in particolare sulla fase di conservazione. Diverse sono le tecniche impiegate per conservare il cibo, quali l'essiccazione, l'affumicazione, la refrigerazione ed il congelamento, e ciascuna di esse è affetta da inefficienze; il presente studio si concentra sulle tecniche utilizzate per la conservazione del cibo mediante freddo.

Le cause che determinano le inefficienze nella conservazione del cibo mediante refrigerazione sono principalmente due: i sistemi di refrigerazione presenti nei paesi in via di sviluppo sono spesso troppo cari per le famiglie e i piccoli produttori e le fonti di energia (elettricità o diesel) che alimentano tali sistemi sono spesso inaffidabili, costose o assenti nelle aree rurali, dove è maggiormente concentrata la popolazione di tali paesi.

Diversi tentativi sono stati fatti per trovare una soluzione a tale problematica ed in particolare questi si sono concentrati nel trovare il modo di sfruttare l'elevata disponibilità della fonte solare caratteristica di tali zone, dove le condizioni climatiche e l'assenza di un collegamento alla rete elettrica o la scarsa disponibilità di carburante aggravano il problema. Questa riflessione ha portato allo sviluppo e all'installazione di sistemi stand-alone di refrigerazione alimentati da fonte solare.

Nel dettaglio il presente lavoro inizia con una review sui sistemi di refrigerazione stand-alone alimentati da fonte solare sviluppati principalmente per l'individuazione di soluzioni tecnologiche adatte ai contesti rurali dei paesi in via di sviluppo: prototipi e studi sono descritti nel dettaglio. I risultati di tale review sono di grande utilità per l'individuazione della soluzione tecnologica più appropriata per il caso propostoci dall'associazione non governativa italiana CeLIM. Tale organizzazione opera da anni in Mozambico e l'ultimo progetto in cui è impegnata riguarda il miglioramento dell'attività di pesca nella provincia dello Zambezia all'interno del quale è emersa anche la problematica della conservazione del pesce fresco, la cui soluzione può essere raggiunta solo mediante sistemi di refrigerazione. A seguito di un'analisi approfondita del contesto e del problema, la tecnologia migliore è individuata e al fine di individuare la configurazione che meglio potrebbe soddisfare i bisogni dei beneficiari, diverse configurazioni sono state simulate mediante un modello Matlab - versione R2014b - sviluppato dalle autrici.

Capitolo 2: Stato dell'arte delle tecnologie di refrigerazione

Una preliminare descrizione dei principali cicli di refrigerazione è stata realizzata in questo capitolo al fine di fornire le necessarie nozioni tecniche utili ad una maggiore comprensione della seguente review. I cicli a compressione di vapore, assorbimento, ed adsorbimento sono stati descritti e le loro principali caratteristiche, quali le performance, le temperature caratteristiche lato caldo e freddo, le coppie di lavoro e gli usi specifici, sono stati illustrati. Inoltre è stata descritta anche la tecnica di refrigerazione che si basa sull'evaporative cooling, poiché diversi prototipi poi analizzati si basano su di essa.
I prototipi e gli studi riportati sono stati classificati in due principali categorie: macchine del ghiaccio e frigoriferi, all'interno delle quali i casi analizzati sono stati suddivisi a seconda del ciclo termodinamico su cui si basano.

Macchine del ghiaccio

- Con ciclo a compressione di vapore: sono descritti due prototipi realmente realizzati ed uno studio sviluppato in laboratorio. Il primo è stato realizzato in Messico per la conservazione del pesce e consiste in una macchina che produce ghiaccio a fiocchi alimentata da un impianto fotovoltaico e da batterie. Il secondo, sviluppato da un istituto tedesco, mira a favorire la conservazione del cibo ed è rappresentato da una macchina che fa ghiaccio a fiocchi alimentata da un impianto fotovoltaico, con le batterie come backup. Lo studio sviluppato in lab mira invece ad analizzare l'accoppiamento diretto tra sistema fotovoltaico e compressore in corrente continua e sull'ottimizzazione del sistema di controllo che avvia il sistema complessivo.
- Con ciclo ad assorbimento: sono descritti due prototipi realmente realizzati e uno studio di fattibilità. Il primo è stato installato in Kenya per permettere la corretta conservazione del latte e consiste nella tecnologia ISAAC, cioè una macchina ad assorbimento ammoniaca/acqua a funzionamento intermittente che produce blocchi di ghiaccio e che è alimentata termicamente da un collettore CPC. Il secondo è stato sviluppato a Bucarest, anch'esso è basato su di un ciclo ad

assorbimento intermittente ammoniaca/acqua e presenta alcune differenze rispetto al precedente, tra cui il tipo di alimentazione solare. Infine il terzo caso consiste in uno studio (sviluppato da un centro di ricerca della Catalogna) di fattibilità di una macchina del ghiaccio ad assorbimento alimentata dai gas di scarico di un peschereccio.

- Con ciclo ad adsorbimento: due prototipi realmente realizzati sono descritti. Il primo è stato sviluppato in Cina per risolvere il problema della conservazione del cibo, si basa su un ciclo frigorifero ad adsorbimento intermittente ed è caratterizzato dall'assenza di valvole e dall'uso di collettori solari piani per fornire l'energia termica necessaria. Il secondo invece, sviluppato in Egitto, mira a migliorare le prestazioni tipiche di questa tecnologia ed è caratterizzato da un sistema che permette di concentrare la radiazione sul collettore solare.

Frigoriferi

- Con ciclo a compressione: sono descritti in maniera generale i frigoriferi alimentati da un sistema fotovoltaico e con la presenza di batterie. Una descrizione più dettagliata è stata fatta per due diversi prototipi di frigoriferi alimentati dal solo fotovoltaico e caratterizzati dall'uso di blocchi di ghiaccio come accumulo termico.
- Con ciclo ad assorbimento: per questa categoria non sono stati trovati prototipi realmente realizzati ma solo studi o simulazioni numeriche. Sono riportati uno studio per un sistema di conservazione dei vaccini, uno per la conservazione del latte ed infine uno sullo sfruttamento di un solar pond come fonte di energia termica.
- Con ciclo ad adsorbimento: sono descritti tre prototipi realmente realizzati, rispettivamente in Nigeria, Burkina-Faso e Marocco. I tre sistemi, pur essendo simili tra loro, presentano delle significative differenze nella modalità di raffreddamento del volume destinato alla conservazione del cibo, nella realizzazione dei componenti e nelle caratteristiche dei collettori.
- Basati sull'evaporative cooling: sono descritti nel dettaglio molti prototipi, tutti realmente realizzati, di diverse dimensioni e realizzati utilizzando diversi materiali.

Al termine della review è poi realizzata un'analisi qualitativa riguardante i prototipi descritti.

Capitolo 3: Caso studio

Una preliminare descrizione geografica, economica e sociale del Mozambico e della provincia della Zambezia permette di introdurre il contesto generale nel quale il progetto di CeLIM si inserisce. Questo mira a migliorare le condizioni economiche dei pescatori, dei commercianti e delle loro famiglie operanti nei distretti di Mopeia e di Morrumbala,

attraverso il miglioramento dell'attività di pesca. Attualmente infatti la coordinazione del settore a livello locale è ridotta, le tecniche di pesca utilizzate non sono corrette e le fasi di trasformazione e di commercio sono profondamente inefficienti; tali problematiche causano elevate perdite nella produzione e quindi nel guadagno economico.
Grazie alle informazioni ricevute dai rappresentati di CeLIM presenti sul territorio e ad alcuni questionari rivolti ai pescatori, è stata ricostruita l'organizzazione dei centri di pesca, fulcro di tutte le attività. I pescatori svolgono la loro attività seguendo turni ed orari abbastanza precisi e i commercianti, che si occupano della trasformazione del pesce e del suo commercio, seguono anch'essi degli orari che dipendono fortemente dalle distanze a cui si trovano i mercati (del pesce fresco o del pesce trattato) e dai loro mezzi di trasporto. Per i commercianti che si occupano del commercio del pesce fresco non esiste un sistema adeguato di conservazione e l'unica modalità che possono sfruttare per preservare la freschezza del pesce è quella di utilizzare blocchi di ghiaccio che acquistano al mercato. A causa delle elevate temperature e delle elevate distanze tra mercati e centri di pesca spesso tale ghiaccio si scioglie prima di aver compiuto la propria funzione. Per questo motivo il pesce fresco è difficilmente reperibile nei mercati, a discapito dei consumatori.

Capitolo 4: Dimensionamento della soluzione tecnologica

L'analisi del contesto fa emergere come l'unico intervento possibile per risolvere il problema della conservazione del pesce sia quello di individuare ed installare presso i centri di pesca un'adeguata tecnologia di refrigerazione che soddisfi le necessità di pescatori e commercianti. Diverse soluzioni tecnologiche sono possibili, come ad esempio un capiente frigorifero comune o una macchina del ghiaccio di elevata capacità, entrambi presenti in ogni centro di pesca, oppure piccoli frigoriferi in dotazione a ciascun pescatore e commerciante. Grazie alla collaborazione dei rappresentanti di CeLIM e agli standard di conservazione del pesce stabiliti a livello internazionale la soluzione tecnologica rappresentata da macchine in grado di produrre blocchi di ghiaccio si è rilevata essere la più adatta al contesto.
Poiché la quantità di ghiaccio necessaria in ogni centro di pesca per una corretta conservazione del pesce è elevata, la soluzione tecnologica più adatta consiste in macchine del ghiaccio a compressione di vapore alimentate da un sistema fotovoltaico. Inoltre, poiché il sistema è stand-alone, la presenza delle batterie è necessaria per garantire l'affidabilità del sistema in caso di fluttuazione della fonte solare.
Un preliminare dimensionamento del sistema rivela come, per soddisfare la totale richiesta di ghiaccio, sia necessario un sistema fotovoltaico di taglia significativa (quasi 100 kW). Considerando il fatto che la tecnologia fotovoltaica è ancora poco nota nell'area d'interesse e che non c'è completa certezza sulle quantità di ghiaccio calcolate, si è deciso

di proseguire con lo studio considerando una domanda ridotta e la possibilità di realizzare il progetto solo in forma pilota per poter così meglio comprendere l'impatto a livello sociale ed economico del sistema.
L'analisi delle tecnologie presenti sul mercato ha portato alla scelta degli specifici componenti del sistema: macchine del ghiaccio a compressione di vapore che producono blocchi, pannelli fotovoltaici policristallini, batterie piombo-acido al gel e inverter.
Diverse configurazioni e diversi funzionamenti del sistema sopra definito sono stati simulati mediante un modello Matlab realizzato dalle Autrici. Le configurazioni considerate sono due e ciascuna di esse presenta due funzionamenti diversi. Nella prima configurazione (*configuration 1*) le macchine del ghiaccio lavorano sia di giorno che di notte per poter soddisfare in orari specifici le richieste di ghiaccio di pescatori e commercianti; in questo caso quindi le batterie, oltre ad avere una funzione di backup richiesta per garantire la continuità al sistema stand-alone, devono essere in grado di alimentare le macchine durante le ore notturne. I due funzionamenti (*operation mode 1* e *operation mode 2*) considerati consistono in differenti macchine con differenti orari di avvio. Nella seconda configurazione (*configuration 2*) invece le macchine del ghiaccio lavorano solo di giorno in modo da sfruttare al meglio la radiazione presente, quindi le batterie hanno solo la funzione di backup. Poiché però in questo modo non c'è coincidenza tra produzione e richiesta di ghiaccio, è stato necessario aggiungere al sistema un sistema di accumulo freddo che conservi il ghiaccio. Sono stati considerati due diversi accumuli termici (che quindi hanno dato origine a due differenti configurazioni 2): un container termicamente isolato (*configuration 2S*) ed un freezer (*configuration 2F*) alimentato sempre dal fotovoltaico. I due funzionamenti (*operation mode 3* e *operation mode 4*) considerati sono i medesimi per entrambe le configurazioni 2 e, come nel caso precedente, consistono in differenti macchine, combinate in differenti modi e con differenti orari di avvio.
Il modello Matlab simula il funzionamento delle diverse configurazioni per un anno tipo e ottimizza il sistema fotovoltaico e le batterie in modo che per ogni configurazione sia scelta la taglia minima di batterie in grado di soddisfare la richiesta di ghiaccio per un numero determinato di giorni all'anno. Per fare ciò il programma prende in ingresso la radiazione giornaliera, la richiesta energetica delle macchine del ghiaccio, range di capacità di batterie e di potenza installata di fotovoltaico e il numero di giorni che si desidera soddisfare. Simulando il funzionamento di ogni componente, il codice restituisce la minima capacità della batteria relativa ad ogni valore di potenze PV installata, la potenza entrante nella macchina del ghiaccio e il costo netto attualizzato, che permette una valutazione economica del sistema. Nel caso della configurazione comprendente l'accumulo isolato, il modello valuta anche l'andamento della temperatura del ghiaccio al variare delle condizioni ambiente e dello spessore dell'isolante.
Per poter individuare la configurazione migliore tra tutte quelle simulate dal codice Matlab, sono stati utilizzati una serie di criteri di scelta. In primo luogo per ogni

configurazione sono state selezionate le combinazioni di fotovoltaico e batteria aventi il minor costo attualizzato. Tra queste sono poi state scelte quelle in grado di soddisfare lo stesso numero di giorni all'anno e successivamente, per ogni configurazione, è stato selezionato il sistema con il minor costo unitario. Tre diverse configurazioni significativamente diverse tra loro emergono come migliori ed in particolare sono *configuration 1, operation mode 1*; *configuration 2S, operation mode 4* e *configuration 2F, operation mode 4*. Per poter individuare la più appropriata tra di esse, diversi fattori devono essere tenuti in considerazione, quali il costo d'investimento, l'energia in eccesso, il costo unitario, la temperature del ghiaccio al momento della vendita, la solidità del sistema al variare della disponibilità solare, l'ingombro, la gestione da parte degli utilizzatori, l'affidabilità e l'impatto ambientale. Per poter valutare questi criteri per ogni configurazione e trarre da tali valutazioni la configurazione più appropriata per il contesto specifico ci si è avvalsi del supporto del software Super Decision. Affinché poi le valutazioni date fossero il più oggettive possibile ci si è avvalsi dell'opinione dei contatti in Mozambico e degli insegnamenti che la review sui prototipi ha trasmesso. Tale processo decisionale ha fatto quindi emergere come soluzione adatta a soddisfare i bisogni specifici quella caratterizzata dalla presenza del freezer.
Infine per fornire a CeLIM non solo specifiche tecniche sulla soluzione migliore individuata ma anche informazioni sulla sostenibilità economica del possibile intervento è stata condotta un'analisi economica e di sensitività, basata sui costi netti attualizzati, sul valore attualizzato netto e sul tempo di rientro dell'investimento.

Dato che queste due ultime analisi hanno mostrato come il sistema ideato sia economicamente realizzabile e dato che l'analisi del contesto ha fatto emergere come il problema della conservazione del pesce fresco sia fortemente sentito dagli stakeholders considerati, si ritiene che un futuro impegno da parte di CeLIM nel realizzare il progetto (anche solo sotto forma di progetto pilota) sia di grande importanza per un iniziale miglioramento degli standard di vita degli interessati.

1. Introduction

“The issue of food losses is of high importance in the efforts to combat hunger, raise income and improve food security in the world’s poorest countries. Food losses have an impact on food security for poor people, on food quality and safety, on economic development and on the environment” [1].

The production of food that will not be consumed, in addition to lead to unnecessary CO_2 emissions, represents a waste of resources such as land, water and energy and decreases the economic value of the food produced.

Food loss and waste are problems that concern the wide world, not just the developing countries. According to the United Nations Environmental Programme [2], the world loses roughly one third of all food produced for human consumption every year (about 1,3 billion tonnes) and consumers in rich countries waste 222 million tonnes per year, a value that corresponds to almost the net food production of sub-Saharan Africa (230 million tonnes). Food losses occur between the moment it is harvested and consumed: in developed countries, food is lost and wasted at a late stage of the food value chain and in most cases this is due to consumers’ behavior. On the other hand, in developing countries food losses occur at an earlier stage because of economic and technical limits in harvesting techniques and conservation [2]. In this last case the areas more affected by this problem are Sub Saharan Africa with 36% of food harvested lost, Asia-Pacific with 15-50% of food crops lost, South Asia that loses a 8-40% and Southeast Asia with 9-25% of losses. In particular, in Sub Saharan Africa the food lost equates to an average 167 kg/cap per year where only 7 kg is at consumer level and 12,7% of total losses occurs at post-harvest. [3] The reduction of food losses may have a key role for increasing life standards. “It is important to note that food insecurity is often more a question of access (purchasing power and prices of food) than a supply problem. Improving the efficiency of the food supply chain could help to bring down the cost of food to the consumer and thus increase access” [1]. It was estimated that the saved food could feed one billion of people and this will have a great impact in particular in Asia-Pacific, characterized by 62,5% of global hunger [3].

In this work we will focus on the food waste problem concerning developing countries. In particular, one of the two main issues causing food losses, that is the inefficient preservation, is the focus of our study. With food preservation we mean all the techniques used to prevent food from spoiling: refrigeration, freezing, drying or smoking which aim to avoid the growth of bacteria or other microorganisms and are essential for the products affected by spoilage like milk, fish, fruits and vegetables.

Food preservation is often a problem for the supply chain in developing countries because of various reasons: in many cases appropriate technologies for conserving perishable products are too expensive, resulting unaffordable for families or small farmers. The unaffordability of suitable preservation technologies can lead to use inefficient and inappropriate methods, increasing product losses. Moreover, the refrigeration technique, which is the key to tackling the loss of perishable produce, presents a very critical problem since it relies on access to reliable and affordable source of either electricity or diesel fuel, which are often lacking or non-existent in developing countries [4].

The International Energy Agency [5] estimates that more than one-fifth of the world's population (1.3 billion people) lacked access to electricity in 2010. The 85% of them live in rural areas, mainly in sub-Saharan Africa and South Asia. Even in areas with grid power network the increasing demand for electricity outpaces supply growth resulting in unreliable electricity. Shortage of access to electricity represents a problem especially for refrigeration that nowadays is the most used and efficient method to preserve food: the present work investigates such specific case of food preservation through cooling technologies.

Since in developing countries there is a large part of the rural population that cannot depend upon electricity for refrigeration, the possibility of utilizing alternative energy sources has been evaluated in order to overcome this critical problem. In particular, as solar radiation tends to be abundant in climates with great needs for cooling, several solar powered cooling technologies were developed and installed in many rural areas.

The necessity of having electricity availability in rural areas and the opportunity of using the abundant solar source make stand-alone solar powered systems the most appropriate and used technologies for cooling purposes in developing countries.

In this thesis a research about existent solar cooling technologies has been carried out: the aim is to analyze the state of art of these technologies and to report the most significant ones installed in rural contexts with no electrification. Some of these systems represent a well-known technology, like vapor compression cycle refrigerators, while others concern a less spread technology, as sorption cooling or evaporative cooling. In any case, the systems are often prototypes developed for a specific case and specific needs, while others are just studies of possible applications.

The review of existent solar powered technologies permits to study an application of these systems to a precise context where food preservation problem emerges. In particular, the idea of analyzing and evaluating a hypothetical real application of solar cooling technology was born because an Italian non-governmental organization proposed to us a real case of food preservation in a region of Mozambique, where it is operating. Since the objective of the ONG is improving small-scale fishery sector, a progress in fish preservation may have a key role for the success of the project.

The analysis and the evaluation of a hypothetical real application of a solar cooling technology consists in conducting a feasibility study: the review of solar powered cooling technologies allows defining the system that better matches the needs. Then, by modeling different selected systems it is possible to define the most appropriate one for the context in question, establishing its technical and economic feasibility.

2. State of the art of refrigeration technology

This chapter aims at illustrating the operation and features - performances, temperatures, working pairs and uses - of main refrigeration cycles and systems. Moreover we present the results of the review about existing prototypes (refrigerators and icemakers) designed to preserve food, beverage or vaccines in remote areas.

2.1 Introduction to refrigeration technology

Refrigeration is defined as the process of extracting heat from a lower-temperature heat source, substance or cooling medium and transferring it to a higher-temperature heat sink.

The refrigeration systems can be supplied by electricity or mechanical energy, as those based on a vapor compression cycle, or they can be thermally driven as the absorption and adsorption refrigeration cycles.

2.1.1 Vapor compression cycle

The basic vapor compression cycle [6] is achieved by means of four components (shown in figure 2-1) through which the refrigerant circulates: the compressor, the condenser, the expansion valve and the evaporator.

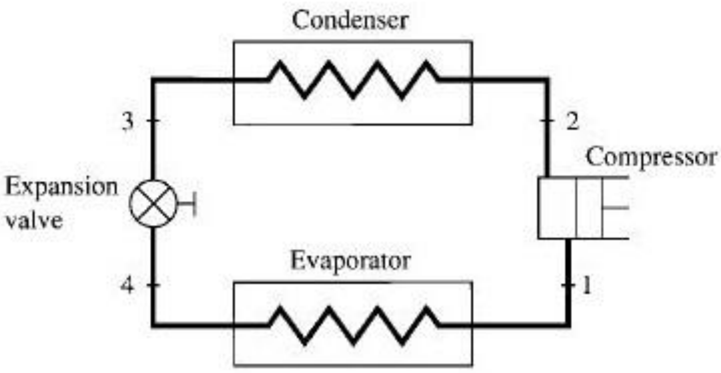


Figure 2-1 Schematic diagram of the vapor compression cycle [6]

Starting point of the cycle is the low pressure and low temperature vapor, coming from evaporator. It flows through the compressor, and the resulting high temperature and high pressure vapor passes through the condenser, where it is condensed back into a liquid state by releasing latent heat to an external sink. It is then throttled to the evaporator pressure through a restrictor device, typically an expansion valve. Finally it flows through the evaporator, where it vaporizes by absorbing heat from the refrigerated space. It can be noted that such a cycle is characterized by two pressure levels (high and low pressure)

related to the required evaporating and condensing temperatures. Such levels depend mainly on the refrigerant and the temperature of the cold source.
The pressure-enthalpy (p-h) diagram [6] is the most common graphical tool for the analysis of a vapor compression cycle and the calculation of its performances.
The following p-h diagram (Figure 2-2) shows an ideal vapor compression cycle: the isentropic compression (1-2), the condensation (2-3), the isenthalpic expansion (3-4) and the evaporation (4-1) processes are shown.

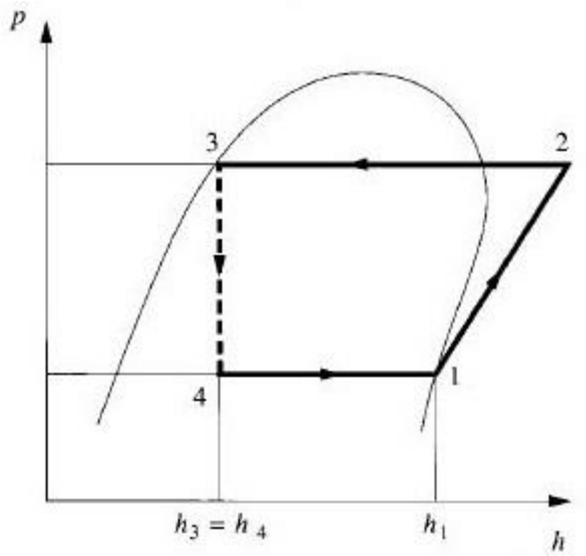


Figure 2-2 p-h diagram of a single-stage vapor compression cycle [6]

A typical performance index of the vapor compression cycle is the Coefficient Of Performance (COP). For a refrigerator the COP is defined as the ratio of Q_{refr}, the heat extracted from the lower-temperature heat source, represented by the segment 4-1 to W_{in}, the work input (represented by the segment 1-2) [6].

$$COP = \frac{Q_{refr}}{W_{in}}$$ Equation 2-1

Other conditions being equal, COP varies with evaporation and condensation temperature. In case of a lower evaporator temperature, the cycle can be represented as in the diagram here below (Figure 2-3).

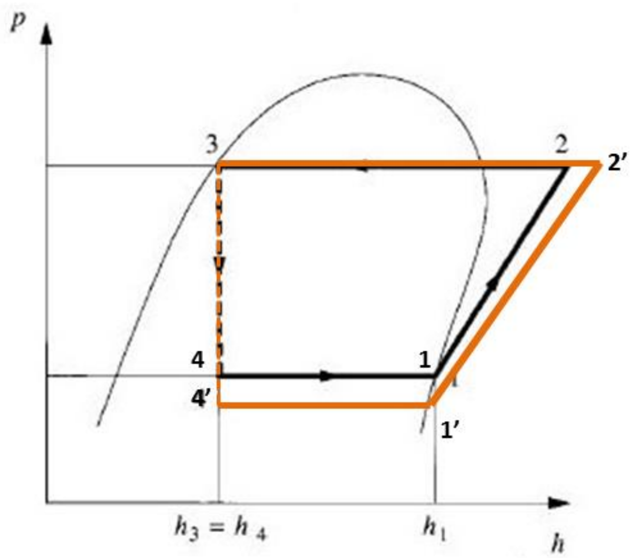


Figure 2-3 p-h diagram (case of lower evaporator temperature)

The refrigeration effect (4' - 1') decreases and the work input (1' - 2') increases compared to the basic cycle. Thus the coefficient of performance (refrigeration effect/work input) decreases.

If the condensation temperature rises, the cycle diagram (Figure 2-4) becomes as follows.

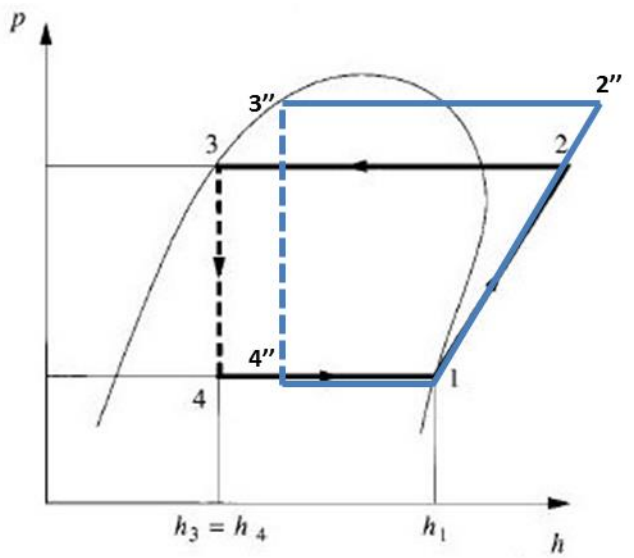


Figure 2-4 p-h diagram (case of higher condensation temperature)

The refrigeration effect (4'' – 1) decreases and the work input (1 – 2'') increases, thus the COP decreases.

The vapor compression cycle can be based on several refrigerant fluids, which are classified according to their nature (natural or synthetic fluids, pure or mixture), according to safety (toxic or flammable fluids) and according to their environmental impact. In order to maximize the energy efficiency, refrigerants should have a high critical temperature and low liquid specific heat (intrinsic losses are restrained), but to maximize cost effectiveness of the system they should have a low critical temperature and high vapor specific heat (resulting in a small and compact compressor). The choice of refrigerant depends also on its compatibility with the other materials and fluids (as water and oil). Most common refrigerant fluids and their principal applications are listed in table 2-1.

Table 2-1 Applications of different refrigerant fluids

Refrigerant fluid	Application
R134a	Vehicle air-conditioning, stationary air-conditioning, high temperature heat pump
R410A	Stationary air-conditioning
R600a	Domestic refrigeration
R717	Industrial refrigeration
R744	Commercial refrigeration, high temperature heat pump

Advanced cycle as LL-SLHX (Liquid Line-Suction Line Heat Exchanger), two stage and EVI (Economized Vapor Injected) configurations have been developed in order to improve cycle performance. We will not consider this topic since it is out of the scope of this work. The main features of cycle are summarized in table 2-2.

Table 2-2 Main features of vapor compression cycles

Typical size ranging	Small (<8,8 kW_{fr}), medium, or large (>264 kW_{fr}) [6]	
COP	Air cooled refrigerators: 2,6÷3,6 [7]	Water cooled refrigerators 3,5÷6 [7]
Freezing temperature	Very low (under 0°C)	

2.1.2 Sorption cycles

Sorption cycles can be based on chemical (absorption) or physical (adsorption) processes. Sorption systems are thermally driven and are characterized by a "thermal compressor" and a sorbent, which replace the mechanical compressor of the vapor compression cycle.

2.1.2.1 Absorption cycles

Two distinct absorption technologies are here presented: water/lithium bromide chillers and ammonia/water chillers. We will just consider the most basic cycle.

The water/lithium bromide machine consists of four external heat exchangers (absorber, desorber, condenser and evaporator), one internal heat exchanger, two flow restrictors and a pump, all represented in figure 2-5. This chiller employs water as a refrigerant and can be divided in two different circuits: solution and refrigerant circuits.

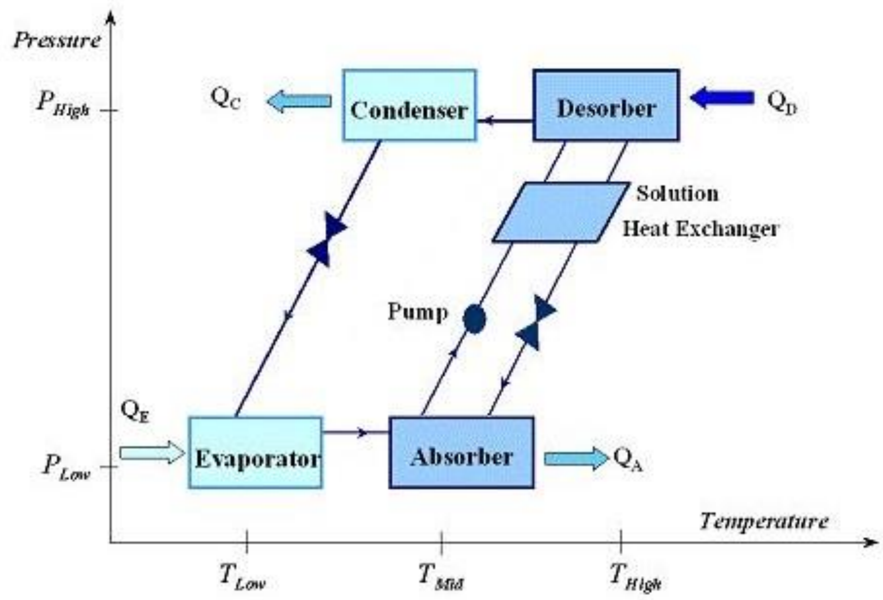


Figure 2-5 Outline of a water/lithium bromide absorption cycle [8]

The solution circuit is made by the absorber, the pump, one valve and the desorber (also called generator). The liquid solution is pumped from the absorber at low pressure to the desorber at high pressure, where a high temperature source (e.g. solar heat) supplies heat. As a result, a partial evaporation occurs in the desorber: the volatile refrigerant is boiled off, vapor flows to the condenser while the remaining liquid solution flows back to the absorber. Since the vapor leaving the desorber is pure refrigerant, the remaining liquid becomes more concentrated. In its way back to the absorber, the solution passes through the internal heat exchanger, to preheat the solution coming from the absorber. The stream gives up energy in this heat exchanger and typically arrives at the flow restrictor subcooled. Finally the stream arrives to the absorber where it comes into contact with the vapor supplied by the evaporator. The liquid solution absorbs vapor and becomes diluted, while the absorption heat is released to an external heat sink (such as a flow from a cooling tower).

The refrigerant loop is identical in function to the corresponding components in a vapor compression machine. "*The refrigerant loop takes the refrigerant vapor from the desorber and directs it to the condenser where it is liquefied by rejecting heat to a sink. The subcooled liquid flows through the expansion valve to the low pressure and this process is typically accompanied by some vapor flashing. Finally the two-phase stream enters the evaporator and evaporation takes place, accompanied by heat transfer from the evaporator environment.*" [9]

Typically an absorption cycle is represented on a pressure-temperature diagram called Dühring chart (Figure 2-6).

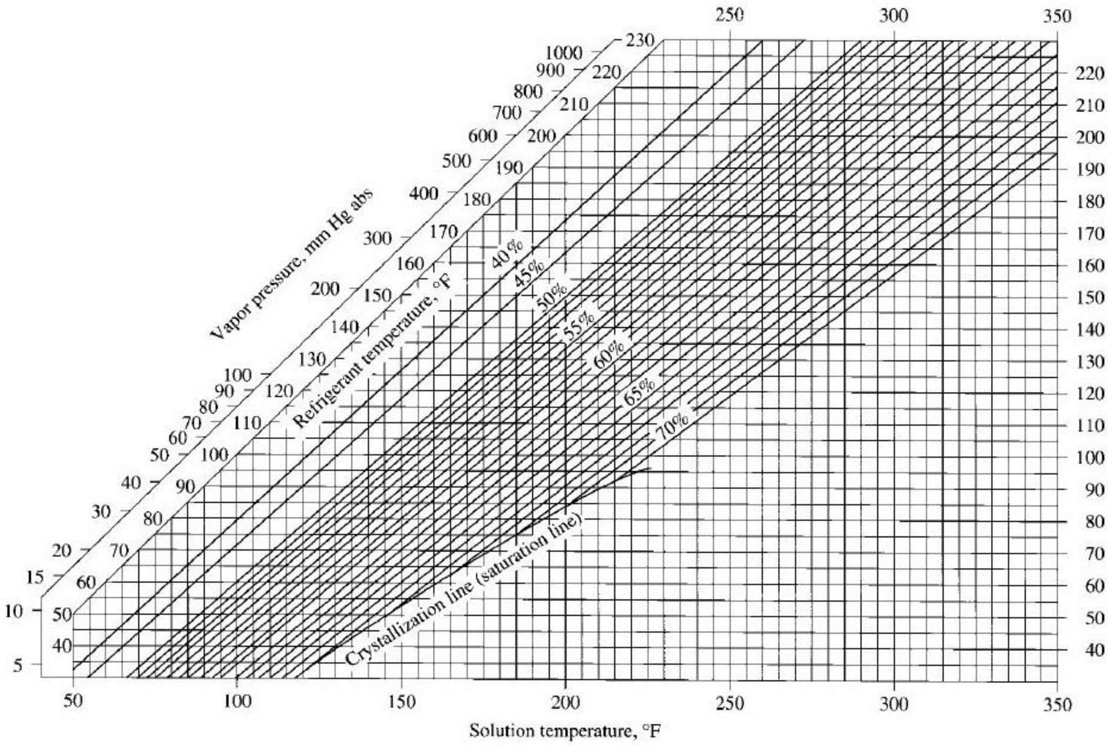


Figure 2-6 Duhring chart with crystallization line [6]

In Figure 2-6 the crystallization line is included because of a salt solution's feature: the lithium bromide (a hydrate salt) precipitates when the mass fraction of salt exceeds the solubility limit. This is the main problem of the working couple water/lithium bromide: the precipitated salt tends to clog up the piping, stopping the flow and stopping the machine operation or damaging the unit. So the crystallization line is included in the Dühring plot in order to remind this feature.

Water/lithium bromide chillers are also characterized by 1) a sub-atmospheric pressure, 2) sensitivity to trace amounts of internally generated gases, 3) hermetically sealed outer vessels, 4) a bulky volume 5) and a refrigeration temperature above 0°C. The latter feature limits its application, indeed they are typically used as water chillers for air-conditioning system in large buildings. Advanced cycles are also available, which were developed to improve cycle performances as the double-effect, half-effect and triple effect cycle.

The ammonia/water basic cycle is very similar to the water/lithium bromide cycle; however there are several differences, as a consequence of fluid properties.

- Ammonia is the refrigerant and it affects the system pressure, which is relatively high at the temperature needed for cooling. As a consequence, internally generated gases are not critical.
- Due to the moderate volatility of water, an additional component placed downstream the desorber is needed, in order to separate ammonia vapor from water vapor. This component is named rectifier and reduces performance losses.

- Ammonia/water chillers have no limits on refrigeration temperature, which can reach very low values; thanks to this they find application also in food refrigeration.

Also ammonia/water chillers can be based on advanced cycles, as the double-effect, double-lift and two-stage triple-effect cycle.
In table 2-3 [7] the properties of the aforementioned working couples are compared.

Table 2-3 Different properties of the working couples water/lithium bromide and ammonia/water

Property	Water/lithium bromide	Ammonia/water
Refrigerant	*Water*	*Ammonia*
Latent heat	Very high	Quite high
Vapor pressure	0,873 kPa [9]	Higher than atmospheric pressure
Freezing temperature	Not below 5°C	Up to -20°C
Viscosity	Low	Low
Absorbent	*Lithium bromide*	*Water*
Volatility	The salt does not evaporate	Moderate (water evaporates with ammonia)
Viscosity	Low	Low
Mixture	--	--
Solubility	Lithium bromide can precipitate	Excellent
Toxicity	No toxic	Ammonia is toxic
Flammability	No flammable	Ammonia is flammable
Corrosion	High	High
Affinity between refrigerant and absorbent	Good	Good

The energy performance of the absorption cycle is evaluated by the Coefficient Of Performance (COP), defined as the ratio of the cooling capacity obtained at evaporator over the heat input for the generator and the work input for the pump. This index is affected by the variation of evaporation and condensation temperatures. The COP will

decrease both if the first decreases or the second increases. This coefficient is affected also by generator temperature: if it increases, the COP will increase.
Finally a table that summarizes the main features of absorption cycles (Table 2-4).

Table 2-4 Water/lithium bromide cycles and ammonia/water cycles properties

Feature	Water/lithium bromide cycle	Ammonia/water cycle
Typical configuration	Water chillers for air-conditioning systems in large buildings	Air-conditioning and food and beverage refrigeration
Typical size ranging	35÷5000 kW_{fr} [9]	10÷90 kW_{fr} [9]
Generator temperature	80÷110°C [10]	120÷150°C [10]
Evaporating temperature	5÷10°C [10]	< 0°C [10]
COP	0,7÷1,2 [9]	0,5 [9]

2.1.2.2. Adsorption cycles

Adsorption is the general phenomenon resulting from the interaction between a solid (adsorbent) and a gas (refrigerant), based on a physical or chemical reaction process. An adsorption refrigeration machine utilizes the phenomenon of physical adsorption between the refrigerant and a solid adsorbent; the molecules of the refrigerant come to be fixed at the surface of adsorbent via connections of the type Van der Waals. It is generally consisted of a generator (or adsorber), a condenser, a pressure-relief valve and an evaporator.

> *"A basic adsorption cycle* (figure 2-7) *consists of four steps: heating and pressurization, desorption and condensation, cooling and depressurization, and adsorption and evaporation. In the first step, the adsorber is heated by a heat source at a temperature of T_H. The pressure of the adsorber increases from the evaporating pressure up to the condensing pressure while the adsorber temperature increases. […] In the second step, the adsorber continues receiving heat and its temperature keeps increasing, which results in the desorption (or generation) of refrigerant vapor from adsorbent in the adsorber. This desorbed vapor is liquefied in the condenser and the condensing heat is released to the first heat sink at a temperature of T_C.[…] At the beginning of the third step, the adsorber is disconnected from the condenser. Then, it is cooled by heat transfer fluid at the second heat sink temperature of T_M. The pressure of the adsorber decreases from*

the condensing pressure down to the evaporating pressure due to the decrease in the adsorber temperature. […] In the last step, the adsorber keeps releasing heat while being connected to the evaporator. The adsorber temperature continues decreasing, which results in the adsorption of refrigerant vapor from the evaporator by adsorbent, producing the desired refrigeration effect. […] The basic adsorption refrigeration cycle is an intermittent system and the cooling output is not continuous. A minimum of two adsorbers are required to obtain a continuous cooling effect (when the first adsorber is in the adsorption phase, the second adsorber is in desorption phase)." [11]

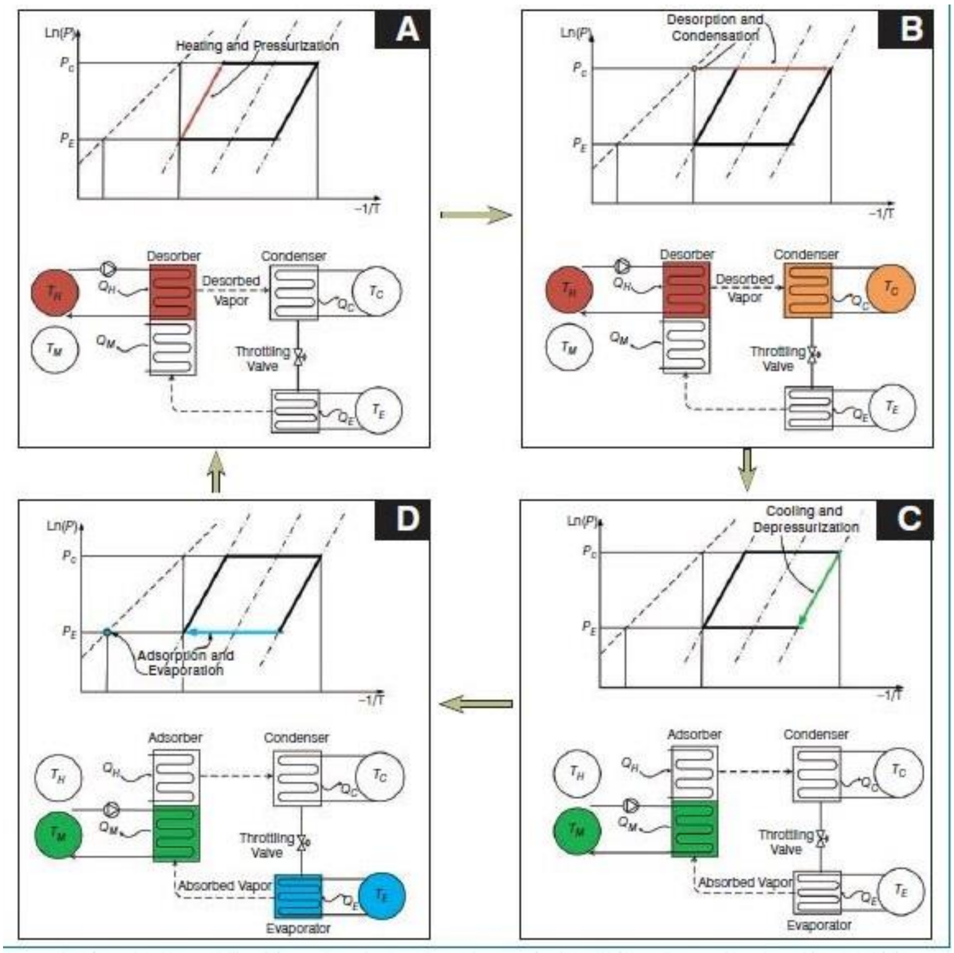


Figure 2-7 Schematic and outline of an adsorption cycle [11]

The solid adsorbent is a material that is able to carry an amount of liquid in its interstice; the adsorption cycle uses different types of adsorbent, which are classified as physical, chemical or composite adsorbents. Main physical adsorbents are activated carbon, silica gel and zeolite, which are porous media; main chemical adsorbents are metal chlorides (as calcium chloride, barium chloride, magnesium chloride, etc.) while main composite adsorbents are a combination of porous media and chemical adsorbents. In table 2-5 the main working pairs (adsorbent and refrigerant) and their properties are summarized.

Table 2-5 Absorption working pairs properties

Working pairs	Advantages/drawbacks	Evaporating temperature	COP
Physical adsorbents			
Activated carbon and methanol	**Advantages** High adsorption quantity[1] Low adsorption heat Low desorption temperature (about 100°C [11]) **Drawbacks** Decomposition of methanol at high temperature (T>120°C [11]) Subatmospheric pressure Hermetically sealed vessel	-5°C [12]	0,55 [12]
Activated carbon and ammonia	**Advantages** Low adsorption heat Low desorption temperature (about 200°C [11]) High operating pressure Compact components **Drawbacks** Toxicity	3 ÷ 8°C with a convective thermal wave cycle (advanced cycle) [13]	0,67 [13]
Silica gel and water	**Advantages** Low adsorption heat Low desorption temperature (low as 50°C [11]) **Drawbacks** Low adsorption quantity Impossibility to produce evaporation temperature below 0°C (as a consequence of water property)	10°C [13]	0,4 [13]
Zeolite and water	**Advantages** Low adsorption heat Low desorption temperature (about 200°C [11]) **Drawbacks**	5°C [13]	0,9 [13]

[1] "The equilibrium adsorption quantity is the amount of refrigerant adsorbed by the sorbent when the reaction time tends toward infinite, and it is an important parameter for adsorption working pairs." [13]

	Low adsorption quantity Impossibility to produce evaporation temperature below 0°C (as a consequence of water property)		
Chemical adsorbents			
Metal chloride and ammonia	**Advantages** High adsorption quantity **Drawbacks** High adsorption heat Metal chloride crystallization	-25 ÷ -10°C (respectively with double and single effect system) [13]	0,4÷0,32 [13]
Composite adsorbents			
Silica gel and chloride and water	**Advantages** Higher adsorption quantity than physical adsorbents Higher performance than physical and chemical adsorbents	N.A.	N.A.
Chlorides and porous media and ammonia	**Advantages** Higher adsorption quantity than physical adsorbents Higher performance than physical and chemical adsorbents	-25 ÷ -15°C [13]	0,36÷0,41 [13]

Adsorption systems can be can be driven by waste heat and low-grade heat such as solar energy.

The major drawback of adsorption systems is the low energy efficiency: the COP (Coefficient Of Performance: the ratio of cooling capacity to thermal energy supplied to the system) is usually in the range of 0,1÷0,6 [11], due to the thermal coupling irreversibility.

Several advanced cycles have been developed in order to increase the performance of the cycle, which implement a heat and/or mass recovery (such as heat recovery cycle, mass recovery cycle, and thermal wave adsorption cycle).

Main features of absorption and adsorption cycles are shown in table 2-6.

Table 2-6 Absorption and Adsorption cycles properties

	Absorption cycle	Adsorption cycle
COP	Moderately high (0,5÷1,2)	Very low (0,1÷0,6)
Capacity	High (10÷5000 kW)	Low
Heat source temperature	High (at least 90°C) [11]	As low as 50°C [11]
Evaporating temperature	Not below 5°C in case of water/lithium bromide and up to -20°C in case of ammonia/water pair	In a range of -5÷10°C in case of physical adsorbents and in a range of -25 ÷ -10°C in case of chemical and composite adsorbents
Electrical consumption	Yes, for the pump	No
Risk of crystallization	Yes, in case of water/lithium bromide pair	No, because sorbent is in a solid state
System	Quite complicated in case of ammonia/water pair, because of rectifier	Simple
Corrosion problem	Severe	Easy
Possible utilization in case of vibrations	No, because of liquid state of sorbent	Yes, because of solid state of sorbent

Figure 2-8 illustrates the variation of COP with the generator temperature in the case of different types of absorption and adsorption cycles.

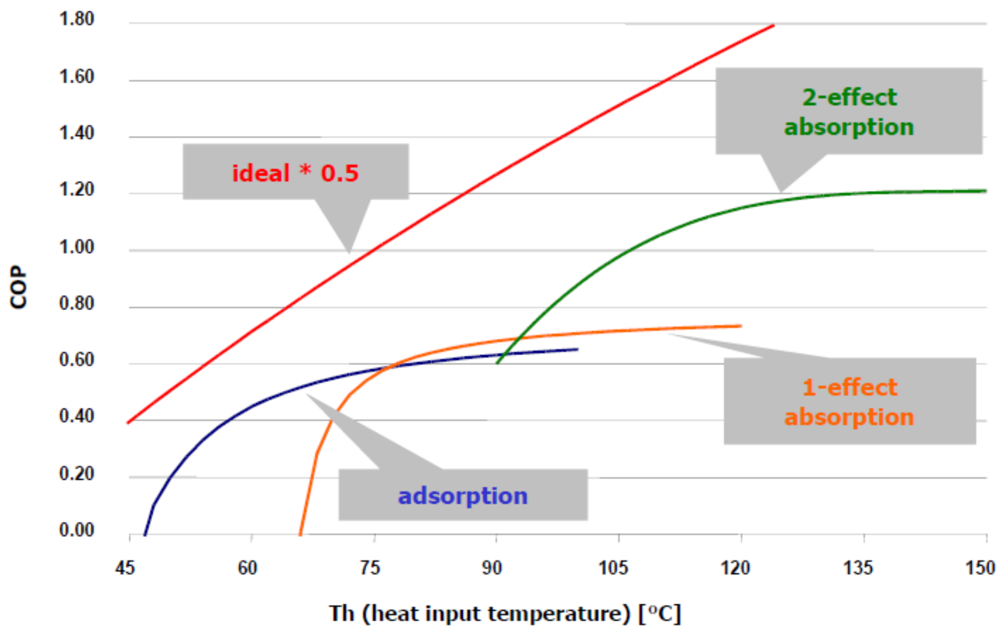


Figure 2-8 COP vs heat input temperature for different sorption cycles [14]

Ideal COP is the maximum COP achievable for a given set of condensation, evaporation and generator temperatures. The graph demonstrates how the irreversibilities (finite temperature difference and mixing) of real processes are responsible for the degradation of the COP. It shows also how advanced absorption cycles, like double effect cycle, improve the performance.

2.1.3 Evaporative cooling

In evaporative cooling devices, refrigeration is generally achieved by evaporating a liquid. Evaporation consumes thermal energy which lowers the temperature of the substrate on which evaporation takes place, and thereby also of the neighboring material. Most common are evaporative systems where water is evaporated into air.
Normally an evaporative cooler consists of two pots of different size, sand and water. The smallest pot is positioned into the biggest and the space between the containers is filled with sand, which is kept wet with water. Often sacks or cloth are used as cover in order to keep low temperature. When the water evaporates from sand, the desired cooling effect occurs in the smallest pot. This effect however has of course a temperature limitation (10°C [15]), , which limits the application to vegetables and fruits conservation. It must be underlined that the efficiency of evaporative coolers depends on the humidity of the surrounding air..
Different materials can be used as earthenware container and sand or bamboo/wooden frame covered by wet cloth, bricks and sand. Thanks to the low cost and simplicity, and to the absence of any external power supply, evaporative coolers are widely spread where the electric grid is not available, as in several areas of developing countries.

2.2 Review of existent technologies for stand-alone systems

The present section consists of the review of the prototypes developed for food preservation powered by solar energy for stand-alone applications. The most significant systems are described in detail by reporting economic and technical specifics. The described systems are both commercial models, laboratory prototypes and computer simulations. Other similar cooling technologies are reported, among which vaccine refrigeration systems and coolers powered by alternative sources.
The prototypes are classified in two main categories, icemakers and refrigerators, and are divided according to the cooling cycle running them. At the end of every subcategory a critical comparison lets emerge advantages and drawbacks of each prototype. A final

qualitative comparison shows how the aforementioned systems are suitable for different needs.

2.2.1. Icemakers

Production of ice is crucial for developing countries to improve social and economic conditions of remote and isolated areas since it preserves agricultural products, food, medicines and vaccines. Moreover, the production of ice can be considered one of the most effective forms of solar refrigeration, because the intermittent solar source can be stored as latent heat in the ice blocks

2.2.1.1. Vapor compression icemakers

PV hybrid ice-making system

The most peculiar icemaker of this type is a photovoltaic hybrid system [16] [17] installed in 2009 in the middle of the Chihuahua desert (northern Mexico) to serve the fishing community of Chorreras. In this community there are seventy fishermen fishing in the artificial lake created by the Rio Conchos. They have problems with fishes' trade because the merchants from the surrounding cities often do not reach the lake to buy fishes, since it is far from the market. Gasoline is too expensive and fishermen cannot pay a trucker for fish transportation. They cannot preserve fishes for a long time because there is neither an electricity grid network providing the community nor a local ice source. As a consequence a lot of fish is wasted.

In order to solve this problem, the State of Chihuahua and Sandia have joined forces, and SunWise Technologies of Kingston (NY) and ENSO have designed and installed a suitable system to provide ice on the premises. Furthermore, because the community needs ice also for personal use, an aqueduct has been built across the desert in order to supply drinking water for ice production. The selected technical solution (shown in the following figure 2-9), is a hybrid system because the icemaker can be powered both by the photovoltaic panels and by a propane generator. The latter has the purpose of increasing the ice production. The backup during cloudy days is guaranteed by a battery bank, which also enables the system operation at night.


Figure 2-9 Photovoltaic icemaker installed in Chorreras [16]

The photovoltaic system has a power of 2.4 kW and consists of a photovoltaic array with monocrystalline solar cells produced by Siemens. The generator power is 6,3 kW, it is produced by Kohler. The battery bank has a capacity of 2200 Ah. Other system components are: two inverters (each rated at 3,6 kW) and a power control. The icemaker is placed in a fish storage building. It is based on a vapor compression cycle and produces from 75 kg to a maximum of 400 kg of flakes ice per day. The whole system has two different operating modes:

- during summer, in order to reduce ice making efficiency losses caused by the high ambient and water temperatures during the day, it runs at night and is driven by the batteries. These are charged by the PV array during the day;
- in winter season the icemaker produces ice during daylight hours. This allows minimizing battery roundtrip efficiency losses and reducing battery cycling: so that the batteries lifetime is extended.

The icemaker has a vertical evaporator, which freezes the water while a crusher breaks ice into flakes, which are conserved in the fish storage room. This chiller has a typical operation: it runs twelve cooling cycles per day, each lasting fifteen minutes for a total of three hours. The cooling cycle is reversed for about thirty seconds at the end of each operation to remove the ice from the surface. This procedure causes a loss of daily ice production of about 3,5%. The battery bank is kept in an insulated plastic container with thick walls filled with water and baking soda. In order to maintain these batteries below 45°C, a passive cooling vent, a small hydrogen vent fan and a dc cooling fan are used.

System monitoring has shown that after thirty months of operation and proper maintenance the hybrid system is able to produce a maximum of 25000 kg of ice per year from the solar source (indeed the Chorreras community used only 3% of propane generator power), 11,5 kg of ice per sun hour and has an overall COP of 0,65. On average the photovoltaic production can match the required load, as it is shown by the graph in figure 2-10, which contains the results of monitoring activity.

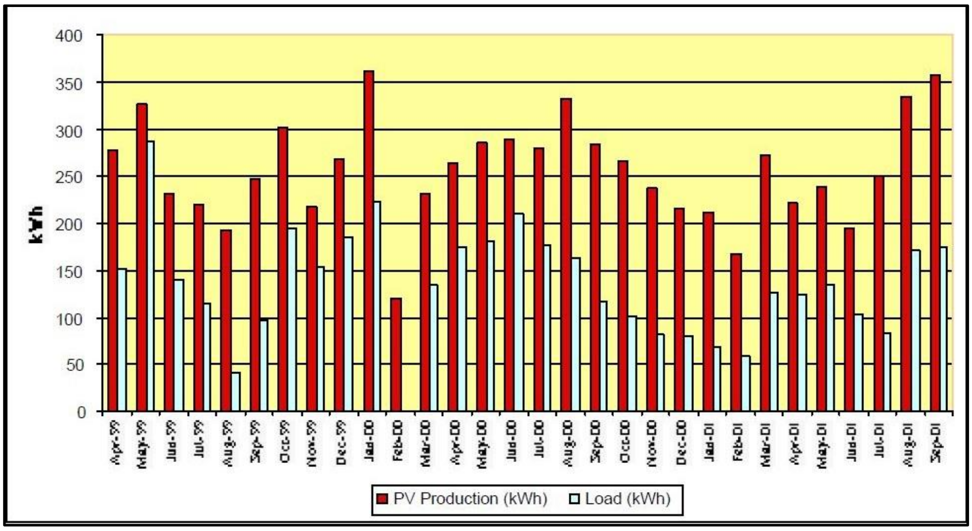


Figure 2-10 Overall Chorreras PV ice-maker system energy performance (first 30 months) [16]

However, in case of irregular maintenance, the ice production is reduced down to 19700 kg of ice per year. Irregular maintenance means irregular cleaning of the icemaker water pipes, which becomes calcified due to large content of carbonate in the water. A regular cleaning consists in rinsing the pipes with vinegar every six to nine months. This system costs US$ 38000, while the final cost, including the aqueduct construction and system monitoring, is US$ 150000. Project managers have done an economic analysis of the system, by estimating the value of ice at US$ 0,3 per kg. They have determined a 7 year Pay Back Time. They presume that the PBT could decrease in case of a better operation and maintenance and if the value of reduced fish spoilage were taken into account.

PV ice-maker

An additional and more sophisticated icemaker [18] is developed by The ILK Dresden-Institute fur Lüft- und Kältetechnik (Institute of Air Handling and Refrigeration) with the support of the German ministry of Economics. In this case there is not a real need behind the project, however its aim is developing a system (easy to transport and to set up) for ice production directed to rural villages without connection to the electrical grid. The ice can have a double aim: cooling directly food or cooling an insulated box. In figure 2-11 we can see the external aspect of the system.

Figure 2-11 PV-Ice Maker developed by The ILK Dresden [18]

The system is supplied only by photovoltaic installation but a battery bank is present as a backup in case of cloudy weather. It is recommended a maximum temperature of 48°C in order to have a good performance of the battery. The components are sixty monocrystalline modules by BP with a total power of 5,1 kW, a battery bank with a capacity of about 4,8 kWh, three dc/dc-converter (each of which with a power of 2,2 kW), one bi-directional charge regulator and also a water storage with a volume of 600 l. The icemaker, water storage and battery bank are contained in a standard 20 ft container. The icemaker can produce up to 300 kg of crushed ice per sunny day and is based on a direct evaporation process: refrigerant evaporates inside evaporator plates which are sprayed with water. As in the system we have previously described, the refrigeration cycle is reversed for some seconds in order to collect ice, which falls in the storage box. One to four plates can be used in order to have a more flexible supplying energy system. This permits to produce a lower quantity of ice with respect to the one produced with high solar radiation. An additional feature is present: in order to increase system efficiency, it is possible to regulate the speed of the two compressors of different size if the evaporator temperature tends to decrease below a certain value. In particular at a evaporation temperature of -10°C and a condensing temperature of 45°C the cooling power of the small compressor is 1,9 kW while that of the larger compressor is 4,0 kW. Because this system is patent-protected, more information about operation, performances and costs are not available.

PV ice-maker without battery

As we have already seen in previous examples, in a typical icemaker, based on the vapor compression cycle, the compressor is driven by photovoltaic panels through a battery bank, a charge controller and an inverter. Battery bank, charge controller and inverter are devices affected by critical environmental, operating and economic problems, thus the Renewable Energy Laboratory at the Technological Educational Institute of Athens has developed a solar photovoltaic icemaker without these devices [19]. It is suitable for health, commercial, agricultural and domestic purpose in remote areas. This system can remain operational even with low solar irradiation and is developed in order to optimize the utilization of the available photovoltaic power. This is possible thanks to a direct connection between four small-capacity hermetic direct-current compressors (produced by Danfoss) and PV panels passing through an efficient controller developed by the Renewable Energy Laboratory. This controller has the goal of limiting compressors' problematic with startup and load management and operating the four compressors in the most energy-efficient way. The researchers' team has chosen a multiple compressor system instead of a single compressor system because the first allows a larger utilization of energy from photovoltaic system (as is shown in the figure 2-12) and it is characterized by a lower startup power requirements and a higher fault tolerance.

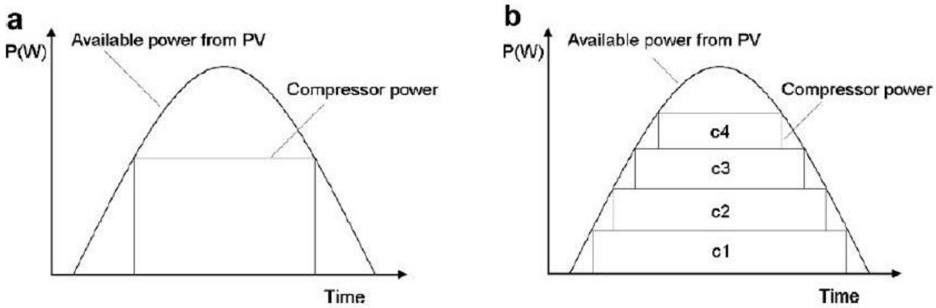


Figure 2-12 A comparison between single and multiple compressor system [19]

In particular, the four compressors are operated in the following way: when the first reaches maximum speed, if excess photovoltaic power is available, its speed should fall to minimum in order to leave an available power level for the second compressor to start. Then the two compressors can reach the maximum speed if the requested power is available. The same is done with the rest two compressors and the same operation pattern is followed during the descendent of the solar irradiance. Figure 2-13 shows solar irradiance and the photovoltaic power supplying the icemaker during a sunny day, highlighting the coincidence between the two trends. It is also possible to see how a multiple compressor system can start at 150 W/m^2 instead of 400 W/m^2 for a single compressor system.

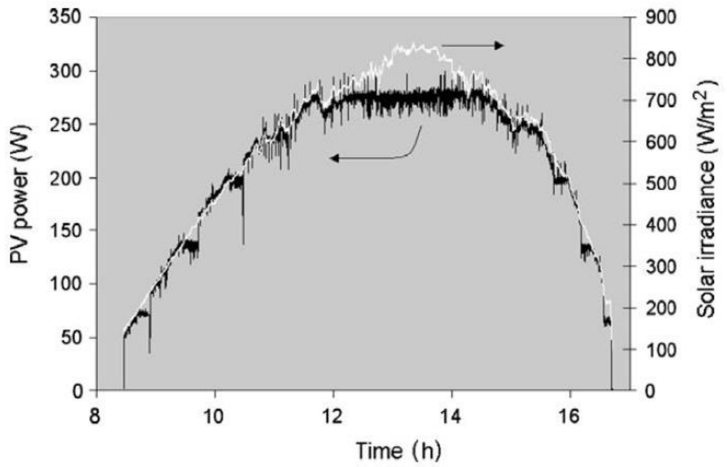


Figure 2-13 Variation of PV power and solar irradiance on a sunny day [19]

The icemaker consists of a photovoltaic array with a power of 440 W_p and an area of 3,3 m^2 connected directly to four compressors, an insulated ice storage tank (with a volume of 175 l) filled with water, in which two plates composing the evaporator are submerged. This system is able to produce 17 kg of ice on a good day and can be used also as a freezer or a refrigerator, thanks to ice storage. We do not have any information about price and performances since it has been designed only to test the particular operation of compressors and the controller.

Critical comparison

The aforementioned prototypes have been developed to satisfy different requirements, thus different technical choices have been taken for each situation. The icemaker installed in Chorreras has been designed from an immediate and specific need for a stand-alone context. So the team has focused on the realization of a simple and reliable system made for the specific needs of fishermen. In spite of the simplicity of the system, they have studied a particular operation that enables to avoid energetic and icemaker performance losses during summer and limits battery roundtrip efficiency drop during winter. However, they have not developed any control system for an optimal use of available photovoltaic power. On contrary, the Greek Laboratory has designed the icemaker prototype with the specific aim of studying a control of this type. They have developed a very efficient system, which is only a laboratory prototype, at the moment without any application. The ILK Dresden icemaker is designed in function of the available solar source, thus it is quite flexible even without a sophisticated system like Greek one. Another important features is that it can be easily transported and set up, so it can be appropriate for isolated areas. It may be the reason of the choice of monocrystalline modules, which have a high produced power per panel surface and so they need a lower total area.
The main features of prototypes described are summarized in table 2-7.

Table 2-7 Main features of the reported vapor compression icemakers

Icemaker	Alimentation source	Coefficient Of Performance	Optimal ice production [kg/day]	Installed PV power [kW]	R^2 [kg/kW]	Cost
Chorreras	Photovoltaic modules (monocrystalline) + propane generator + battery bank	Overall COP 0,65	75	2,4	31,3	US$ 38000
Dresden	Photovoltaic modules (monocrystalline) + battery bank	N.A.	300	5,1	58,8	N.A.
Greek Laboratory	Photovoltaic modules	N.A.	17	0,44	38,6	N.A.

A possible comparison between the icemakers can be done using the parameter R. It confirms that the Chorreras icemaker is less energy efficient than the others and Dresden and Greek Laboratory icemaker have been developed to maximize their performances.

2.2.1.2. Absorption icemakers

The ISAAC solar icemaker

The most particular icemaker based on the absorption cycle is a solar powered icemaker [20] installed in two rural Kenyan villages in order to produce ice to preserve milk. In these villages dairying is widespread but the farmers cannot conserve extra milk, which is not destined to self-consumption, for long time. Thus they often cannot sell extra milk, also because of the distance to the market, with a resulting loss of additional income. The project, funded by the World Bank's Development Marketplace program and developed by Solar Ice Company (SIC) and Heifer, has the aim of establishing dairy co-operatives, providing farmers with cooling technology in order to improve the process of milk collection and transportation. The system is based upon ISAAC (Intermittent Solar Ammonia Absorption Cycle) technology developed by Energy Concept Company of Annapolis (Maryland) and produced by SIC. It is necessary a brief description of this

[2] R is the ratio of the ice production in a sunny day to the installed photovoltaic power.

specific cycle: first of all it belongs to ammonia/water absorption cycle family, it is supplied only by a solar source and it differs from basic cycle due to an intermittent operation. This means that there is only one external heat exchanger which performs alternately the function of absorber and desorber. This is possible thanks to an operator, who switches a control valve each half cycle. In detail the ISAAC technology consists of a compound parabolic collector (CPC) [21], which focus solar radiation on a cylindrical pipes, that is the absorber or the desorber and therefore contains ammonia/water solution; an air condenser, a percolated evaporator placed in a cold box and a thermosyphon system are also present in the system. About technical choice, the CPC collector has been chosen because it provides acceptable collector efficiency (about 40%) at the required temperature of 105°C, it is characterized by a low concentration ratio[3] and it focuses all radiation (bean and diffuse) within the acceptance angle and thus it do not need a tracking system. This last features allow having a simpler system. The aqueous ammonia has been chosen because it is the lowest cost, most widely available and, in many ways, the most thermodynamically desirable working fluid. It has also some drawbacks that cause a lower cycle COP in respect to other fluids. In particular the disadvantages are the high sensible heat content and high volatility of water, which led to the requirements to rectify the vapor and to drain residual liquid from the evaporator each morning. But these drawbacks are slight in respect to the advantages, in particular the possibility to reach evaporator temperature below 0°C. Ammonia is a toxic gas and thus shipping of ISAAC must be carefully planned because of the ammonia shipping regulations.

The icemaker operates in two modes: during the day, the solar radiation heats the ammonia/water solution and enables generation of ammonia vapor, which flows to the condenser and then the liquid refrigerant generated gathers in the cold box. During the night, after switching the control valve, the thermosyphon system removes heat form the collector so that the temperature and the pressure of absorber decrease till allowing refrigerant to be reabsorbed. As the ammonia evaporates, the water in the cold box freezes. In the following figures the daily and nocturnal operations are shown (respectively in figure 2-14 and in figure 2-15).

[3] Concentration ratio is the ratio of the area of aperture to the area of the receiver. [76]

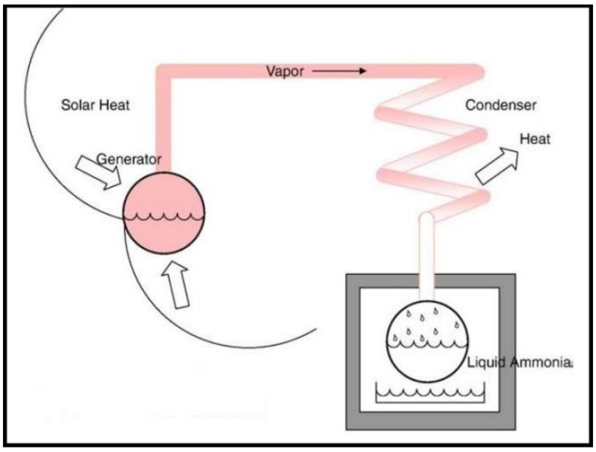


Figure 2-14 ISAAC day mode diagram [20]

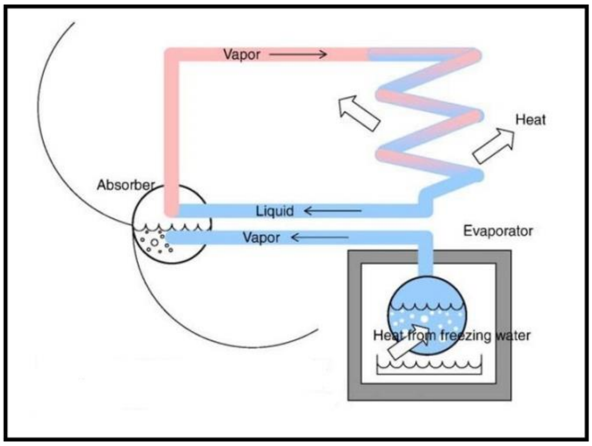


Figure 2-15 ISAAC night mode diagram [20]

The solar icemaker installed in Kenyan villages has a 8 ft by 16 ft (about 11 m^2) solar collector and it can produce six blocks of ice, weighing 8,3 kg each. In a sunny day farmers have up to 50 kg of ice, which are sufficient to chill 100 l of milk; in order to preserve milk they immerge it in an ice bath. This technology, which can be also used for artisan fishing, cold drinks and vaccine preservation, is appropriate for application in remote areas because it does not use electricity and has not moving part, with a consequent decrease of maintenance. Furthermore its construction involves no expensive materials and so its cost is quite low, around US$ 7000. In figure 2-16 we can see three ISAAC icemaker installed in Kenya.

Figure 2-16 ISAAC icemaker [20]

In Kenya, after two years of operation, the system is still operative, it had few maintenance problems regarding the deterioration of the reflective surface, that had inhibited the performance of the solar collector, and it had a positive effect on income's farmers.
Our researches have led us to discover that in the nineties several ISAAC icemakers have been installed in the village of Marvata, on the Pacific coast of Mexico, in order to produce ice for fish conservation during its transport to distant markets [21] [22]. Moreover, unlike the Kenyan application, the technology is used in order to provide refrigeration to an ice tank lining the inside walls of a cold room, on which three machines were mounted. Unfortunately this system is no longer functioning, because of several hurricanes which struck this coast in last years.

The solar ammonia/water solar icemaker

In the eighties the Solar Energy Laboratory of ICSITEE (Bucharest) has developed a laboratory model of an intermittent single-stage ammonia/water solar absorption system [23] able to produce ice for fish preservation in the isolated area of Danube Delta. This model is interesting because it uses in a different way, compared to ISAAC technology, the absorption cycle and because the researchers' team of the project has studied on it a series of improvements, in order to increase ice production and performances. The intermittent single-stage cycle, in respect to ISAAC cycle, differs in the following characteristics: the absorber and the desorber are separated, the rectifier forms a part of the system (like in the continuous cycle) and the condenser and the absorber are cooled by water (indeed the model is assembled on a pontoon which floats on Danube water).

Instead in the same way as ISAAC, the complete cycle of solution circulation is achieved as a result of differences in density and the re-absorption of ammonia vapor and the cooling effect can be achieved only after the weak solution is cooled by a radiator. Another difference, related to whole system, is the type of solar collector: flat-plate collectors with a non-selective surface (polyurethane insulating layer with three transparent shields: one of glass and two of polyethylene) are used. The basic model consists of fifteen solar modules (26,9 m^2 of total surface) with a fixed orientation of 30° and absorption cycle components. It can produce 10,5 kg of ice per m^2 of collector with a total solar insolation of 750 W/m2 available 7 hours daily, which coincide with about 282 kg of ice per day. It can reach a COP value of 0,25. The researches' team has found out some enhancements of the basic system. First of all they have demonstrated that tracking of the sun azimuth increases energy absorbed by the collectors of 25% and a zero-incident angle tracking leads an additional energy gain of 5% (but this second tracking implies a complicate installation which is not justified by the moderate gain of energy). Then they established that refrigerant sub-cooling, internal heat recovery and evacuated solar collectors with selective surface are expedients which improve COP. In the following diagram (Figure 2-17), the improvements are illustrated and a legend is necessary to understand its meaning.

- (▲): COP trend of basic system,
- (●): COP trend of system without recovery heat but with refrigerant sub-cooling,
- (Δ): COP trend of system with partial heat recovery,
- (■):COP trend of system with heat recovery and refrigerant sub-cooling,
- (□): solar efficiency trend of system with evacuated collectors with selective surface.

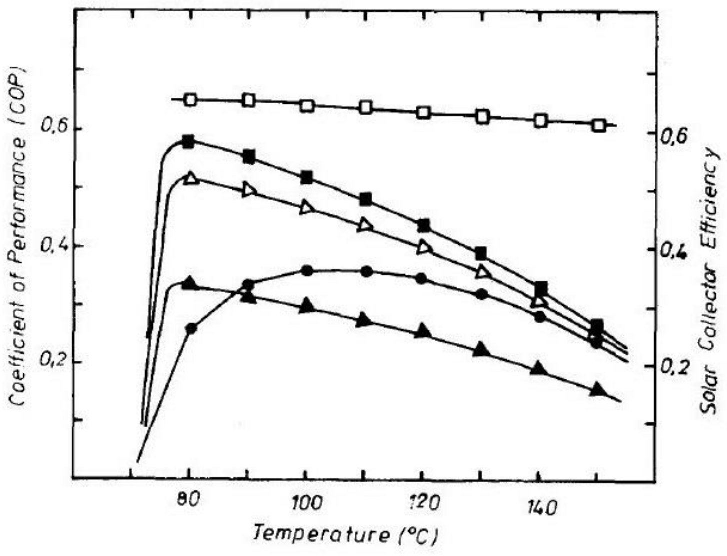


Figure 2-17 COP and solar efficiency function of the outlet generator temperature [23]

In particular the solution with solar evacuated collector achieves a generator temperature of about 80°C and a system COP of 0,30-0,33, which is the maximum value obtained.
With these improvements of system components, the icemaker might produce 1000÷1500 kg of ice per day and the whole system might have a Pay Back Time of 4÷6 years and a lifetime of 15÷18 years. We have to use conditional mode because these values derive from theoretical studies and not from practical tests.

Critical comparison

These two cases demonstrate how an intermittent absorption cycle rather than a continuous cycle is usually used for applications in remote areas. This is due to different reasons: first of all, the intermittent cycle does not need any auxiliary power consumption and this is relevant in order to save energy where there is not an electric grid network or where electricity is too expensive. Second, because it uses solar energy instead of combustion or waste heat, which are normally limited source in remote/rural areas. It can also use natural resources not only for heating the desorber, but also for cooling the absorber, indeed the natural characteristics of nighttime ambient temperature can complete the refrigerant process. However, the less complexity of the system affects the performance, thus intermittent cycle has a lower COP compared to the continuous cycle. Another drawback of this cycle operation is that it is unable to supply a constant cooling power, unless it is provided by means of two or more absorbers working out of phase.
About solar technology, two different choices have been done. The ISAAC icemaker uses a CPC collector, which permits to achieve a generator temperature of about 105°C, while the Danube icemaker can achieve a maximum generator temperature of 80°C only with the evacuated plate collectors with selective surface. The first solution allows reaching an higher temperature, because it is a concentrating collector. It is characterized by interposing an optical device between the source of radiation and the energy-absorbing surface in order to reduce the area from which heat losses occur, in respect with a flat-plate collector. In particular, the CPC collector does not require tracking, reducing mechanical complication, and has the capability of focusing to the receiver all of the incident radiation on the acceptance angle. Instead, the flat-plate solution can be improved by the use of the evacuated technology and, as illustrated in the aforementioned study, the use of a tracking, which introduce a complexity in the system, especially in the rural context.
Finally, considering a wide variation of factors that affect system performances (such as air temperature and solar radiation) the ammonia/water pair has been chosen, because it is the most efficient, has the lowest cost and is most widely available. Despite that, it is important to remind that ammonia is a toxic gas and thus the system has to be treated with attention in particular during its shipping.

Here below table 2-8 summarizes the features of aforementioned absorption icemakers.

Table 2-8 Main features of the reported absorption icemakers

Icemaker	Type of solar thermal collector	Working pair	Generator temperature	Coefficient Of Performance	Optimal ice production [kg/day]	kg of ice per m^2 of collector area	Cost
ISAAC	Compound Parabolic Concentrator (CPC) (total area of 11 m^2)	Ammonia/water	104°C	N.A.	50	4,5 kg/m^2	US$ 7000
Danube	Flat-plate collector (total area of 26,9 m^2)	Ammonia/water	Theoretical value of 90°C obtained with evacuated plate collectors	System COP 0,25	282	10,5 kg/m^2	N.A.

The icemaker powered by exhaust gases

Now we report a case of cooling technology which is not supplied by the solar source.
The Centre de Recerca i Investigació de Catalunya has designed an icemaker [24] addressed to fishing vessels using engine exhaust gases to heat the refrigerant in an absorption cycle. This study has the aim of developing an ice manufacturing system which can reduce energy consumption, size, weight and cost for small and medium fishing vessels. An absorption cycle has been chosen because it has very low mechanical work, such as the work necessary to drive the working pair through the refrigeration cycle. The icemaker has been designed with specific characteristics in order to work without problems in a fishing vessel ambient. Indeed, generally, ammonia/water absorption machines have a problematic operation in an environmental where there are many vibrations: there is a risk of ammonia leakage endangering surroundings, due to high level of toxicity and flammability of ammonia. So the main features are the robust structure and a vertical multi-tubular heat exchanger used instead of a film exchanger, a high-efficiency packed distillation column instead of a traditional plate column and a partial

condensation instead of a rectifier (the last in order to compensate the possible discontinuities in the reflux flow rate). The prototype (Figure 2-18) has been designed to satisfy a cooling load of about 15 kW with a thermal energy of about 100 kW, as in the figure X is shown.

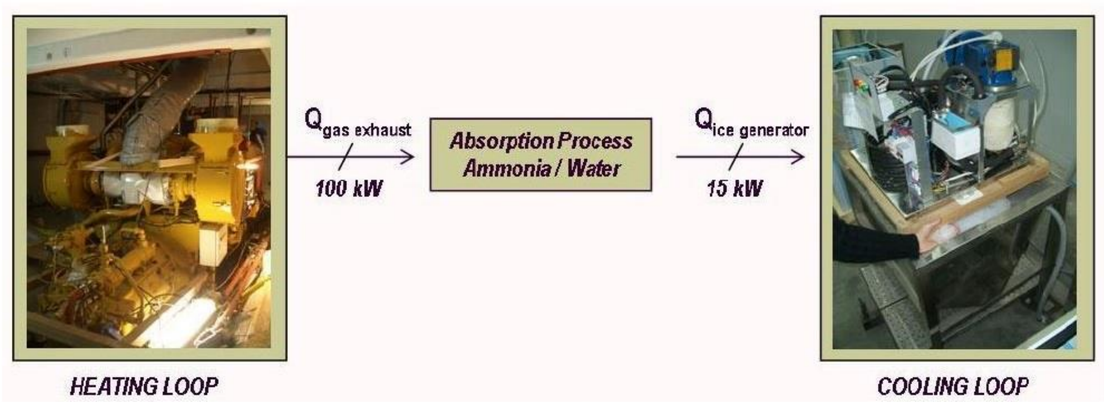


Figure 2-18 Schematic and power flows of the prototypes [24]

The cooling load has been calculated using the ice demand while the thermal energy is originated from the exhaust gases at the moment of vessel's departure from the port (the worst situation).

This icemaker design has not been realized yet because during the study a new European legislation introduced strict security rules regarding the use of the use of ammonia in vessels. The observance of this guideline would have increased a lot the final price of the icemaker and so the researchers and their partners have decided to find an alternative solution. They finally decided to use an electrical compressor (using R404 as refrigerant) coupled with two fluid ice generators assembled in serial configuration.

However this study is interesting and may find a realization in a static application, coupled with a cogeneration system or others, which have available waste heat.

2.2.1.3. Adsorption icemakers

The solid adsorption technology is a promising application to produce ice by using solar energy, thanks to its simple operation and its ability to utilize low grade thermal energy. Our research shows how for this technology the line between ice production and cooling application is thin in this technology. So in this part of review we display only prototypes developed with the specific aim to produce ice, but, as we will see later, these prototypes and their operation are not so different from cooling ones.

No valve solar icemaker

In 2002 four Chinese researchers have developed a solar icemaker [25] in order to find a solution to refrigeration problem in west of China, where solar resource is abundant while electric grid is unavailable or electricity is not sufficient to the cooling goal. This system is based on the solar intermittent solid absorption refrigeration cycle with, as working pair, activated carbon and methanol (the first is the solid adsorbent while the second is the refrigerant). As the intermittent solar absorption cycle, this specific cycle has a daily and a nocturnal operation. During the day, the solar energy received by the collector allows the desorption of methanol from the sorbent bed. The methanol vapor flows to the condenser and then is collected inside the evaporator (which is partly immerged in a water tank). During the night the different environmental conditions allows adsorption of methanol and the evaporation of it inside the cold box cools the liquid water down which is converted in ice.

In detail, the solar icemaker is composed by an adsorbent bed, a condenser, an evaporator, a water tank, an insulated box and connecting pipes. An additional characteristic is that it has not valves and this makes the system very simple. Two systems of this type, which is displayed in figure 19, have been built on a factory and they have the following features.

- The adsorbent bed is made of a thermal insulated box (3) covered with two sheets of fiber plastic (1). It contains in turn a flat plate stainless steel box (2), with a selective coating on the top surface, charged with 19 kg of activated carbon. In order to promote a better heat transfer between front side of the box and adsorbent, many stainless steel fins are placed inside the bed. Its total surface is about of 1 m^2.
- The condenser (5) is made of copper tubes with external aluminum fins.
- The evaporator (7) is designed as a series of four trapezoidal cells.
- The water tank (8) is made of stainless steel.
- The insulated box (9) contains the water tank in which the evaporator is partly immerged.
- About 500 ml of methanol are charged in the refrigerant circuit thanks to the only valve of the system, which has also the function of depressurizing the whole system.

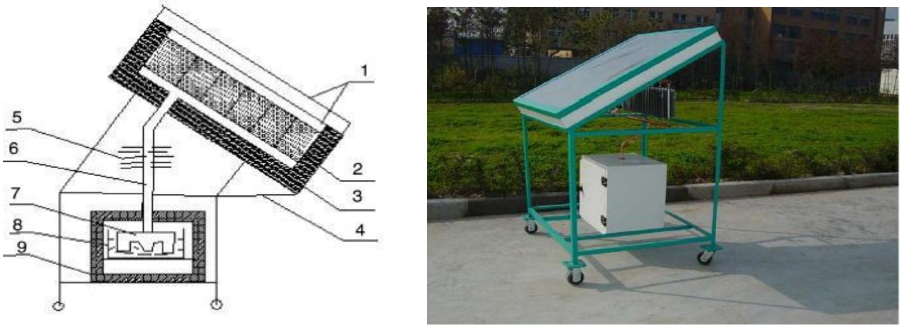


Figure 2-19 The schematic and a photograph of the solar icemaker [25]

This icemaker can produce 5 kg of ice per day when the solar radiation is about 18÷22 MJ/m^2 with a COP_{solar} of about 0,12÷0,14 (COP_{solar} is defined as the ration of useful cooling to the total solar incident radiation) and costs US$ 250.

The novel solar adsorption solar icemaker

In Egypt in 2000 a very particular refrigeration unit [26] has been developed by the Solar Energy Department of National Research Center (Cairo) in order to improve performances also in cold climates, when the solar radiation may be insufficient to heat the generator and to generate refrigerant vapor. Its peculiarity is that "sorption bed, condenser and evaporator are all in one part": they are included in a modified glass tube. The tube is called modified because it is composed of three elements which have not the same shape: the sorption bed is a circular container with small thickness, the condenser is the tube while the evaporator is a cylindrical container covered by foamed polystyrene resin. Figure 2-20 displays the schematic and a photograph of the unit manufactured by the Department.

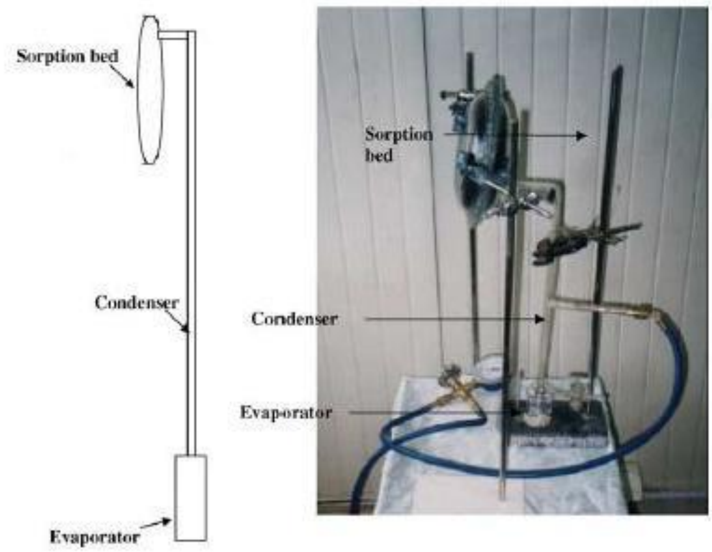


Figure 2-20 The schematic and a photograph of the modified glass tube [26]

The adsorbent bed (of 0,2 m diameter) contains small granules of domestic charcoal (used instead of the typical activated carbon because cheaper). In order to improve its conductivity different types of bed have been studied: bed with black metallic meshes on both faces, bed with black metallic plates on both faces, bed charged with charcoal grains mixed with small pieces of blackened steel and bed charged with charcoal grains bonded with small pieces of blackened steel. Then in order to concentrate the solar radiation on the adsorbent container, different arrangements of plane reflectors (made of wood plates with aluminum foil sticker) have been studied and also a glass shell has been tested to reduce heat losses of the bed in winter. The following figure displays the different types of reflectors and the glass shell (Figure 2-21). Only the type (d) has a fixed orientation over the whole year, while the orientation angles of the others have to be changed every month in order to receive the maximum solar energy at noon.

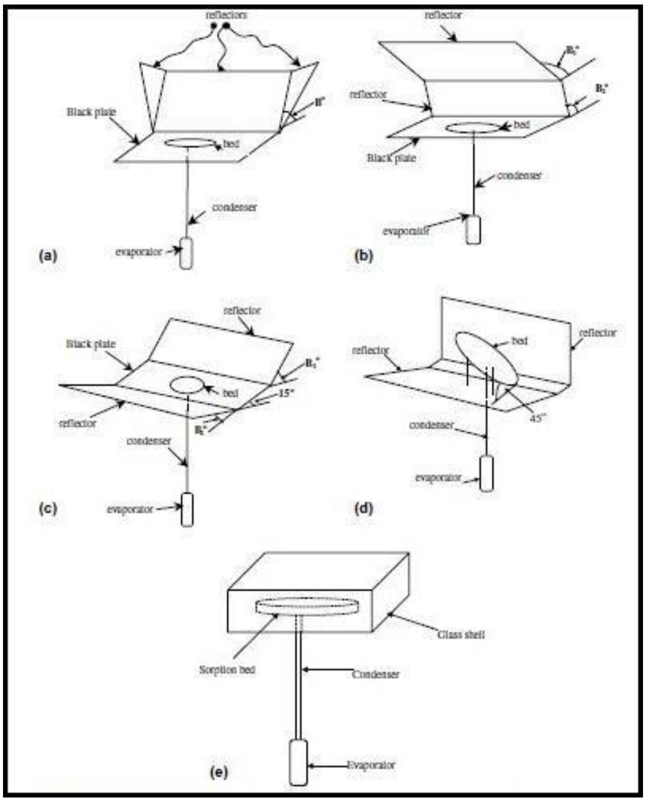


Figure 2-21 Different types of reflector [26]

The prototype has been tested and the results have showed how the fourth bed technique and the reflector type (c) have the best performance, especially when tested in winter. This is possible thanks to several characteristics of module: the glass adsorbent bed enables directly absorption of solar energy and its circular shape increases the exposed area to the Sun and insures uniform temperature distribution inside the bed. Then the use of materials with high thermal conductivity (as blackened steel) inside the bed increases temperature reached by adsorbent and reflector arrangement is able to heat both faces of sorption container.

In regard to performances, the system (which consists of many units) has a daily production of 6,9÷9,4 kg/m^2 and a net solar COP (defined as the ratio between net cooling produced and total energy input to the system during the day) of 0,136÷0,159 in cold and hot season respectively. It can achieve a generator temperature of 120°C (cold season) and 133°C (hot season) and the evaporator reaches the minimum temperature of -1°C.

This results show how the novel adsorption icemaker has good performance, regarding on other similar prototypes.

Critical comparison

From the comparison between the two cases it emerges how the use a certain type of concentrating collectors leads to a specific icemaker performance (higher ice production per unit collector surface). Indeed the particular technology used in the novel solar icemaker allows having high generator temperatures (120-133°C) that are not achievable through flat-plate collectors. Even if temperature data of no-valve solar icemaker are not reported, we can assume that a temperature over 100°C cannot be achieved, due to the solar technology used.

The main features of icemakers are summarized in table2-9.

Table 2-9 Main features of the reported adsorption icemakers

Icemaker	Type of solar thermal collector	Working pair	Generator temperature	Coefficient Of Performance	Optimal ice production [kg/day]	kg of ice per m^2 of collector area	Cost
No valve Solar IM	Flat-plate collector with selective surface (total area of 1 m^2)	Activated carbon/ methanol	N.A.	Solar COP 0,14	5	5 kg/m^2	US$ 250
Novel Solar IM	Black plate and/or plane reflectors	Domestic charcoal/ methanol	133°C	Net solar COP 0,159	N.A.	9,4 kg/m^2	N.A.

2.2.2. Refrigerators

During our research we found how solar refrigerators are often used as vaccine coolers. This is connected to the fact that absorption refrigerators, powered by kerosene or liquid petroleum gas, have been widely used in remote areas for vaccine preservation, but starting from 2007 [27] they have been forbidden according to the new stringent requirements established by the World Health Organization (WHO) Performance, Quality and Safety (PQS) system [28]. Indeed the absorption refrigerators suffer from fuel supply interruptions (due to thefts, fuel changeable price and shortage), low efficiency, poor temperature control and frequent maintenance and therefore these problems make absorption refrigerators inadequate to provide the vaccine cold chain[4]. Therefore solar refrigeration, which does not have this kind of problems, becomes the technology that WHO and UNICEF recommended for vaccine preservation in remote areas with unreliable electricity and sufficient sunlight.

2.2.2.1. Vapor compression refrigerators

Generic photovoltaic refrigerators for vaccine

As reported by Practical Action, "an international non-governmental organization that uses technology to challenge poverty in developing countries" [29], photovoltaic refrigerators [30], driven by a vapor compression cycle, with battery are developed and used in remote areas around the world for vaccine preservation. Usually these systems are characterized by the following components: a photovoltaic array, mounted on the roof or ground, with a typical power of 150÷200 W_p; lead acid, long life and deep cycle batteries; a well-insulated cabinet; a battery charge regulator and a converter. Most of them include also a freezer compartment for ice pack freezing. In order to guarantee the vaccine cold chain, the battery bank has to be able to run the refrigerator for five days without sunlight and the insulated container has to maintain internal temperature for at least ten hours when it is disconnected from battery and solar array. These systems are available in different sizes (from 10 to 85 liters of vaccine storage) and cost around US$ 3500÷7500.

Solar PV refrigerator without battery

Starting from 1999 Greenpeace International, GTZ, UNICEF, UNEP, WHO, Danish industrial partners (Vestfrost and Danfoss) and Danish Technological Institute (DTI) have

[4] The cold chain is a system of transporting and storing vaccines within a recommended temperature range of +2 to +8°C; this temperature range has been selected by the World Health Organization (WHO)[77].

collaborated for the development of a photovoltaic powered vaccine cooler without battery [31]**.** The result of this partnership has been the SolarChill technology for vaccine preservation. They have also realized another type of solar refrigerator, named upright type, with the aim of providing a refrigerator for food and beverage to rural areas where electric grid is non-existent or unstable. Researchers are still testing this last type of refrigerator in laboratory, we do not know much about it, so we report extensively about the vaccine cooler's characteristic and main differences between coolers and refrigerators.

The main feature of SolarChill technology is that ice is used as energy storage instead of batteries. This specific storage permits to avoid some problems typical of chemical storage like the tendency to deteriorate, especially in hot climates, or the possibility of reducing the standard lifetime caused by an inappropriate use. Moreover, this solution makes the system cheaper and does not endanger environment. This alternative is possible thanks to the high specific cooling capacity of the ice.

The vaccine cooler (Figure 2-22) is composed by a commercial cabinet of chest type (made by Vestfros) with 100 mm of polyurethane insulation, within which a wall divides vaccine compartment from ice storage. The latter is composed of standard plastic containers (about 18 kg) in contact with a wire on tube evaporator, which provides cooling effect in the cabinet.

Figure 2-22 SolarChill refrigerator [31]

In detail the system has the following operation: three photovoltaic panels (with a total power of 180 W) drive a direct current compressor (made by Danfoss), this runs the refrigeration cycle (which uses R600a as refrigerant fluid, not contributing to greenhouse effect) which in turn produce ice in the cabinet. An integrated electronic control is also present in order to optimize the utilization of available photovoltaic power through a control of compressor speed (in a similar way to icemaker without battery). An additional component within the cabinet, peculiar only of vaccine cooler, is an electrical heater. It is necessary because the vaccines, in order to be effective, cannot freeze: when the temperature decreases below 2°C this component begins operating.

The main differences between vaccine cooler and food refrigerator are compared in table2-10.

Table 2-10 Differences between SolarChill vaccine cooler and SolarChill food refrigerator

Features	Vaccine cooler	Food refrigerator
Net volume	50 liters	100÷160 liters
Autonomy, when input power is unavailable at 32°C ambient temperature	4 days	3 days
Status of development	Commercially	Testing

The prototype has been tested in DTI but also in Senegal, Indonesia and Cuba, then it has been commercialized (it costs about US$ 1800÷2800 depending on geographical area) and it has been installed in 15 countries of East Asia, Africa and Latin America. Producers have adapted the technology to each location and so it is possible to find SolarChill technologies with little differences compared with the original prototype.

Battery-free solar powered refrigerator

Originally developed by innovators at NASA's Johnson Space Center, a solar powered refrigerator without battery [27] [32] has been realized by SunDanzer Refrigeration Inc for storing vaccine or conserving food and drinks. This system, shown in figure 2-23, is very similar to the previous one, so we now highlight the differences.

Figure 2-23 The solar photovoltaic icemaker developed by NASA researchers [27]

The unit is designed to run on 90 to 150 W of photovoltaic power (needed for compressor start-up), but only draws about 55 W when cycling. This photovoltaic panel powers a variable speed, direct current compressor, which enables refrigerant flow through a vapor compression refrigeration cycle, which in turn extract heat from an insulated cabinet. In particular, the refrigeration effect consists in freezing a water-glycol mixture, different from the only water of the previous system, contained in the cabinet. Another difference concerns the control system: a capacitor is used to smooth the power voltage and thus provides additional current for compressor start-up. Finally in this system the ice pack enables to maintain the desired temperature inside the cabinet during cloudy weather for a whole week, even in a tropical climate.
The SunDanzer company has launched the refrigerator on the market only in 2010, after that prototype units have been tested at various locations around the world. In particular the New Mexico State University tested it successfully in 2002 in Navajo Indian Reservation in New Mexico, in Chihuahua and Quintana Poo in Mexico and in Guatemale highlands. Because this solar refrigerator is patented, more information about performance and cost are not available.

Critical comparison

In photovoltaic refrigeration field, some systems have been developed with the main objective of realizing economical, reliable and environmental friendly refrigerators. These

features derive from the use of ice pack instead of batteries as energy storage, and DC compressor that avoids the necessity of inverters.
These specific systems are appropriate for rural areas where electrical grid network is not present or is not reliable, more expensive technologies are not affordable and maintenance is often managed without the proper tools and techniques.

2.2.2.2. Absorption refrigerators

Absorption cycles powered by solar source have not practical application in refrigeration field, but only theoretical studies and/or computer simulations have been done, in order to find a solution for food or vaccine conservation in not electrified areas.

Solar energy powered vaccine cabinet

The first study [33] that we report is a computer simulation (through MATLAB and EXCEL programs) of a mobile refrigerator unit for vaccine preservation, powered by a ammonia/water continuous absorption cycle (Figure 2-24), developed by Faculty of Engineering and Technology at University of Jordan. The absorption cycle is powered by solar energy, in particular the generator is replaced by a cylindrical concentrator collector with an aperture area of 1,5 m x 0,5 m which reflects the solar radiation on a pipe (containing ammonia/water solution) at the center. This type of collector leads to a concentration ratio of 0,9. The researchers have chosen the ammonia/water solution because it enables to reach lower evaporator temperatures compared with other working pairs. Typical features of absorption cycle have been simulated.

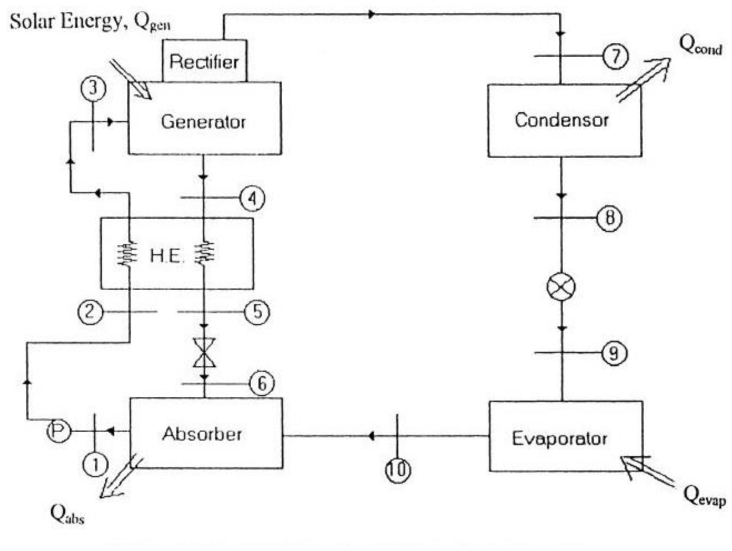


Figure 2-24 Schematic diagram of continuous absorption cycle [33]

In particular, the condenser and absorber are cooled by ambient air and the heat exchanger is shell and tube type.
By means of computer simulation the researchers' team has studied the performance and characteristics of the cooling cycle and they concluded that the maximum value of COP reached is about 0,62 (a reasonable value in respect to typical absorption cycle performance).This value is obtained with a generator temperature of about 100°C and an environmental temperature of 25°C, as shown in figure 2-25.

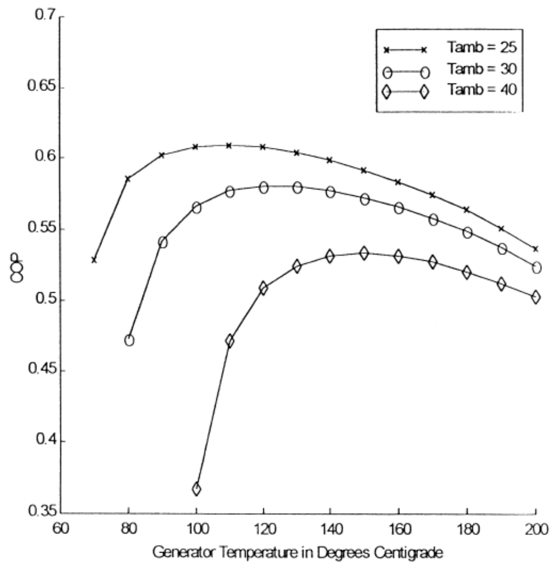


Figure 2-25 Variation of the COP versus the generating temperature with the ambient temperature as a parameter [33]

This optimum range of the generator temperature validates the use of concentrator solar collector, instead of plate collector (which does not permit to reach high temperature). The specific type of concentrating solar collector is unknown but it may be a compound parabolic collector because it achieves typical CPC temperatures (mentioned above)

Solar absorption refrigeration system for milk cooling purposes

The second study [34] reported is a theoretical thermodynamic simulation of a solar absorption refrigerator for milk cooling developed by three Mexican researchers. This study aims to find a technical solution for milk cooling in rural areas of Mexico. Indeed in these areas small dairy farms are widespread but the milk production is very low because heat and humidity affect negatively milk cows. Moreover, farmers do not have refrigeration systems to cool milk and so, in order to avoid a bacterial development, they are able to collect only the morning milking.
A very restrictive regulation exists about milk conservation: milk (which is collected at a temperature of 35°C) has to be cooled as rapidly as possible after milking and, if it is not

collected daily, it has to be conserved at no more than 4°C, in order to check bacterial development. These are the conditions that the technical solution has to respect.
The cooling cycle chosen by researchers is a single stage absorption cycle with monomethylamine/water solution driven by the solar source and an auxiliary heating system. The second supplies additional heat when the solar source is not enough to reach the cooling effect. The monomethylamine/water solution is not a typical choice in absorption refrigeration cycle, but it represents a promising refrigerant/absorbent pair and this study examines its applicability.
In general, the solution has good thermodynamic and physical-chemical properties: it has relatively low vapor pressure at moderate generator temperatures, the latent heat is less than ammonia/water solution but its absorption capacity is greater. The absorption cycle simulated in this study is a typical single stage cycle with typical components (as the generator, the rectifier, the refrigerant condenser, the evaporator, the absorber etc.) and has a standard operation. The supply source is an auxiliary heating system, consisting of a propane gas burner, and a solar system which consists of a collector field. Each collector is made of six evacuated tubes which absorb the solar radiation to heat a thermal fluid (that is not the solution) and for computer simulation researchers assumed a surface emissivity of 0,1, a tilt angle of 30° at 18°55' of north latitude and a 0° azimuth angle. Evacuated tubes notably allow reaching high temperatures in the collector with respect to the classic flate-plate collectors
The absorption cycle and the heater represent only two of four subsystems of the whole refrigeration system, indeed, the milk precooling system and the milk refrigeration system are also present. The first has the aim of precooling rapidly the hot milk just produced through a water heat exchanger. The second instead has the purpose of cooling the milk up to the desired temperature through refrigerated brine in another heat exchanger. The refrigerate brine, which is able to bring milk at 4°C temperature, is obtained by means of the refrigerant evaporation. Finally the milk cooled is collected in a storage tank. The precooling is very important because it permits to reduce the cooling load and the solar collector area.
The study has consisted of two different computer simulations. The first has simulated the absorption cycle performance at typical semi-tropical climate. The results have shown how a cycle COP value of 0,15÷0,7 can be reached with an evaporator temperature of -5÷10°C, a low generator temperature of 60÷80°C and a condenser temperature of 25°C. The second instead has simulated the behavior of the solar system during a year. The results show that the monomethylamine/water solution is a good candidate for solar absorption refrigeration systems and that the use of evacuated tube collectors with high efficiency permits to reduce the solar collector area, without reducing load of heat required.

Absorption refrigeration system powered by a solar pond

In the third study reported [35], three Mexican researchers, during the nineties, have explored the possibility of coupling a salinity gradient solar pond with the ammonia/water absorption cycle.
In general the solar pond can be considered the less common type of solar energy collector and it represents a low temperature heat source. The solar pond analyzed in the study (Figure 2-26) is of salinity gradient type, that is “a solar pond based on the use of a salt gradient column”[35]. The detailed operation is described in the relative scientific article.

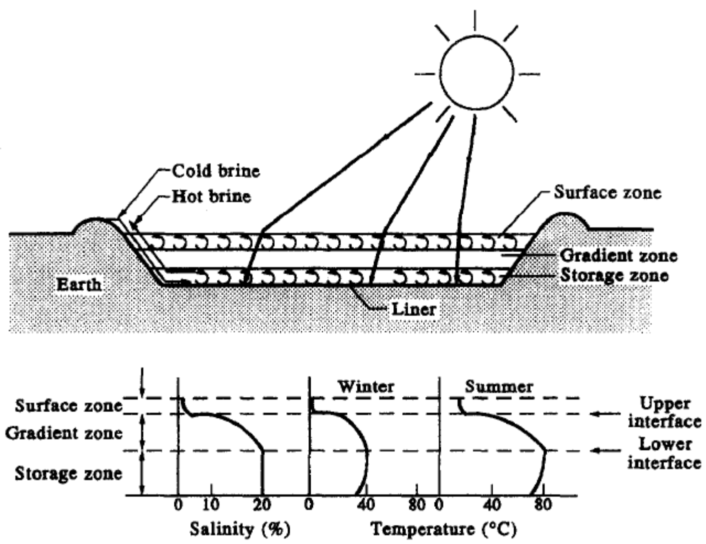


Figure 2-26 Schematic diagram of a salinity gradient solar pond and typical temperature and density profiles [35]

The researchers have carried out this particular investigation in order to solve the refrigeration problem in the villages situated in the northwest coastal regions of Mexico, where the main income is based on sea and agricultural products which need to be preserved at low temperature. Because these regions are characterized by vast expanse of land, a good yearly average of direct and diffusive solar radiation, a source of fresh water or low concentration brine and large amount of salt, a technical solution based on solar pond appeared as an optimal option. The ammonia/water absorption cycle has been chosen due to the low evaporator temperature achieved (below 0°C), but the possibility of coupling a solar pond with this cooling cycle is not immediate because the first can achieve a maximum generator temperature of 90°C, while the second normally requires generator temperature above this value. Thus a series of laboratory experiments has been carried out in order to study the technical feasibility of this system. In these tests, to simulate the solar pond, in the generator researchers used a thermal oil, which is heated up to a maximum temperature of 80°C with electric resistors.

The absorption cycle uses the ammonia/water solution at 52% concentration by weight and it has run in an intermittent mode. In particular, in a different way in respect to intermittent absorption cycle that we have already seen, this operation is not divided into daily and nocturnal stage, but it runs the two stage in two different days. In the first day the regeneration stage, started in the morning, is operated thanks to heat supplied by the hot thermal oil and it has a duration that varies from 6 to 10 hours. In the following day the refrigeration stage, initiated during the morning, is operated, thanks to the generator's cooling occurred during the previous hours, and it has a duration that varies from 3,5 to 7,5 hours. During the experiments also a continuous cycle has been tested adding an electric pump which permits solution circulation in the cooling loop.
The tests have shown how the counter-current circulation of the oil is better than the concurrent one because allows reducing the difference of temperature between the oil and the solution in the generator. In laboratory seven complete refrigeration cycles have been carried out and the results obtained are the following:

- the refrigerator system has the COP in the range 0,24÷0,28
- in case of continuous cycle the same system has the COP between 0,35 and 0,5
- the generator can achieve a temperature of 73°C
- the evaporator can achieve a temperature of -2°C.

These results show how the intermittent absorption cycle has a lower COP in respect to the continuous one, as already discussed in this review. Moreover, the intermittent cycle used in these experiments has a lower COP in respect to the range 0,28÷0,36 reported in the literature. This results from the use of a low level of temperature at generator. Although this drawback in performance, the researchers have concluded that the salinity gradient solar pond represents a clear possibility in absorption refrigeration system.

Critical comparison

The two first simulated refrigerators show the real necessity of using concentrating solar collectors in order to reach high temperatures in the generator (above 100°C). Indeed, the second case illustrated has flat plate collectors and, although the improvement through the use of evacuated tubes, a maximum temperature of 80°C is achieved.
A peculiar characteristic of these simulations is the attempt to study the feasibility of some particular operations of the basic absorption cycle, as using a continuous cycle coupled to a solar source, resorting an unusual working pair or coupling an absorption refrigerator with an alternative solar source.
The studies show the feasibility of these systems, but their real applications may encounter some difficulties.
The main features derived from simulation are summarized in table.2-11

Table 2-11 Main features of the reported absorption refrigerators

Refrigerator	Type of solar collector	Working pair	Generator temperature [°C]	Evaporator temperature [°C]	Cycle COP
Solar energy powered vaccine cabinet	Compound parabolic collector	Ammonia/water	100	N.A.	0,62
Solar refrigerator for milk cooling	Evacuated tube collector	Monomethylamine/ water	60-80	10	0,7
Refrigerator powered by a solar pond	-	Ammonia/water	73	-2	0,28

2.2.2.3 Adsorption refrigerators

Solid adsorption solar refrigerator in Nigeria

An interesting model of refrigerator powered by the intermittent adsorption cycle has been designed, constructed and tested in Nsukka (Nigeria) by Anyanwu and Ezekwe [36]. The researchers' objective has been to develop a refrigeration system able to avoid the fresh food spoilage which occurs in remote rural areas. Indeed in these areas affordable refrigerators are not available due to irregular electric grid. Moreover the inadequate transport facilities do not enable their trade at distant lucrative markets. This situation affects the producers but also the consumers because during the harvest season the agricultural products are abundant and cheap, while during the other times these are scarce and expensive. So the researchers have decided to study a solar powered refrigerator using predominantly local technologies.

The adsorption cycle, which runs the refrigeration system, uses activated carbon and methanol as working pair and it is operated in an intermittent mode. During the day the generation phase is operated and lasts 6 hours, while during the night, thanks to natural cooling, the refrigeration phase is operated and lasts 12 hours. The durations of two phases have been planned in this way because they correspond to the periods of available high solar flux and low air temperature during the night (which permits the adsorber and condenser cooling) in Nsukka climate. The heat requested by generator is

supplied by a solar flat plate collector with an exposed area of 1,2 m^2 made of a galvanized steel sheet painted with black oil paint. Six collector tubes are bonded to the rear face of the plate and they have a coaxial perforated inner tube. Each space between the inner and outer tube is filled with 1,4 kg of activated carbon. The plate and the grill of pipes are mounted inside an insulated galvanized steel sheet box with a clear glass cover. This system, which is inclined at the local latitude of 7° facing south, has the function of generator during daily stage and of adsorber during nocturnal one.
The others components of the refrigeration system are the evaporator, the condenser and the liquid receiver, as can be seen in the following figures.(Figure 2-27 and 2-28)

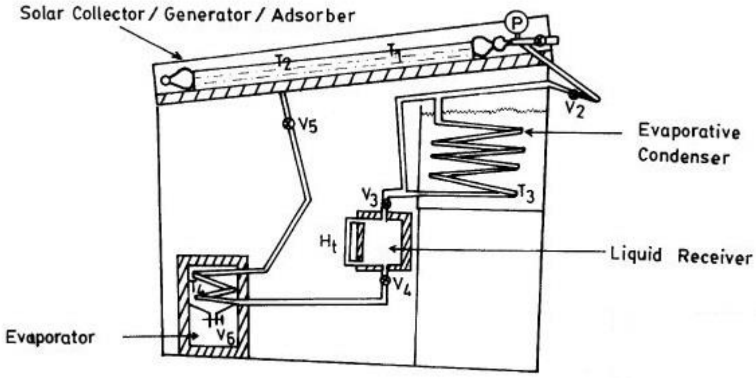


Figure 2-27 Schematic of the Nigerian refrigerator [36]

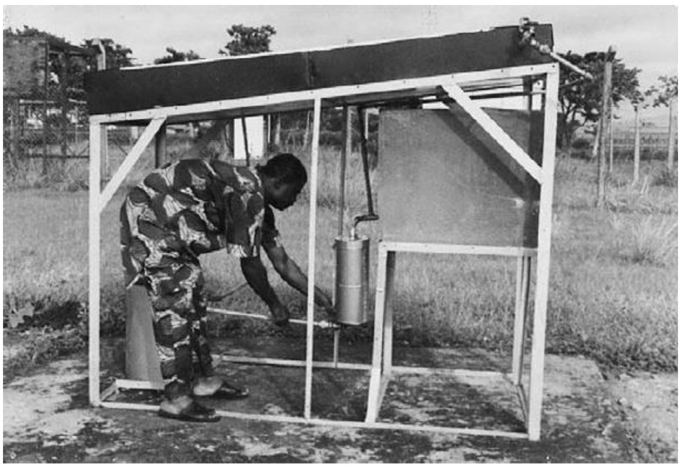


Figure 2-28 Nigerian refrigeration in operation [36]

The evaporator is a coiled copper tube immerged in 3 l of water contained in a steel vessel. The evaporator and the cylindrical steel receiver are contained separately in a larger steel box. Specific attention has been paid to the condenser, because the researchers have used an evaporative condenser. It consists of a coiled steel tube contained in a sandcrete water tank with a volume of 350 l, which is made of a mixture of sand and cement. The condensation effect is eased by the water seeping through the

sandcrete walls and evaporates at the outer wall surfaces. This permits to keep the water contained in the tank cooler and thus to enable the condensation inside the tube.
The tests carried out have shown that on average, the temperature reached by the collector is 96°C. Regarding the evaporator, the lowest temperature reached varies from 1,0°C to 8,5°C, starting form a water initially temperature of 24-28°C. Because this evaporation temperature can produce only chilled water, this system can be used only to preserve drug, fruits and vegetable, which have to be conserved in the temperature range of 4÷16°C. Another interesting result is the solar collector efficiency, which achieves the low value of 11,6÷16,4% and this is attributed to the non-selective coating used for the collector. Thus a system improvement may be the use of a selective surface coating in order to increase the collector efficiency and also the refrigerator COP. The cycle COP achieves the range of 0,056÷0,093, while the overall COP stays between 0,007 and 0,015.[5]
This means that only 10% of the collected energy by the activated carbon granules and only 2% of incident solar energy is converted to the refrigeration effect.

Solar powered adsorptive refrigerator in Burkina-Faso

Butcher, Dind and Pons [37] in 2003 developed a solar powered adsorptive refrigerator, in order to find a good compromise between the possibility of construction the system in developing countries, high reliability and good performance. They built and tested in Ouagadougou (Burkina-Faso) a refrigeration system driven by an intermittent adsorption cycle with activated carbon and methanol as working couple. The figure 2-29 displays a schematic of the prototype.
The first peculiarity of this prototype is that it is equipped with manually operated ventilation dampers. They consist of a mechanism that opens during the night the thermal insulation (2.2) on the rear side of the collector in order to improve the cooling. During the day it remains close (2.1) to avoid thermal losses of the collector (1). Another peculiarity is that the refrigeration effect produces in part ice, which acts as a cold storage and keeps the cold cabinet below 5°C.
The solar collector is placed on the roof of the building, while all the other components are located inside the building in order to protect them from the sun. About solar system, the researchers chose the single-glazed flat plate collector with a selective surface because this type is simple but also efficient at temperature around 100°C. The solar collector, with a total area of 2m^2, has a tilt angle of 14,2°, an absorptance of 0,9 and an emissivity of 0,10-0,15, values possible thanks to the selective layers. About the other components of the system, the condenser (3) is made of parallel finned tubes cooled by

[5] The cycle COP is defined as the ratio between the useful cooling energy and the required energy to make the desorption process possible.
The overall COP is defined as the ratio between the useful cooling energy and the total incident solar energy.

natural convection while the evaporator (6), submerged in a water tank of 40 l, consists of parallel tubes welded to the receiver (4) that collects the liquid methanol. Finally the cold cabinet (7), that contains the evaporator and the water tank (8), is of the chest type, is well insulated and has an available volume of 440 liters. A manually throttle valve (5) is present between the condenser and the evaporator and it is opened just when the desorption and the condensation of methanol is complete.

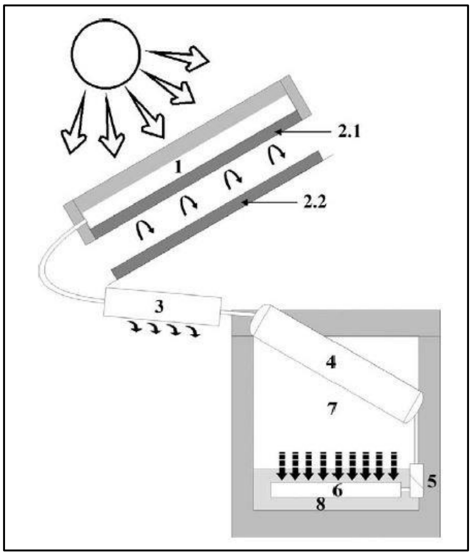


Figure 2-29 Schematic of the refrigerator [37]

The tests carried out show how the evaporator temperature can remain at 0°C or below and a net solar COP (defined as the ratio of the total heat extracted by evaporation of methanol to the incident global irradiance) can achieve a value of 0,12. These results confirm that the use of ventilation dampers increases the performance of the machine by roughly one third.
The prototype has worked and produced cold for more than one year without any intervention or special maintenance and may be improved through an automatic system for operating the dampers, in order to make the system fully autonomous and thus very attractive for remote areas.

Solar adsorption refrigeration in Morocco

In 2005 Lemmini and Errougani [38] [39] have developed at Laboratoire d'Energie Solaire of the faculty of science of Rabat (Morocco) a solar adsorption refrigerator, which uses the pair activated carbon and methanol. The researchers, as in other cases previously seen, have designed this prototype in order to enable perishable food and fish conservation in remote rural areas far from the electric grid network.
The system, very similar to others observed, consists of four main components: the generator/adsorber, the condenser, the evaporator and the cold box. The adsorption

cycle do not differ from the classical intermittent cycle used in this type of refrigerators. In particular the collector, which has the function of generator and adsorber, is composed of a copper plate with the front face painted with a selective coating and glazed with a transparent cover in order to improve the solar absorption. In order to gain the maximum solar radiation during the whole year, the collector has been tilted with an angle of 34°. The union of these elements creates a box which is filled with 14,5 kg of activated carbon spread between 13 fins, whose role is to allow a good heat transfer in the adsorbent. The condenser is made of copper tube covered with 380 fins in order to facilitate its cooling. The only particularity of this prototype is about the evaporator: it is made up of a copper tube placed inside the cold box, but is not submerged in water tank. Indeed the refrigeration effect is not achieved through the water cooling or freezing, but through the ambient air cooling inside the cold box.
The system, shown in figure 2-30, has been tested in Rabat.

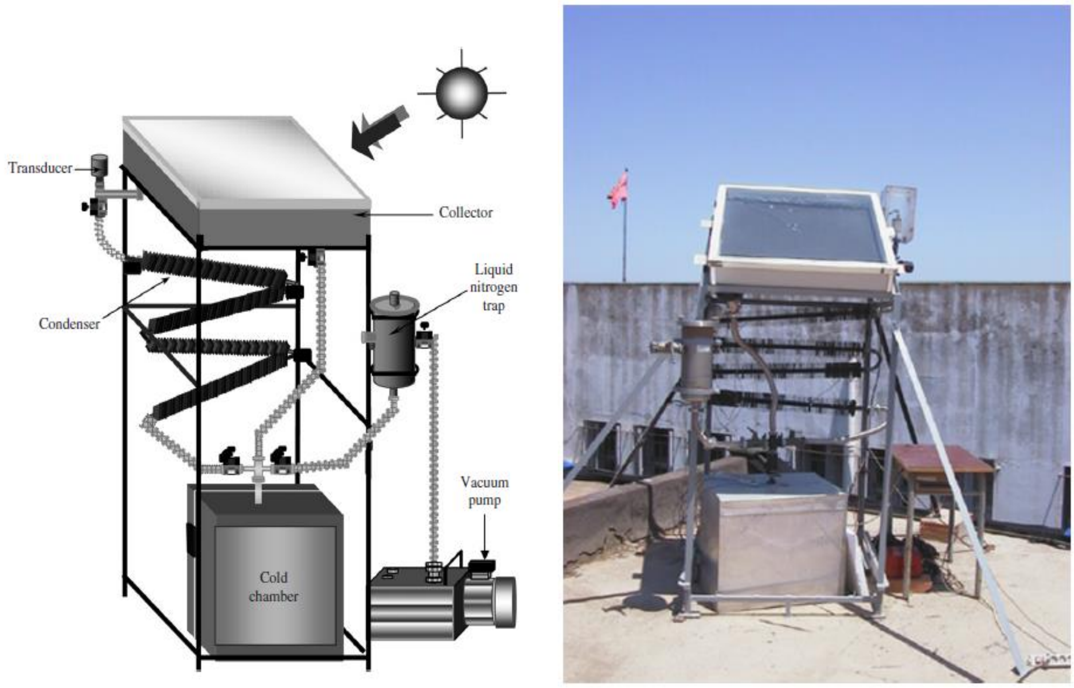


Figure 2-30 A schematic and a photograph of the refrigerator [38]

The results show that with a good daily irradiation (in Rabat a good irradiation correspond to a value above 20000 kJ/m^2) the front surface of collector can achieve a temperature over 90°C and the evaporator temperature are always less than 0°C and sometimes can reach a value lower than -5°C. In particular, the minimum temperature achieved is -11°C, with a daily solar radiation of 28400 kJ/m^2. This means that the refrigeration effect is guaranteed during these days. Instead for days with very low solar irradiation (especially rainy days), desorption does not happen but the collector can adsorb refrigerant, at night, if it is not saturated with the adsorbent.

Regarding the system performance, the solar COP, defined as the ratio of the heat extracted from the evaporator to the daily solar irradiation received by the collector, is between 0,02 and 0,08 and the solar collector efficiency is between 0,63 and 0,77 (good values). The COP value may be improved with a better insulation of the cold box, because it is exposed to climatic conditions, as solar irradiation, wind and ambient air.
Despite that, the prototype has good performance in a Mediterranean climate and so represents an attractive system for refrigeration.

Critical comparison

As mentioned in the icemakers paragraph, the operation and the components of this specific kind of refrigerators are quite similar to adsorption icemakers.
Since this type of cooling technology aims to the preservation of fruits and vegetables, it does not necessarily have to reach temperatures below 0°C. Thus, different methods to maintain the cold box at the desired temperature have been used: cold air, chilled water and a mixture of ice and water have been chosen. Since the three prototypes reported used flat plate collectors, some improvements have been necessary to reach temperatures between 90 and 100°C: in the case of the refrigerators in Burkina Faso and Morocco, selective surfaces have been chosen to optimize the collector capacity of absorbing solar radiation and to reduce the collector emissivity. The Nigeria prototype utilizes black oil paint to increase the collector absorptance.
The lacking information about the costs of the described systems does not permit an economic comparison, so we limit to compare them in an energetic view (Table 2-12).

Table 2-12 main features of the reported adsorption refrigerators

Refrigerator	Type of solar collector	Working pair	Generator temperature [°C]	Evaporator temperature [°C]	Coefficient Of Performance
Nigeria refrigerator	Flat plate collectors (1,2 m^2)	Activated carbon/ Methanol	96	1-8,5	Cycle COP 0,056 -0,093
Burkina Faso refrigerator	Flat plate collectors with selective surface (2m^2)	Activated carbon/ Methanol	100	0	Net solar COP 0,12
Morocco refrigerator	-	Activated carbon/ Methanol	90	< 0	Net solar COP 0,02-0,08

2.2.2.4 Evaporative cooling

This refrigeration system enables only fruits and vegetables conservation because it can achieve the lowest temperature of 10°C. This technique has its roots at least 4000 years back in time, but starting from '90s it has been widely reinvented.

In 1995 Mohammed Bah Abba in Nigeria developed a refrigeration system called zeer (because zeer is the Arabic name of the large pots used) [40]. The system consists of two containers of different size: the smallest is placed inside the larger. The space between the pots is filled with sand, which is got wet with water, so the cooling effect can happen in the inner pot. This system is very simple, can be produced with household or easily available materials and therefore is free or very cheap (it costs maximum 1 US dollar).

As reported by the non-governmental organization Practical Action [15], in Sudan the storage designed by Mohammed Bah Abba has been experimented in food conservation. The tests has reported that the zeer pot is effective and economical and so the local Woman's Association for Earthenware Manufacturing started to produce and market the refrigerator system, shown in figure.2-31

Figure 2-31 The zeer pot produced and market in Sudan [15]

The Janata cooler [15], developed by the Food & Nutrition Board of India, is an adaptation of the basic double pot design of Mohammed. This system consists of a storage pot, an earthenware bowl, water, a cloth and sand. The bowl is filled with water, which has the function of reservoir, and the storage pot is placed inside it. The storage is covered with a wet cloth, which is dipped in the water. Sand is used to isolate the pot from the hot ground. The evaporative effect is obtained through the evaporation of the water contained in the cloth, which is replaced by the reservoir. In figure 2-32 the schematic of the system is displayed.

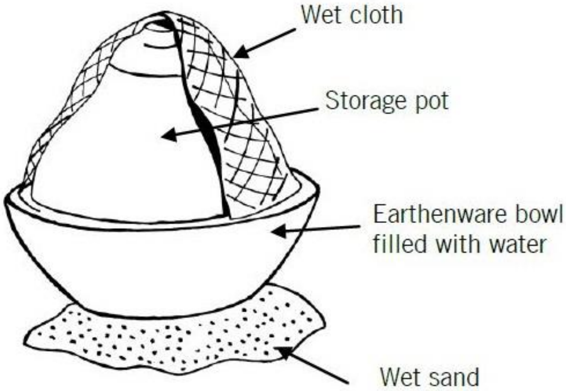


Figure 2-32 The schematic of the Janata cooler [15]

Refrigerators of this type can be built also with materials which differ from earthenware. The first example is the bamboo cooler [15]. In place of the earthenware bowl, a large diameter tray filled with water is used and it contains bricks. An open weave cylinder of bamboo is placed on top of the bricks and it is wrapped with hessian cloth, which has to dip in the water reservoir. On the top of the cylinder a lid is placed to preserve the food.
The second example, called Almirah cooler [15], is more sophisticated: it has a wooden frame instead of bamboo one. This system is also equipped with a hinged door and internal shelves to access easily to the stored food.
The third, called charcoal cooler (Figure 2-33) [15], is quite different from the other models. It consists of a wooden framework which is covered in mesh inside and out in order to create a small cavity. The mesh is filled with pieces of charcoal, which are sprayed with water, thus when this water evaporates, the cooling effect happens. Moreover one side of the frame can be open and has the function of door. This refrigerator is placed out of the house, thus a series of precautions have to been taken in account to avoid that animals, such as rats and ants, get to the food.

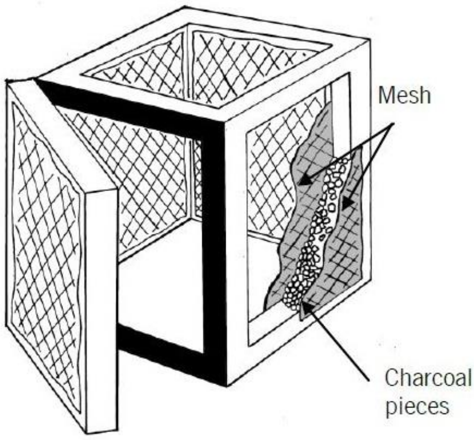


Figure 2-33 The schematic of the charcoal cooler [15]

Finally a system developed by the Indian Agricultural Research Institute (Figure 2-34) [15] is similar to the double pot design, but it has larger size. It consists in a double brick wall, which forms a cavity filled with sand. The chamber so created is covered with cane or other plant material and sacks or cloth. The sand in the cavity and cover are thoroughly saturated with water and a twice-daily sprinkling of water is enough to maintain the temperature level in the chamber.

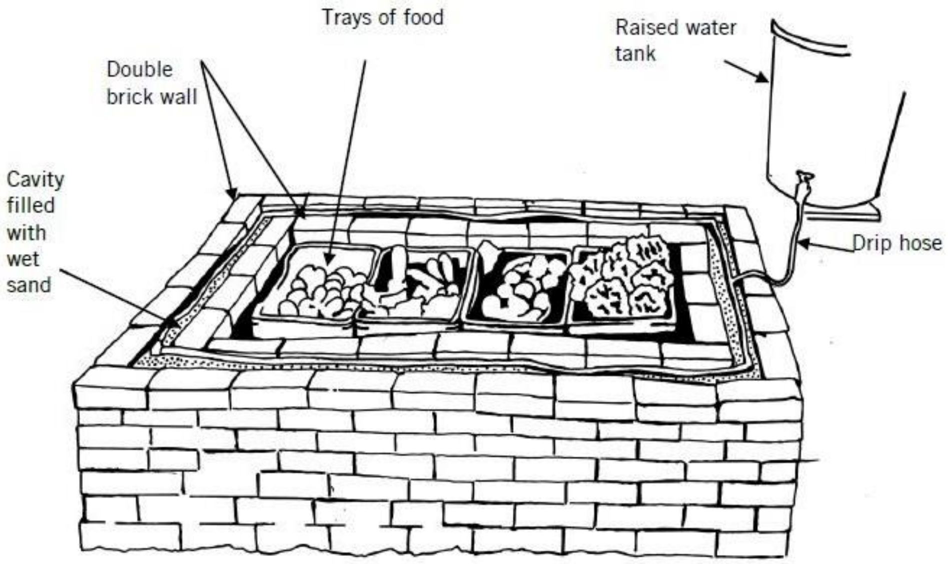


Figure 2-34 The schematic of the static chamber developed in India [15]

A very similar system, called Naya Cellar Storage, has designed in Nepal by Dr. Gyan Shresthra from the Green Energy Mission and Mr. Joshi and it has successfully tested by a young woman to conserve vegetables.

Moreover, several designers have taken the challenge of developing a useful refrigerator which uses evaporative cooling. David Weatherhead has developed the Eco Cooler (Figure 2-35)[41], similar to the Janata cooler, while Oliver Poyntz has developed a zeer refrigerator [42] that fits into a modern kitchen. But the more interesting design product is the fridge developed by Emily Cummins (Figure 2-36) [43]. This prototype consists of two metallic cylinders of different size, one insider the other, between which sand or wool, soaked with water, is placed. This prototype is able to keep the contents dry and hygienic because the water does not come into contact with the product. It can be built using barrels, spare car parts and ordinary household materials, thus is ideal for use in developing world.

Figure 2-35 The Eco Cooler zeer pot [41]

Figure 2-36 The fridge developed by Emily Cummins [43]

2.3 Refrigerators and icemakers: different technologies for different needs

In rural contexts where electrical grid is often absent, unreliable or unaffordable, conserving products of communal activities (like fishery and diary), preserving vaccines and preserving food for households uses is a relevant problem. These different needs lead to develop different cooling technologies.

In particular, icemakers produce different type of ice (blocks or flakes), typically used to keep fishes or milk within the conservation temperature range or rarely to make an energy storage. Generally they are managed by a community or a cooperative, they have large sizes and they permit to increase the fishery or dairy production and consequently the income. Smaller icemakers (like the no-valve solar icemaker) already exist, they may have a domestic application and be transported if equipped with wheels, but a real application has not emerged from our research.

On the other hand, refrigerators are realized with the purpose of conserving vaccines, beverages, fruits and vegetables. The formers requires a more restricted temperature range, while the others a temperature below 10°C. Generally, they are small size refrigerators because they have to conserve vaccines, do not require large volumes or they are destined to domestic uses (food preservation). The only refrigeration developed to communal use may be the evaporative cooling system realized in India. It is a fixed and large size system, so it may be used in a market or near a small farm.

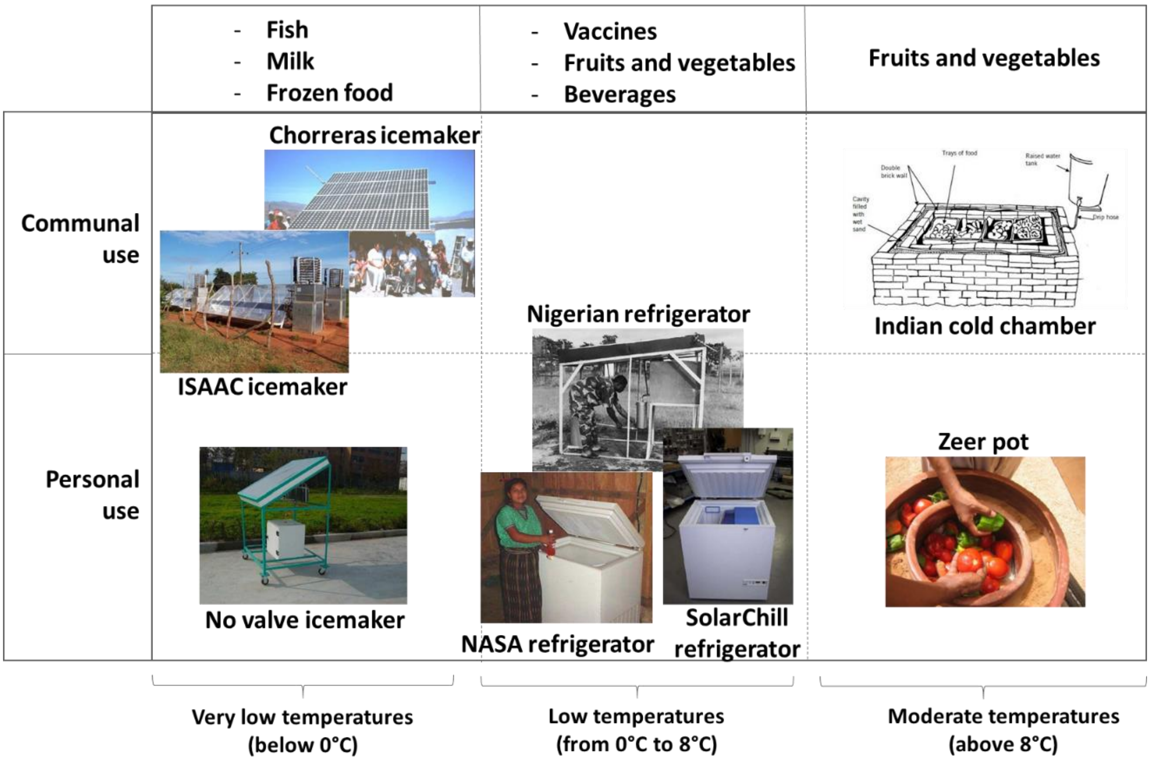


Figure 2-37 Prototypes divided according to applications and uses

Since icemakers can produce different amounts of ice, we now demonstrate how this feature is related to the cooling cycle, which in turn influences the maintenance level of system (Figure 2-38).

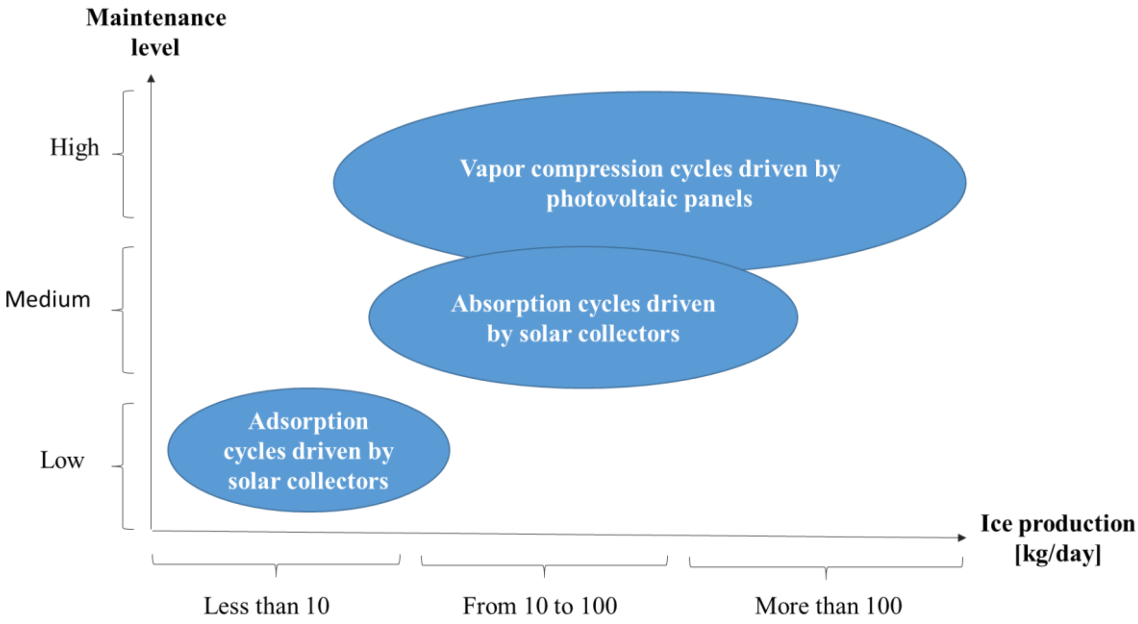


Figure 2-38 Bubble chart representing ice production and maintenance level of different cycles

Adsorption icemakers generally do not have more than one valve and, once charged the refrigerant fluid and made the vacuum in the system, do not require any particular maintenance. The absorption cycle are instead characterized by a more complex system, that requires at least one valve used to reverse the intermittent cycle and usually utilize ammonia as refrigerant, a toxic fluid that necessitates a particular care. Moreover in case concentrating solar collector are used, like in ISAAC icemaker, a regular cleaning is fundamental to avoid a decrease of collector efficiency. Finally vapor compression system powered by photovoltaic panels needs a high level of maintenance because shows more critical components, like batteries and inverter. In particular, the first has to be replaced frequently, kept below a specific critical temperature and, depending on the type of battery, filled with distilled water. In addition, photovoltaic panels need a regular cleaning as concentrating solar collectors.

The chart illustrates the quantity of ice allowed by different cycles. Vapor compression cycles allow a wide range of ice production: systems as Chorreras or Dresden icemakers produce large amounts of ice (more than 80 kg), while refrigerators using ice as energy storage (like SolarChill) produce a lower quantity. Absorption systems produce already a significant quantity of ice (more than 50 kg per day) and it is possible thanks to a significant collector area. Finally, the adsorption system produce a small quantity of ice, (no more than 5 kg per day), because of the lower cooling heat produced by this cycle, due to low COP typical of adsorption systems.

When large amounts of ice are needed the use of vapor compression cycles is preferred because sorption icemakers, in particular those with adsorption cycle, are characterized by lower acting cycles and poor thermal conductivity of the generator. According to

Critoph [44] in case of carbon/ammonia adsorption icemaker "[…] *the time taken for a cycle could be an hour or more and the cooling power per mass of adsorbent could be as low as 10 W/kg. This is not a problem with solar powered vaccine refrigerators which produce a few kg of ice each day and operate on a diurnal cycle. However, a refrigerator producing one tonne of ice in a diurnal cycle would need 5 tonnes of carbon and contain 1.5 tonnes of ammonia. When contemplating larger icemakers it is obviously necessary to use a much faster acting cycle in order to reduce the mass of adsorbent and the cost of the system*".

Finally table 2-13 containing typical collector type and their characteristic, obtained from literature [45], is shown in order to demonstrate how the features of solar system of prototypes (only absorption and adsorption ones) are distant from the theoretical values.

Table 2-13 Features of different collectors types [45]

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking			5–15	60–300
	Linear Fresnel reflector (LFR)	Tubular	10–40	60–250
	Parabolic trough collector (PTC)	Tubular	15–45	60–300
	Cylindrical trough collector (CTC)	Tubular	10–50	60–300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100–1000	100–500
	Heliostat field collector (HFC)	Point	100–1500	150–2000

In the prototypes with a real application (like ISSAC, no-valve icemaker, Morocco and Nigeria refrigerators), the solar collectors are all of stationary type, in order to make the system simpler and easily manageable in rural context. On the other, hand tracking solar collector have been studied (like Danube icemaker), but there is no real application of this system between the prototypes described. Regarding the absorber temperature, it is possible to find a correspondence between real system and theoretical value. CPC collector of ISAAC icemaker achieves 104°C, the flat evacuated plate of Danube achieves a maximum temperature of 80°C, flat plane collectors of Morocco, Nigeria and Burkina Faso refrigerator reach a temperature over 80°C because different method of improving solar radiation absorption are used.

3. Case Study

In this chapter a specific case of food preservation is illustrated and analyzed. It concerns a remote area of Mozambique, in the province of Zambezia, where the problem of fish preservation emerges. An Italian non-governmental organization is operating in the area of interest and one of the objectives of its project is the improvement of fish preservation. Because of shortage of technical skills they proposed to us this matter.
We start with the description of the general and local context. This, with the knowledge acquired through the review illustrated in the previous chapter, will permit to define problems and strategy, fundamental elements that enable to identify an appropriate solution and its consequent design.

3.1. Context description

3.1.1. Mozambique

Mozambique (Figure 3-1) is an ex-Portuguese colony, gained independence in 1975. It is situated in Southeast Africa and has a total population of 25,83 million people [46]. Its capital is Maputo and the country is divided into eleven provinces: Cabo Delgado, Gaza, Inhambane, Manica, Sofala, Maputo city, Maputo, Nampula, Niassa, Tete and Zambezia [47].

Figure 3-1 Mozambique physical map [48]

Mozambique is one of the poorest countries in the world: 70% of the population lives below the poverty line [46] and the country ranks among the lowest in GDP per capita and human development index.
According to World's Bank evaluations [48], GDP per capita in 2013 was 605 US$ (the referential value for low income countries is 722 US$), while UNDP [46] shows a human development index of 0,393 (ranked 178th over 187 countries) , as it is possible to see in figure 3-2.

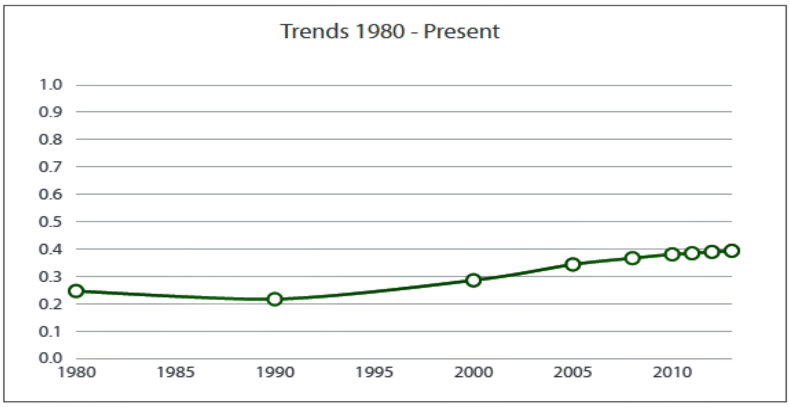


Figure 3-2 Human Development Index trend, United Nation Development Programme

The 68% of the total population of the country lives in rural areas [48], most of them working the land. Infrastructure nationwide still suffers from colonial neglect, war and under-investment. The two provinces of Nampula and Zambezia have the 40% of population, while the others are lightly populated [49].
As many other Sub-Saharan African countries, one of the biggest problems of rural areas is electrification lack. This issue still represents a problem that concerns the majority of population: according to the World's Bank latest data [48], only a 15% has access to electricity and most of it is situated in Maputo and in its proximities. In particular, energy is available just for the 1,7% of rural population, while 44,7% of people living in urban areas is connected to the grid.

According to EIA [50], electricity net generation in 2011 was 16,7 billion kWh, of which almost all was from hydropower and a very small amount from natural gas; at the household level, the vast majority of the population relies on traditional biomass and waste (typically consisting of wood, charcoal, manure, and crop residues) for household heating and cooking.
As regards natural resources, Mozambique has more development potential than many other African countries: in addition to relatively plentiful water resources, the country has large untapped coal reserves mainly in Tete Province and prolific natural gas reserves,

many of them just discovered. However, energy provision has been poor, as the bulk of these reserves remains untapped, resulting in rapid environmental degradation.

On the other hand, this abundance of resources creates a good potential to attract foreign investors: in the recent years, many of them showed interest principally in Mozambique's untapped oil and gas reserves, in addition to the exploration of mineral resource like titanium, gold and bauxite.

Foreign investments may represent a strategy to rebuild the economy and restore growth after 30 years of conflict: they are sources of capital, technical know-how, they can create job and contribute to infrastructure development.

Thanks to these investments, the country has emerged as one of the world's fastest growing economics, showing an annual growth of GDP of about 7%, as shown in figure 3-3 (in the last 4 years annual GDP growth had an average of 7,4%).

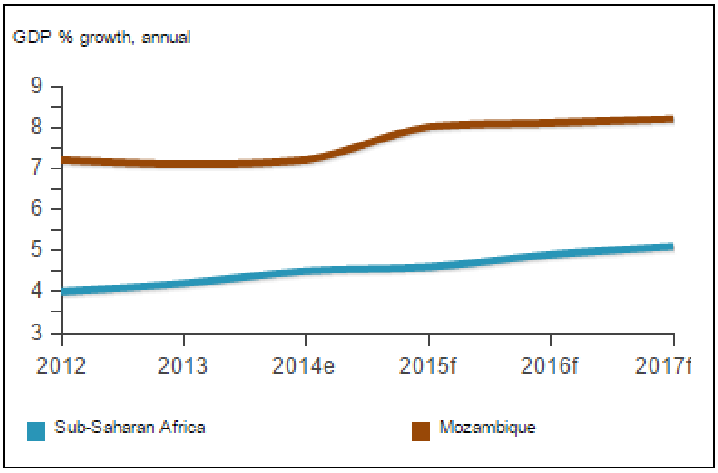


Figure 3-3 GDP annual growth [49]

The main drivers of this growth, apart from foreign investments, are constructions, services, implementation of large infrastructure projects, transport and communication; a key factor in Mozambique's economic growth was the opening of an aluminum smelter near Maputo in 2000. It is one of the world's largest smelters of aluminum, which has become an important export for Mozambique.

Industrial and manufacturing development began to resume in the early 1990s, when the country's overall social and economic climate improved; nowadays some industries are expanding and the sector contributes with 20,8% to the GDP (Figure 3-4) .

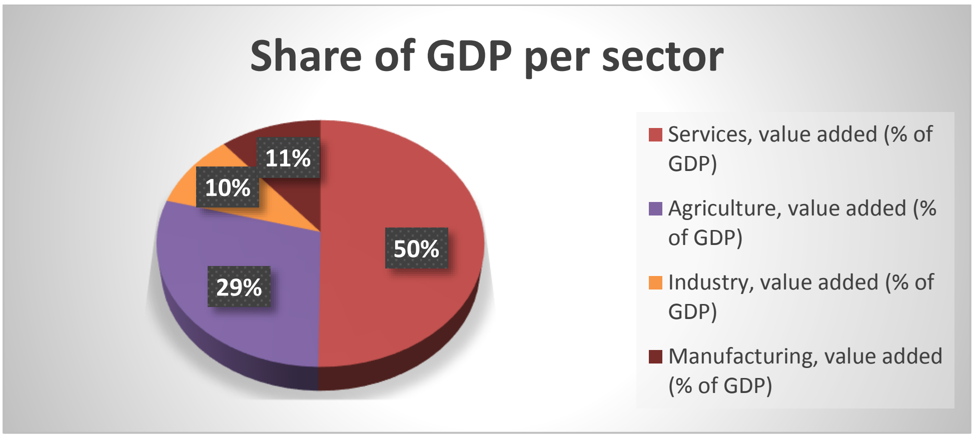


Figure 3-4 Share of GDP per sector [48]

However, agricultural sector still employs about 70% of the population [51].
Greater social and political stability the 1990s led to an increase of the production in this sector. Unfortunately, agricultural performance is particularly vulnerable to natural disasters such as droughts and flooding that are frequent in this country.
In spite of the large employments that agriculture creates and of its importance in exportation, it contributes just with a 29% to GDP, principally because the production comes from family farming operations (a good part is at a subsistence level) and because the sector is still technologically underdeveloped.
Fishing is one area of the economy that is immune to rural insecurity and has a key role for both internal market and exportation.

Focus on the fishing sector

Mozambique is endowed with rich fisheries resources, both marine and freshwater. In addition to a long and rich marine coast, Mozambique has many lakes and rivers in the hinterland. For this reason fishery is an important source of employment for the country.
The central area is dominated by the valley of the Zambezi, one of the world's largest river and the fourth largest in Africa. To the north, the Ruvuma and Lugenda rivers are sources of water and irrigation, while in the south of the Zambezi there are the Pungwe, Save, Limpopo and Komati rivers. With inland lakes, of which the most important is Lago Niassa, they constitute an optimal resource for fishery.
Total marine products are estimated between 100.000 to 120.000 tons per year and consumption is evaluated 7.5 kg per capita [49]. The fishing industries provide direct employment for around 90.000 people, excluding those involved in trading and processing.
This sector is characterized by its economic diversity and we can divide it in three main types of fisheries: industrial fisheries, semi-industrial, and artisanal for both marine capture fisheries and inland capture fisheries.

The industrial fishing sector produces the 10% of the export. The artisanal one, instead, the 93% of the total, employing about 350.000 people [52].

3.1.2. Focus on the context of the action

In this paragraph we explain the steps followed to obtain a deep knowledge of the area, activities and people involved in the action, of which the present work of thesis examines the feasibility.

In particular, this consists of a focus on the existent CeLIM project, which our action is related to, followed by an analysis of the local context, concluding with a data collection about customs of interest.

CeLIM project

CeLIM (Centro Laici Italiani per le Missioni) is an Italian nongovernmental organization that has been operating in Zambezia since 2006. After completing a rural development project, in 2013 CeLIM presented the project “Promozione della pesca fluviale di piccolo scala nei distretti di Mopeia e Morrumbala – Mozambico” for the promotion of small-scale fishing in the districts of Mopeia and Morrumbala, both situated in the province of Zambezia.

The main goal of this project is improving the economic conditions of anglers, merchants and their families thanks to a progression in the fishing activity that has a strategic importance for the development of the two districts.

Three are the principal problems that characterize the sector and that CeLIM aims to solve:

- the inefficient management of fishing sector, due to a poor local coordination between those who work in the sector, a low exchange of competence and knowledge and the presence of communitarian conflicts.
- scarce production and use of unsustainable techniques, like toxic products or bottom trawling: in addition to the subsistence fishing, many people practice artisanal fishing with the same low efficiency and productivity, due to a scarce knowledge of innovative technologies and a poor availability of adequate equipment.
- inefficient commercialization and transformation systems: a low availability of ice for transportation and preservation of fish and the utilization of inappropriate techniques of transformation lead to a substantial product drop, until a 50%, and to his fall in price. Furthermore, the commercial grid is not enough developed: many fishing

centers are really far from the main markets and an appropriate transportation system that could allow a fast transfer of the product does not exist.

The beneficiaries of the project are all the fishermen, the merchants and their families that lives and work, even not directly, in the fishing sector of the two district of Morrumbala and Mopeia, that are in total 31.860.

Local context of Zambezia

Zambezia (Figure 3-5), one of the ten provinces of Mozambique, is located in the central coasted region of south-west of Nampula province and northeast of Sofala province. It presents a considerable forest inland and its main river, Zambezi, flows through a vast area of this province, arriving to the Indian Ocean in the vicinity of the capital, Quelimane.

Figure 3-5 Zambezia map

The province, the second most populated of Mozambique with 3,85 million of inhabitants, is still one of the poorest region of the country: it has a GDP per capita of 288$ and a human development index of 0,293.
Primary sector hires about the 90% of the population but, due to low efficiency and productivity, it contributes just with the 28% to provincial GDP [52].

Climate

Thanks to its location, the Zambezi province has a tropical climate, and two main seasons can be distinguished in the course of year, a wet and a dry season.
The first one starts in the middle of October and finishes at the end of March, while the dry season goes from April to the first middle of October; June and July are the rainiest months and for this reason they are considered part of a short rainy season.
Anyway, rainfall is heavier along the coast, and the climatic conditions vary depending on altitude.
Wet season presents high average daily temperatures (above 30°C); on the other hand, in dry season, the mean values of temperatures are lower, varying from 22°C to 26°C in the coldest months (from June to August) and reaching a minimum of 12°C.
A graphic that shows the annual trend of temperature is reported below (Figure 3-6).

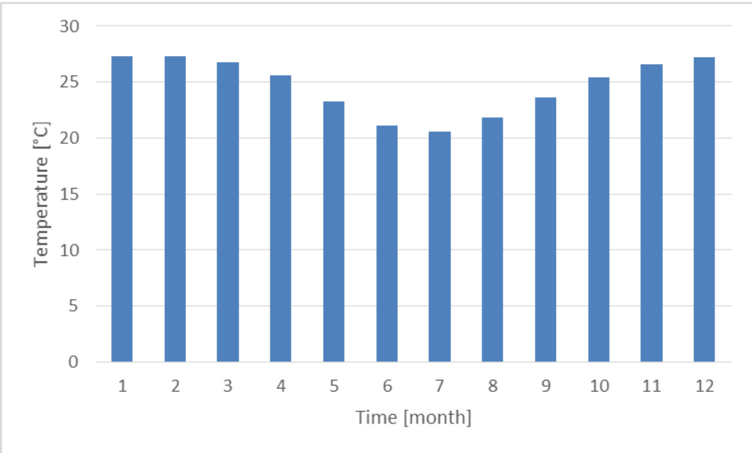


Figure 3-6 Average monthly temperature of Zambezia [54]

The province is extremely prone to floods during the wet season and normally, every 5 years, an important flood occurs.

Fishing centers and fish organization

As explained before, the richness that Zambezia hydrographic grid donates to this land allows having a widespread fishing sector, that in many areas constitutes an important source of employment.
In particular, small-scale fishing of Zambezia hires about 50.300 workers (fishermen and merchants), divided into 142 fishing centers.
Nevertheless, nowadays, small-scale fishing activity, overall in inland districts, is still at a subsistence level, although the rich hydrographic grid present in the region.
As for the whole country, the sector is still quite far from the technological innovation: fishing activity is practiced through inefficient and unsustainable techniques, credit and financial services for anglers are insufficient and the commercial grid is still underdeveloped.

Natural disasters, like floods, are at the same time a problem and an opportunity for this activity: when they occur, the majority of the structures and storages where fish is conserved, is destroyed. Nevertheless, these floods bring also some advantages, generating a renewal and an enrichment of the ichthyic fauna and, therefore, an improvement in the fishing activity during the consecutive months.

Fishing centers in Morrumbala and Mopeia districts

We now focus our attention on the fishing activity of the two districts of Morrumbala and Mopeia, in which CeLIM is operating for its project.
In order to do this, first of all we came in contact with the two representatives of CeLIM, Marco and Flavia, that have been operating for the project in question. Thanks to a preliminary information exchange, we started understanding the general context of fishing activity. Because of the necessity of having more details, we sent a series of more specific questions to local technicians which CeLIM is collaborating with.
Thanks to their answers (reported in appendix A), a more correct and faithful description, displayed below, of the local context has been possible.
A fishing center, according to the definition of Fishing Minister, is “any permanent or temporary site where vessels are regularly docked and fish is discharged to the bank”.
As mentioned above, in the province of Zambezia there are 142 fishing centers: 20 of these are in the area of interest, in particular 12 in the district of Mopeia and 6 in Morrumbala.
These centers have a communal organization and for each one there are one head and one vice. Distances between each center can vary notably: those considered quite close are 1km (300m in the best cases) distant to each other, and can share the same river or the same lagoon; others, instead, that could distant even 10 km from the others, are totally independent.
Every fishing center is connected with one or more markets, located in the nearest cities, where fish is sold; the principal and more accessible markets are in the cities of Mopeia, Morrumbala and Chimuara, while others are in Quelimane, the capital, Mocuba, Cuamba, Milange and in the near Malawi (Figure 3-7).

Figure 3-7 Principal markets in the province of Zambezia

Three are the activities done in the fishing centers: fishing, transformation and commercialization.

For fishing activity, they utilize some basic equipment: the most common vessel is made of wood, has a length of about 3 m and is destined to one or two people; other boats, instead, can arrive to hold even ten people.

Fishes are caught through nets and, in most cases, placed on the floor of the boat until anglers return to the bank.

Each fishing center has between 20 and 50 fishermen, depending on the richness and potential productivity of the area, and on the period of the year.

Fishing activity is conducted continuously all the day and night. Fishermen are divided into two groups, one that works during the day, approximately from 6-7am to 3pm (daytime turn), and the other that starts around 5pm and finishes in the early morning (nocturnal turn).

Depending on the season, they work and produce differently: in the rainy season, thanks to the big potential typical of that period, they can make just one exit, going back to the bank with an average of 40 kg of fish per person. In the dry season, on the other hand, two exits are necessary and the average quantity of fish per person that they can achieve is about 20 kg per exit. Part of the fish is kept apart and destined to self-consumption, the rest is sold to merchants that bring it to the closest markets.

Afterwards, fishing and commercialization are two activities clearly separated, carried out by two different figures.

Normally there are about ten merchants per fishing center: they leave the markets in the morning, arriving to the river possibly when fishermen have just gone back from the exit, and return to the markets with the fish.

If the closest market is less than 3 hours distant, they move by bicycle or by motorbike, bringing from the market blocks of ice through small insulated boxes with a volume of

about 70 l. This allows having a **fresh fish market** because the product has the possibility to be well conserved until the moment in which arrives to the market, where other ice, just produced, is available.
However, sometimes long travel times and high temperatures make the ice melting; in these cases, merchants cannot preserve all the fish and, once arrived to the market, part of the fish is thrown away.
When there are not markets in the proximity of the fishing centers, merchants are forced to utilize different ways to preserve fish, as the transportation can last also one week. Alternatives methods of preserving fish (Figure 3-8) include drying, salting and smoking:

- Drying: one of the oldest methods to preserve food, it consists in removing water from the fish, thanks to sun radiation and wind, to inhibit the growth of microorganisms.
- Salting: it is another method to avoid food spoilage. Salt hinders the spread of microorganisms by drawing water out of microbial cells through osmosis.
- Smoking: extending the shelf life can be achieved also exposing fish to smoke burning plant material (generally wood); smoke deposits some pyrolysis compounds onto the fish that help in the drying and preservation.

Figure 3-8 Dried and smoked fish in Zambezia fishing centers

Often these methods are practiced not fully correctly, as the salt used is quite always impure, smokers are simple holes in the plot and the duration of drying process is inappropriate. An incorrect handling of the transformation process takes to high losses of the product and to low hygienic conditions.
Merchants are the only ones that deal with the transformation process; they can work individually or in small groups of 2-4 people, sharing communal smokers present in the fishing center.
Anyway, in most cases, the fish to be transformed is left without preservation in the ice also for 2 or 3 hours before the treatment.
Once the treatments are finished, merchants leave the fishing center by bicycle, motorbike or, more rarely, little tracks, depending on the road conditions and on the

distance from the markets; they carry transformed fish through baskets or carton boxes with a load of about 60-80 kg.
Based on the distance that merchants have to cover, two markets can be distinguished: fresh fish market and transformed fish market.
Because of the long process of transformation and its relative costs, the transformed fish has to be sold at a higher price than fresh one (4 €/kg vs. 1,7-2,4 €/kg). Although this, from the survey performed, it emerged that merchants prefer selling fresh fish to have immediate earnings and a considerable time-saving due to the absence of all treatment phases. Moreover, there are some kind of fish, like tilapia, that are very appreciate from both merchants and consumers, but are less available because they cannot arrive fresh until the market.

Before analyzing problems and objectives, we underline all the stakeholders involved in the action with their features (Table 3-1):

Table 3-1 Features of the main stakeholders

Stakeholders	***Features***
Fishermen	Direct beneficiaries of the action. They may have a positive attitude because they expressed a strong need of a technologic solution for fish preservation.
Merchants	
Ice production managers in markets	At the moment, they represent the only possibility of a partial solution to preservation problem. In case of the realization of the project, they may be negatively affected at economic level and so they could represent a threat.
Fishermen and merchants families	Indirect beneficiaries: they may be positively affected by a higher possible income deriving from our action.
CeLIM	They may benefit from the action, because this regards a part of their project.
Fish consumers	Indirect beneficiaries: they may take advantage of our action thanks a higher availability of fresh fish in the markets

3.2. Problem identification

From the previous context description, the problem of fish preservation in fishing centers and during transportation emerges as relevant. For this reason, we have studied different possible solutions to propone to CeLIM; in order to do this, the problem has been analyzed following the steps of analysis and strategy definition, typical of PCM (Project Cycle Management) theory.
The first step of the analysis phase consists in problem tree construction (Figure 3-9), that shows the causes and the consequences of our problem:

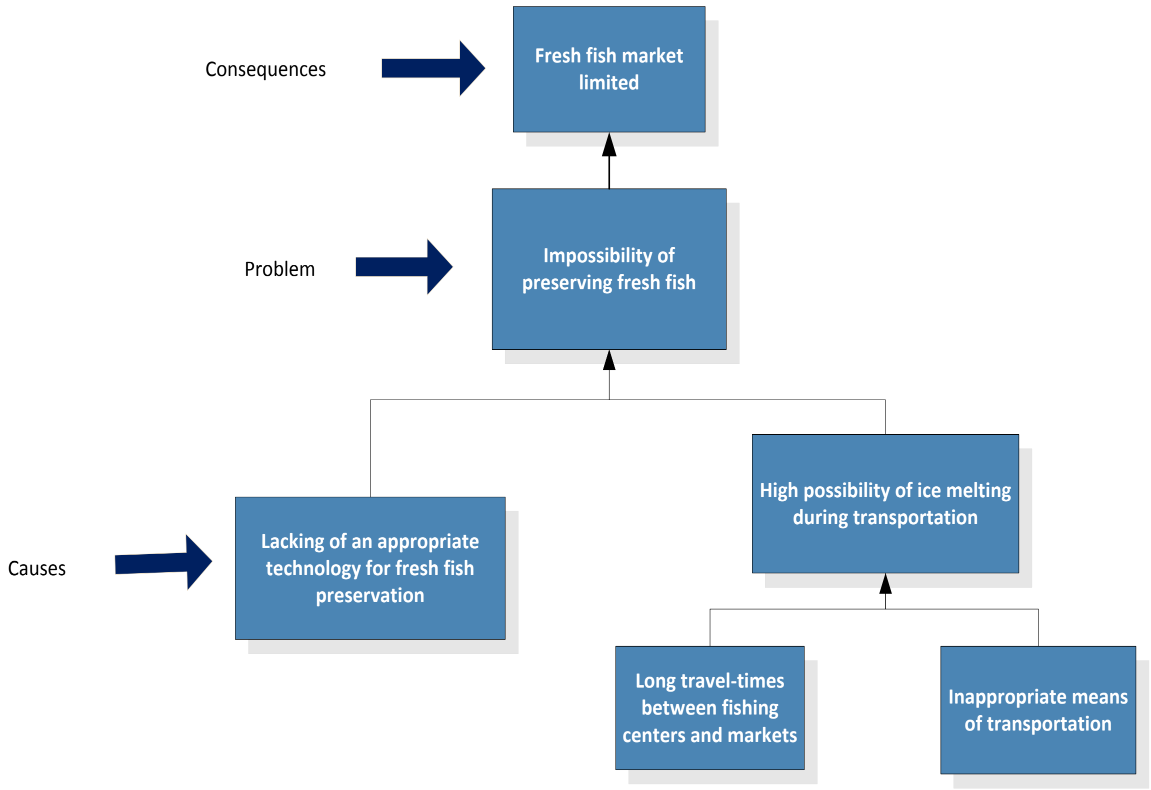


Figure 3-9 Problem tree

As shown, the specific problem identified is the impossibility of preserving fish; this is due principally to two factors. The first one concerns fishing centers: a technology that guarantees to keep the fish cold is absent, and this causes a risk of spoilage during fishing turns for fishermen and does not permit to merchants to come back to the market with fresh fish.

The second factor regards fishes transportation, indeed, merchants bring ice directly from the market, but because of long travel times and inappropriate means of transportation used, ice is melt when they come back.

The consequence is that the difficulties in preserving fish facilitate transformed fish trade, disheartening fresh fish one.

The second step is the definition of an objective tree (Figure 3-10), in order to develop solutions from the identified problem:

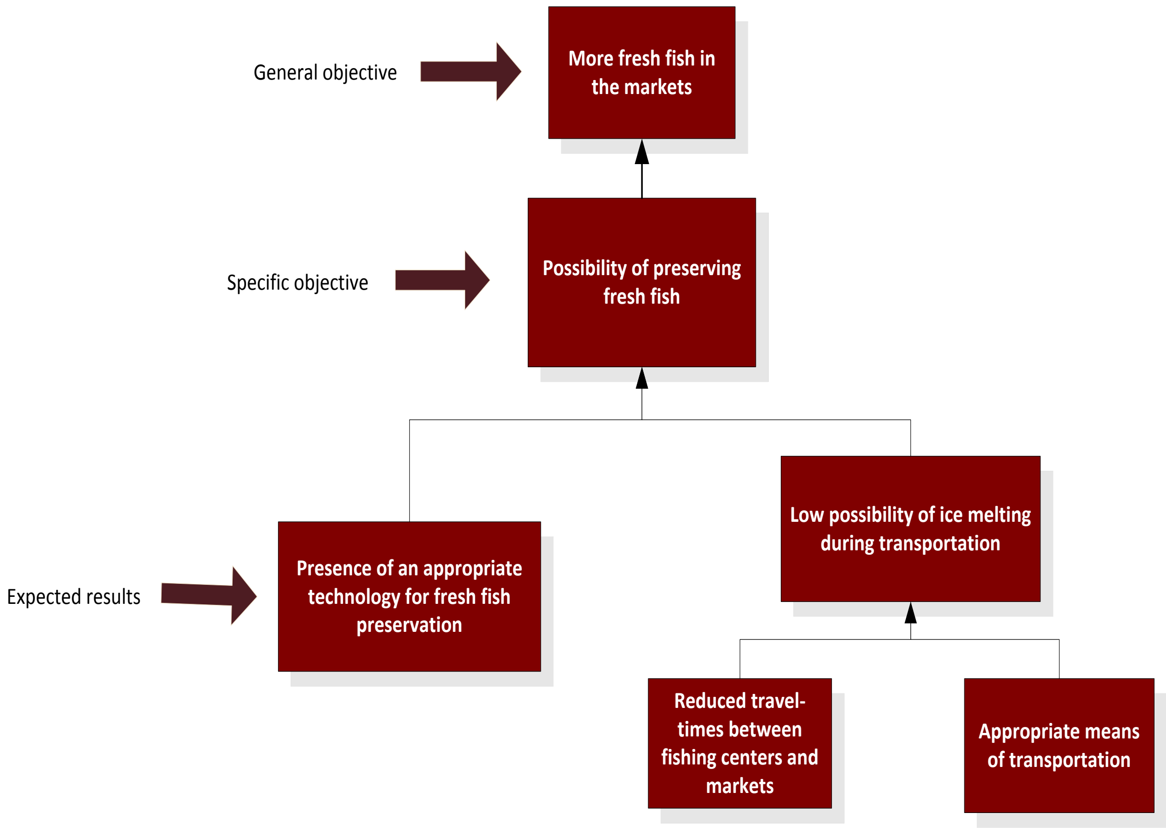


Figure 3-10 Objective tree

As can be seen in the graphic above, in order to achieve the specific objective, two results have to be obtained: the first one consists in the installation of an appropriate technology for fish preservation in fishing centers, since no technological solution for this purpose is present at the moment. The second expected result is decreasing the possibility of ice melting during transportation: this can be achieved thanks to the reduction of travel-times between fishing centers and markets and the use of more appropriate means of transportation to cover this distance.

3.3. Strategy definition

Following the PCM theory, after having identified the problems and the objectives, the most appropriate strategy to achieve solution has to be selected.

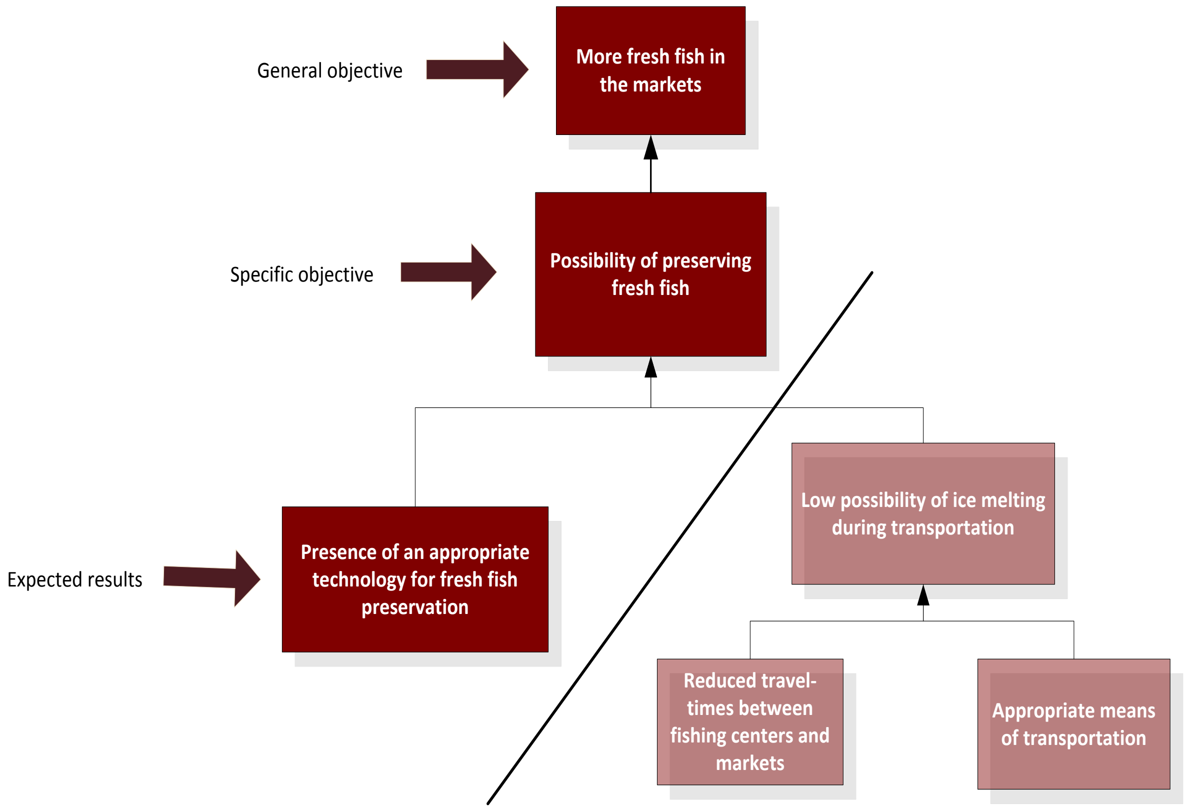


Figure 3-11 Modified objective tree

Figure 3-11 shows how we will focus our attention just on a part of the objective tree, the one that concerns the installation of an appropriate technological solution.

Elevate travel-times between markets and fishing centers could be faced improving street conditions but, in any case, it cannot be completely solved, since there are some markets that are not destined to fresh fish trade because of their high distance. On the other hand, having appropriate means of transportation would improve a lot the situation, but this is not among CeLIM's objectives, that aims more to the progression of fishing activity; in any case, merchants could not afford to buy them by themselves.

This is why our unique expected result is procuring a technology in order to give the possibility of preserving fresh fish; this objective constitutes the center of attention of the next chapter.

4. Solution design

Once understood how fishing activity is organized and which is the strategy chosen for the achievement of the objective, the solution design can start. This chapter will begin with the determination of the request of fishermen and merchants, which has been possible thanks to some researches and data collections; once defined the demand, different technological solutions will be analyzed, with the goal of choosing the most appropriate for the context.

4.1 Demand evaluation

4.1.1 Fish preservation needs of farmers and merchants

Many could be the technical solutions to solve the problem of the preservation of fresh fish for the specific context; in particular, two are the most efficient and obvious methods that can be utilized: refrigeration and freezing.
These are the alternatives analyzed:

1. Having a refrigerator in every fishing center, that can be used communally by people who work there; this could be useful when there is not a coincidence between the arrival of merchants from the market and that of anglers from the fishing turns.
2. Giving small portable refrigerators to both, merchants and fishermen. In this case, firsts could preserve the fish into the refrigerator during their travel, and fishermen could place them at the bank, putting the fish when returned from the fishing turn.
3. Installing a unique large ice machine that provides the necessary daily ice for all people concerned.

The selection process of the final solution started by asking CeLIM representatives present in the area, in direct contact with fishermen and merchants, which alternative among the proposed could be the most appropriate and useful for their needs.
From the answers received, helpful and additional information came out and it has been possible to develop a short SWOT analysis of the alternatives, that we report in the following tables.

Table 4-1 SWOT matrix of the communal refrigerator

Communal refrigerator	
Strengths	**Weakness**
It represents a cold storage for fish, both for fishermen and merchants	Its management in common may be the cause of tensions and this technology cannot be transported
Opportunities	**Threats**
It may give an additional comfort: conserving cold drinks during hot days	It may be not used because fishermen and merchants are not used to this type of conservation technology. It may be damaged by floods.

Table 4-2 SWOT matrix of small portable refrigerators

Small portable refrigerators	
Strengths	**Weakness**
They are portable and each fishermen and merchants may own one	Their sizes may be a problem for transportation on boats, bicycles and motorbikes
Opportunities	**Threats**
It may give an additional comfort: conserving cold drinks during hot days	It may be not used because fishermen and merchants are not used to this type of conservation technology

Table 4-3 SWOT matrix of the unique icemaker

Unique icemaker	
Strengths	**Weakness**
Ice can be transported and fishermen and merchants already know and use this technology	It may have a big impact
Opportunities	**Threats**
It may create an ice market near fishing centers and thus an additional income for managers	It may be damaged by floods

The principal goal of fishermen consists in selling the fresh fish as soon as possible to merchants, if they are present in the fishing center at their arrival; on the contrary, fish is destined to transformation process. Moreover, when they are still fishing, the caught fish that is put on the floor of the boat remains at high ambient temperatures until they go back, so there is the frequent possibility of returning with spoiled fish from the fishing turn.
Owning a refrigerator on the boat would be impossible given its dimension. On the contrary, having available ice to bring on the vessel would be more feasible and useful.
Furthermore, also merchants expressed their preference for icemakers: they already use ice for preservation, holding it in insulated boxes, and they are accustomed and comfortable with it. Carrying a refrigerator by bicycle or by motorbike would be a problem, and the trucks, that would be perfect for this kind of transportation, are rarely available.
Anyway, if they are not able to bring the fresh fish immediately to the closest market, they transform it.
Moreover, acquired information about the general context of fishing centers let emerge some opportunities and threats that every system may have. First of all, we should consider that a communal use of a system, as the refrigerator, may provoke some tensions between fishermen and merchants. On the other hand, this technology may offer them an additional comfort during hot hours of work, given the possibility of conserving cold drinks. This comfort may be offered by small portable refrigerators, too. Regarding to the unique icemaker, it may offer the opportunity to develop an ice market near fishing centers, giving a possible additional income to the community. The main threat that may affect a unique and large installation, like an icemaker or a refrigerator, is its eventual damage caused by floods.
The analysis performed indicates that the best solution for both merchants and fishermen could be having ice in fishing centers. To establish if this solution allows the correct conditions in which the fish has to be preserved, we analyzed the standards for fish preservation.

4.1.2 Fish preservation conditions

There are different techniques used to preserve fish quality and to increase their shelf life; they are designed to inhibit or reduce the metabolic changes that lead to fish spoilage by controlling specific parameters of the fish and/or its environment.
In this paragraph we will focus on the techniques based on temperature control: these include a wide variety of technologies used to decrease the fish temperature to levels where metabolic activities are reduced or completely stopped. This is possible by

refrigeration or freezing, where the fish temperature is reduced, respectively, to approximately 0 °C or < - 18°C.

Fish refrigeration can use cool air circulating around the fish (mechanical refrigeration) or icing. [53]

It is necessary to mention that the spoilage process is continuous and cannot be reversed: any amount of ice will never convert poor-quality fish back into a good-quality product. Then, the time span from the capture of the fish to when it is properly preserved must be as short as possible, with minimum exposure to high temperatures. In tropical conditions, this would also require to keep the fish in the shade and out of direct sunlight. [54]

If ice is used for the refrigeration, then the quantity of ice required needs a particular consideration.

FAO (Food and Agricultural Organization of the United Nations) conducted some studies for the determination of proper ratios of fish to ice.

Table 4-4 shows a theoretical weight of ice needed to chill 10kg of fish to 0°C from various ambient temperatures:

Table 4-4 Theoretical weight of ice needed to chill 10 kg of fish to 0 °C from various ambient temperatures [54]

Temperature of fish ***(°C)***	**Weight of ice needed** ***(kg)***
30	3.4
25	2.8
20	2.3
15	1.7
10	1.2
5	0.6

In practice, much greater quantities are required to ensure that the fish remains chilled once its temperature has been reduced to 0 °C, and that it can be stored at chill temperature for some time.

It is generally accepted as "rule of thumb" to use an ice to fish ratio of 1:1 in the tropics. In many instances, ratios of up to 3:1 ice to fish are used. The main influence on the ratio is the length of the fishing trip.

In addition to the choice of the quantity, also the type of ice is an important parameter that affects the preservation. The most frequent types of ice utilized for fish chilling are:

- Block ice/crushed ice: block ice plants are still commonly found in many countries because of their simplicity of operation and maintenance. Block ice is preferred by fishermen in many parts of the world because it lasts longer and takes up less space in the fish hold. In any case, for a more effective use of its cooling power, it has to be crushed after having been transported and stored as block.

- Flake ice: in comparison to block ice, this can be more efficient in cooling fish because it is lightly sub cooled and can be packed better around fish; the disadvantage of this ice is that it melts more quickly than the first one.
- Slush ice: it is an extremely efficient cooling agent for fish. It is capable of reducing fish temperatures to 0 °C very rapidly. This type of ice is mostly used to stow fish in closed containers such as boxes or insulated tubs [54].

Currently, in the specific context of the districts of Morrumbala and Mopeia, some ice machines are present in the markets, in order to permit to having ice both for the market and the merchants that leave to reach the fishing centers. Actually, they are not real ice machines but freezers in which they place recipients full of water, waiting until this has changed phase. Once the ice is formed, it is removed manually from the container; normally merchants use blocks of 5 kg that are brought entire to fishing centers.
Therefore, the solution of installing a machine that provides the necessary daily ice seems a good alternative to avoid current issues identified, in line with local uses and with the standard of fish preservation.

4.1.3 Determination of ice request

To start the design of the solution, it is necessary to estimate the daily quantity of ice that anglers and merchants.
In order to do this, we report the data collected from the information procured by CeLIM and from some questionnaires that have been sent to the fishermen of a specific fishing center. To compensate part of lacking documentation, setting some hypothesis about the fishing activity has been compulsory.
The preparation of the questionnaires has been thought with the intention of understanding the real needs of local people, the stakeholders that would be mainly affected by the project; by not considering their opinion, the work risks to result not appropriate or even useless.
A questionnaire was distributed to all the fishermen of a fishing center close to Mopeia that in total are about 20.
The objective of the questionnaires was to understand principally their organization and the timetable of the fishing turns, in addition to the real quantities of fish that, depending on the season, everyone can collect at the end of the day.
Principal information obtained are reported in table 4-5.

Table 4-5 Data obtained from questionnaires

	Wet season	Dry season
Number of fishermen per day in a fishing center	30	30
Number of fishermen working in daily turn	15	
Number of fishermen working in nocturnal turn	15	
Average duration of exits [hours]	2	4
Number of exits per turn	1	2
Fish caught per person in one exit [kg]	40	20
Sale price that fishermen do to merchants [€/kg]	0,53	
Price that fishermen are willing to pay for ice [€/kg]	0,06	

Once these data have been reported, some hypothesis have been made to arrive to a final definition of the activity characterizing fishing centers. This necessity was due to the impossibility of having a direct knowledge of the place of interest.

These are the hypothesis about fishing centers that have been done:

- All the fishing centers are similar in terms of productivity and organization (number of fishermen and timetable).
- When anglers return from the fishing turn, merchants are already present, then those that are interested in fresh fish market can buy it directly.
- 7 out of 10 are the merchants that deal with fresh fish market. In the dry season two third of the total fish caught is destined to fresh fish market, while in the rainy season just one third, considering that the number of merchants remains constant and the quantity of fish increase.
- For 1 kg of fish is necessary 1 kg of ice.
- The fish caught during the evening is not destined to fresh fish market, since the markets are closed in the evening. Afterwards, this fish is transformed immediately.
- In nocturnal turns, fishermen need half of the normal quantity of ice, as temperatures are lower and the solar irradiation is absent.
- The months of June and July are part of the rainy season because of their similar characteristics.

Here below a recapitulatory table shows all the data that have been be used (Table 4-6):

Table 4-6 Data collection

		Dry season				Rainy season	
		Daytime turn		Nighttime turn		Daytime turn	Nighttime turn
		1° exit	2° exit	1° exit	2° exit	just 1 exit per turn	
fishermen	kg of fish/fisherman	20	20	20	20	40	40
	Number of fishermen	15	15	15	15	15	15
	Total kg of fish	300	300	300	300	600	600
	Ice needed [kg]	300	300	300	150	600	600
merchants	Fresh fish bought [kg]	200	200	200	200	300	300
	Number of merchants	7	7	7	7	7	7
	kg of fresh fish/merchant [kg/p]	29	29	29	29	43	43
	kg of ice/merchant	29	29	0	29	43	43
	Ice needed [kg]	200	200	0	200	300	300
	Total ice [kg]	500	500	300	350	900	900
	kg of ice/day	1650				1800	

Thanks to all this information, an ice request curve can be done for both wet and dry seasons (illustrated respectively in Figure 4-1 and in Figure 4-2)

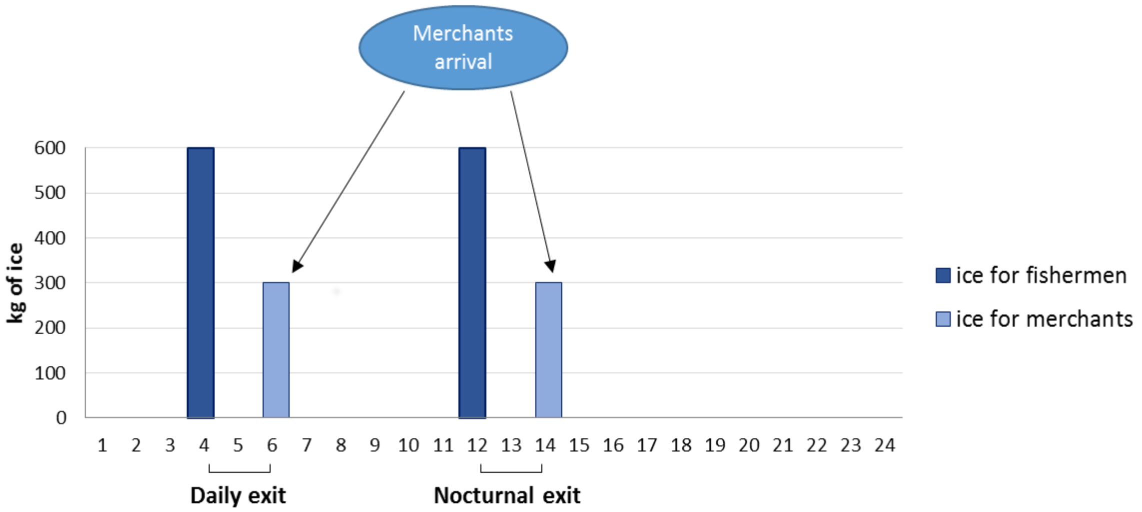


Figure 4-1 Daily ice request, wet season

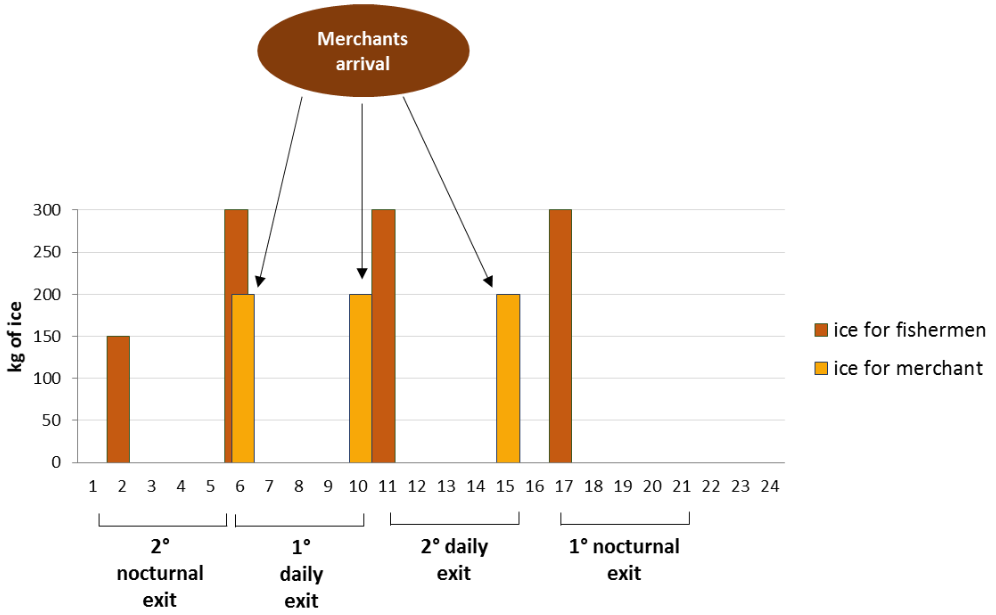


Figure 4-2 Daily ice request, dry season

4.2 System definition

4.2.1 Selection of suitable technology

At this point, it has been ascertained that fishermen and merchants need a high quantity of ice to preserve fish. Only icemakers can satisfy this need. According to the critical analysis of existing prototypes, two cooling technologies match all our requests: making ice, preserving fish and having a system that can be shared by fishermen and merchants of the same fishing center. These are the vapor compression icemaker supplied by photovoltaic modules (as Chorreras icemaker) and the absorption icemaker supplied by CPC collectors (like ISAAC technology). Given the high daily amount of ice that has to be produced, vapor compression icemaker results as the most appropriate solar cooling technology, despite the high maintenance level (as shown in the bubble chart of paragraph 2.3).
Chosen the suitable technology, it is possible to begin with the design of the system, which will be composed of photovoltaic system, a battery array and an icemaker.

Preliminary sizing of system energy needs

A preliminary analysis has been done to define the size of the whole system and its components, and assess the feasibility of the project.
According to the daily ice request, the cooling energy is calculated considering:

- the highest ice demand, that characterizes wet season (m=1800kg of ice per day)
- a temperature of the inlet water at 20°C, that is a temperature difference ΔT = 30 °C between the inlet water and the ice

Cooling energy is so calculated as:

$$E_c = m \times \left(c_p \times \Delta T + h\right)\ [kWh/day] \quad \text{Equation 4-1}$$

assuming an average c_p (specific heat of water) of 4,186 kJ/kg K and a latent heat of fusion of water h =333 kJ/kg [55], it is:

$$E_c = 230\ kWh/day \quad \text{Equation 4-2}$$

As a result of the review of commercial ice maker, which is reported in chapter 4.2.2, it was possible to define an average COP value of 1,5.

So, the electricity consumption is computed as:

$$E_{el} = E_c/COP \cong 153\, kWh/day \quad \text{Equation 4-3}$$

Based on the energy request, we carried out a preliminary sizing of photovoltaic system. From Meteonorm database [56], we got the monthly mean value of global daily radiation of the worst month (June), which is approximately $H_g = 4800\ Wh/m^2\, day$ (value referred to a surface with an optimal tilted angle of 20°)

The following calculation considers twice the actual energy request, since we assumed one day of autonomy from the battery. Therefore, photovoltaic system (with surface S) has to provide the daily energy need and has to be able to charge the battery in order to supply icemakers during an entire cloudy day.

$$E_{el} \times 2 = S \times H_g \times \eta_{BOS} \times \eta_s \times \eta_{cell} \quad \text{Equation 4-4}$$

For this preliminary calculation, we assumed $\eta_{BOS} = 80\%$ (coefficient that takes into account losses produced by the Balance Of System, that refers to all PV components, excluding the modules), $\eta_s = 90\%$ (battery charge-discharge performance) and $\eta_{cell} = 15\%$ (PV cell efficiency).

Reversing the formula, a total surface of S = 594 m² has been calculated.

Overall power of PV system is then calculated through the following relation:

$$P_{inst} = P_{mod} \times \frac{S}{S_{mod}} \quad \text{Equation 4-5}$$

By reference to a commercial polycrystalline PV module, $P_{mod} = 265\ W$ is the nominal power and $S_{mod} = 1.67$ m^2 is the surface of a single photovoltaic panel. The total installed power is thus $P_{inst} = 94\ kW$.

More than 90 kW of installed photovoltaics seems to be excessive in a context where now there are no power installations. The present work aims to conduct a study of a small-scale system that allows the definition of feasibility, costs and times of a hypothetical future real project.
Installing in every fishing center a technology that produces the ice effectively calculated would make no sense. In a preliminary stage of the project a single system should be installed in one of the several fishing centers, supplying just in part the total request. It would give the possibility of evaluating if the system is efficiently used and if a larger quantity of ice would be effectively utilized.
For this reason, the daily target of ice production is reduced with respect to the original calculation, as it is possible to see in figure 4-3.

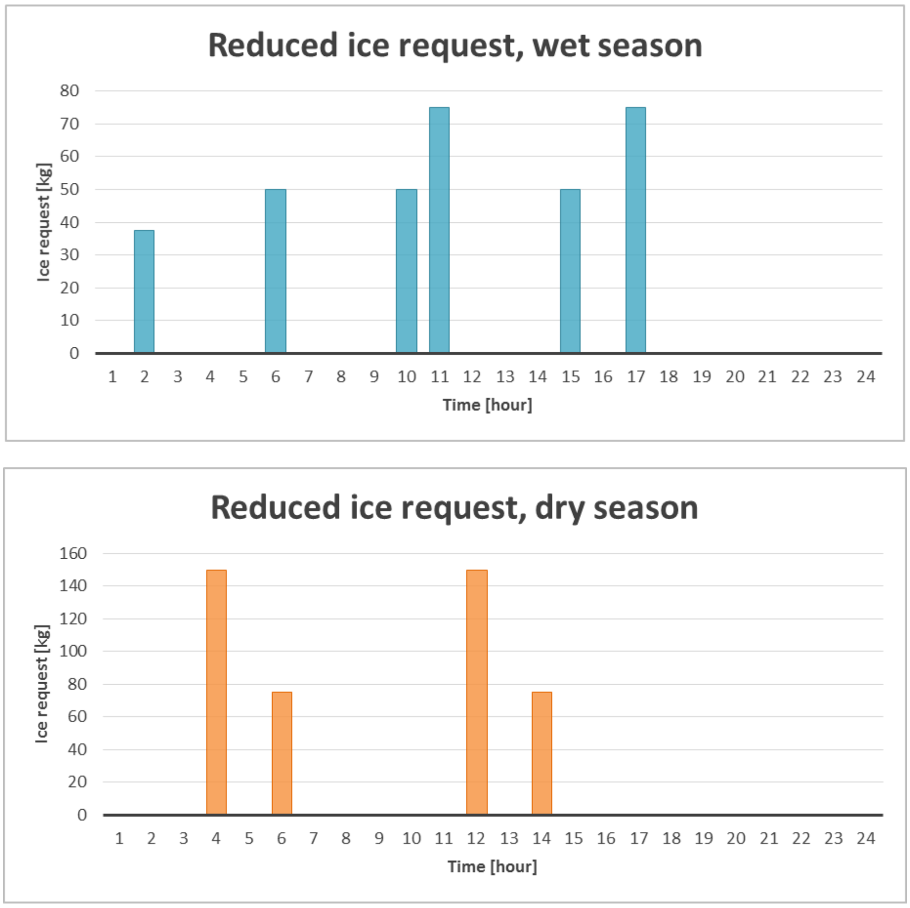


Figure 4-3 Reduced ice request in wet and dry season

4.2.2 System components

In this paragraph each component that will be part of the entire system is introduced and characteristic features of different commercial typologies are illustrated in order to assess which of them better meet our specific needs. This review has to bring to the choice of existing models present on today's market that will be simulated in the paragraph 4.2.4

Icemakers

Icemakers are chillers that use an energy input to freeze water. The energy input can be both electrical (vapor compression cycle) or thermal (absorption or adsorption cycle).
In this section, only systems based on vapor compression cycle will be discussed, since in our case the source of energy is, as mentioned before, a photovoltaic installation.
Every icemaker has its characteristic "basic cycle" that permits to produce a specific quantity of ice in a specific interval (it does not coincide with the thermodynamic cycle).
Normally these cycles last from a few hours up to 10-12 hours and, if the quantity of ice required is considerable, the cycle may last even one whole day. If an icemaker produces, for example, 600kg of ice per day, this does not necessary imply a 24 hour cycle to have 600 kg: this quantity could be the results of three basic cycles, each one producing 200kg of ice and lasting 8 hours. Therefore, the two parameters affecting the choice of the icemaker model are (1) the quantity of ice required and (2) the time required to produce it.
Once the ice is produced, it has to be removed: this can be achieved by heating the container walls or by removing it mechanically.

We made a research about commercial icemakers to select a group of machines having the needed features to be installed in fishing centers.

Various kinds of icemakers can be distinguished, depending on the type of ice produced (Figure 4-4):

- Flake ice machines
- Block ice machines
- Cube ice machines
- Tube ice machines

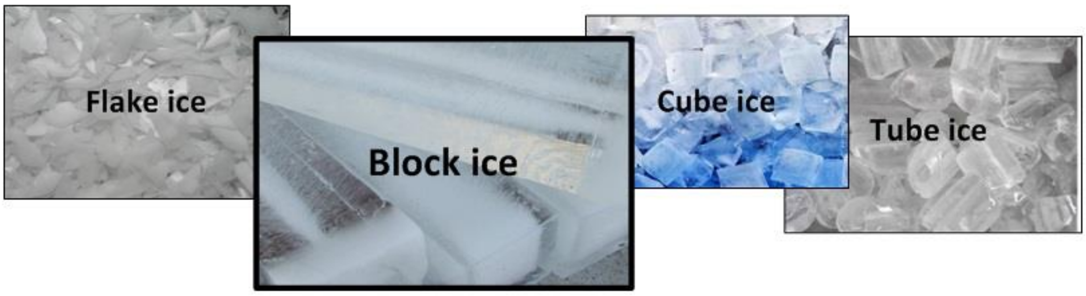


Figure 4-4 Different type of produced ice

As already clarified, currently merchants use ice blocks of 5kg in order to avoid rapid melting. Therefore, icemakers that do not produce ice blocks are discarded from the list of the machines considered in the system design.

Once the most suitable icemaker type has been selected, a list of possible models can then be defined. The required quantity of ice is considerable (450 kg/day of ice in rainy season and 412 kg/day of ice in dry season), but ice demand is irregularly distributed during the day. A suitable approach is to have several icemakers working simultaneously to produce the desired amount of ice by means of short basic cycles.

Table 4-7 shows a selection of commercial icemakers which are suitable for the present application.

Table 4-7 Technical data of some commercial icemakers

Model	Basic cycle production	Input Power [kW]	Price [€]	COP
NORDON [57]	72kg/11h	0,47	8766	1,80
SNOWELL [58]	250kg/6h	7,27	5838	1,60
GZKOOLER [59]	200kg/4,8h	6,00	5027	1,17
US I.M. [60]	126kg/6h	2,88	9730	0,96
MINUS 40 [61]	280kg/10h	3,42	7220	1,04
SNOWKEY [62]	2500kg/24h	7,46	25550	2,35
ROSEN1 [63]	60kg/6h	1,12	2138	1,14
ROSEN2 [63]	250kg/6h	5,22	7813	1,02

All the models reported above do not need the cycle reversion to take the ice off. It is possible to remove the ice manually and in this way losses in ice production are avoided

(as mentioned in paragraph 2.2.1.1. they represent a 3,5% of the total production for Chorreras icemaker).
Moreover, all these icemakers operate with alternate current and consequently necessitate an inverter to convert the direct current coming from photovoltaic modules and battery array. Some machines working with direct current can be found on the market, but they are expensive systems and their spread is still limited. Providing icemakers of this type to avoid the use of the inverter would be a risky decision in a context where eventual problems as damages or malfunction can be not easily solved. In addition, the inverter would permit to use a possible excess of electricity production for other purposes.

Photovoltaic modules

A photovoltaic module is an assembly of solar cells and is generally a component of a larger photovoltaic system [64].
A PV module produces electrical energy directly from solar radiation: this is thanks to the photovoltaic effect, based on a physic phenomenon that occurs in semiconductor materials (the most common is crystallized silicon) hit by solar radiation: excited electrons from the valence band reach the conduction band and are released. These electrons pass through an electrical loop, called a diode, in which an electrical field is generated. Therefore, the direct conversion of sunlight to electricity occurs without any moving part and environmental emissions during the operation.
The nominal power of a photovoltaic module is measured under standard test conditions (irradiance: 1000 W/m2, cell temperature: 25°C, AM[6]: 1,5). The output current is direct current, which can be transformed in alternate current by means of an electronic device called inverter
There are several types of photovoltaic panels on the market: the most used ("first generation modules") are monocrystalline and polycrystalline silicon modules that constitute 80-85% of the global market, followed by the thin film modules (second generation, i.e. amorphous silicon, Cadmium Telluride, copper indium gallium selenide). Most recent modules can be classified as third generation, and are still at the research phase.

FIRST GENERATION

<u>Monocrystalline modules</u>

---

[6] AM (air mass) is the ratio of the mass of atmosphere radiation has passed through in order to reach the ground to the mass of atmosphere radiation would pass through if the Sun was perpendicular to the ground [76].

Monocrystalline modules, characterized by their dark black color, are composed of cells realized from a wafer with a homogenous crystal structure. Due to the high purity of these cells the modules become extremely high performance and easily achieve an efficiency of 18-21% (the most competent prototype panel in the world is a Panasonic and has an efficiency of 25,6%). Monocrystalline modules are an optimum choice if room space is an issue, since these panels present the highest ratio between panel surface and energy produced. These performance values are maintained quite well during its entire lifetime, as it is capable of lasting over 20 years with a 90% initial performance. They have been around a long time, so we have solid evidence of their durability and longevity.
Unfortunately, because of high production costs, these modules are still quite expensive (for large volumes 0,8 €/Wp).
Fragility is another drawback of monocrystalline modules: depending on the type of the safety glass that cover them, they may be broken easily by tree branches or objects carried by a strong wind. Therefore, it is essential to take into account environmental conditions of the area in which the system will be installed.

Polycrystalline modules

To overcome the commercial expense of monocrystalline technology, it was possible to reduce production costs by manufacturing cells of multiple small silicon crystals, called polycrystalline modules, which present a framework containing grain boundaries. Lower production costs were attained and these modules being cheaper than monocrystalline ones (about 0,6 €/Wp) facilitated their diffusion on the global market. In any case, one of the most important parameters to be considered in the choice of a photovoltaic panel is the cost per power relative to the entire installed system (€/Wp) and not of the single component.
At the same time, a disorganized structure makes the panels less efficient: they achieve a performance of 13-16 %, which after 20 years may be at least a 85% of its initial value.
Like the monocrystalline modules, their efficiency is reduced with the increasing of panel temperature (0,4-0,6%/°C).
Both monocrystalline and polycrystalline photovoltaic modules have the advantage of being proven and reliable technology.

SECOND GENERATION

Thin film modules

Well known since the late 1970s, thin film cells constitute the second generation. They are composed of one or more thin layers of photovoltaic material deposited on a glass or plastic substrate.
The main advantage of this technology is its moderate price range, compared with other conventional modules. Low production costs can be achieved and a lot of money saved,

as the amount of material needed for the construction of the panels is definitely less significant than that used for first generation family (these are produced with a thickness of not more than 1-2 µm instead of 200-300 µm as the traditional modules,). Furthermore, this technology allows reduced production phases which can furthermore be realized at lower temperatures, unlike crystalline modules requiring high temperatures for the fusion and purification of silica.

With the cited cost reductions, the price stays below 0,5 €/Wp.

Other favorable features of thin films are its minor sensibility at high temperatures (the drop off temperature increase is around 0,25%/°C), a better-quality conversion of diffuse light and a low energy payback time.

However, defectiveness in the structure causes low efficiencies: the best performance reached by commercial models is around 11%.

Here below different kinds of thin film modules are classified:

- **Amorphous Silicon modules**: They are made of non-crystalline allotropic form of silicon. They have an efficiency that does not exceed 6% and present a strong initial degradation of performance in the first 1000 hours of operation. After this period, the efficiency value reached remains quite constant for the remaining lifetime. They are utilized principally for larger installations.
- **Cadmium Telluride modules:** These modules constitute more than half of the thin film market. Cadmium Telluride is an excellent semiconductor material and so a relatively high performance can be achieved: as regards laboratory cells, the certificate value16,5%, while commercial models are less efficient. They can always maintain a stabilized efficiency of 11%,.
- **Micromorphous Silicon modules:** They are characterized by two cells superimposed. The top one, which is directly exposed to solar radiation, is made of amorphous silica and absorbs the visible light. The bottom cell is made of microcrystalline silica for the absorption of the infrared part of the light.

  These kind of modules have the advantages typical of thin film modules and thanks to microcrystalline silica they can achieve a higher performance than classic thin film modules. Despite this, today one of the best performance values achieved is still far from those of monocrystalline modules (they reach an efficiency of 13% for small modules).

  Micromorphous technology, with few producers on the market, reaches satisfying performances with production costs lower than 0,6 €/Wp.
- **Copper Indium Selenide** (**CIS**) or **Copper Indium Gallium Selenide** (**CIGS**): They are produced by depositing a first layer of molybdenum on a glass substrate and on the top, different alloys of copper, indium, selenium and sometimes, to increase the energy gap, even gallium. The modules on the market, designed especially for residential sector, have an efficiency between 11% and 13%, while laboratory prototypes can reach even a 19-20%. For large values, production costs are around 0,6

€/Wp and market prices about 0,8€/Wp. Despite the time efficiency and an improved reliability during the past years, this kind of technology is still at an unsatisfied maturity phase.

THIRD GENERATION

Third generation includes innovative photovoltaic technology that uses principally organic semiconductor materials: they have the advantage of low production and material costs, but at the moment lifetime and performances are still unacceptable for a hypothetical market (maximum efficiency levels ever reached in laboratory are 10-11% for cell dye sensitized, DSSC, and 4-5% for totally organic cells). Commercial versions will be available in about 4 years.

A summary table with main features of different photovoltaic modules is shown below (Table 4-8):

Table 4-8 Photovoltaic modules main features

Module	Typical power range [Wp]	Market price [€/Wp]	Efficiency η	η drop off with T [%/°C]	η drop off with time [%/yr]
Crystalline	100-300	0,8	18-21	0,4-0,6	0,5
Polycrystalline	100-300	0,6	13-16	0,4-0,6	0,5-1
Thin film	60-100	< 0,6	6-11	0,25	15-20 in first 1000hrs

Having evaluated all characteristics of the described photovoltaic families, polycrystalline modules seem to be the most appropriate for the system concerned. In fishing centers where there are no space problems, having efficient, expensive modules like those of monocrystalline would be impractical.
In this particular context, installing a cheaper technology is more important than having a highly efficient system, which would be useful when the objective is to produce the desired power with the minimum possible surface. Looking at the installations described in the chapter 2, in the case of Dresden icemaker the need to have a highly efficient system emerges, given the necessity of creating a technology easily to transport and to set up.
Moreover, besides having a similar price, a higher efficiency and a better time stability than thin film modules, they are widely spread in African rural contexts, where they are well known and considered reliable, unlike second generation panels.
For these reasons, photovoltaic modules simulated will belong to polycrystalline family and will be represented by a commercial model, of which all necessary technical data are known (Table 4-9) [65]:

Table 4-9 Technical data of a commercial polycrystalline PV module

Model	Power [W]	Module surface [m²]	Efficiency [%]	Price [€/Wp]	η dropp off with T [%/°C]
Q CELLS, Q.PRO-G3 265	265	1,67	15,9	0,67	-0,43

Batteries

An electric battery is a device that converts chemical energy into electrical energy through one or more electrochemical cells; it has the function of energy storage, supplying the power when needed [66] [67]. This leads stand-alone photovoltaic systems to require this device: PV modules charge the batteries during daylight hours, which supply the power at night or in cloudy days.

A battery's principal characteristic is its capacity, or the amount of energy it can deliver at the rated voltage. Normally it is expressed by multiplying 20 hours by the current, at ambient temperature, a new battery is able to deliver for a period of 20 hours (Ah); it can also be defined by the power supplied in a certain number of hours (Wh).

Charge and discharge phases have a specific performance (typically near a 95%), that in most cases depends on the state of charge of the battery and on the ambient temperature. Also a self-discharge has to be taken into account, as the storage can lose from 2% to 8% of its initial capacity in one month [68].

There are two major categories for electrical storage batteries: primary batteries, that cannot be recharged, and secondary batteries, rechargeable.

Depending on the allowed depth of discharge (DoD), secondary batteries are divided into shallow batteries and deep cycle batteries: firsts are designed to discharge from 10% to 25% of their total capacity (low DoD), while deep cycle batteries can be discharge up to 80% without being damaged (high DoD).

This work will focus on the sizing of a photovoltaic system, then only batteries utilized in this field will be considered: the two most common batteries in use are lead-acid and alkaline batteries, naturally both are rechargeable, but in the following section alkaline batteries will be not considered because of their very high costs.

<u>Lead acid batteries</u>

Lead acid are the oldest type of rechargeable batteries; they are composed of an electrolyte that consists of sulphuric acid, and plates made up of lead to chemically store electrons.

Their large utilization in photovoltaic systems is due to the low costs and to their availability almost anywhere in the world.

They can be both deep cycle and shallow batteries but, as already stated, the analysis will only focus on those of deep cycle.
Almost all deep cycle lead-acid batteries could be discharged to 80% of their capacity, but they will last longer if the cycles are not below 50%; moreover, they will have a shorter life if not completely recharged after each cycle and in such cases while that they are not being used for extended periods.
These types of batteries are generally divided into flooded and settled batteries:

- **Flooded or wet batteries** are the most cost effective and the most widely used in photovoltaic applications: they usually have the longest life and the lowest cost per amp-hour of any of the other choices.

  They have a wide variety of shapes and sizes due to their widespread usage in a multitude of industries and applications.

  Usually flooded batteries are not sealed, and do not recombine the gases to liquids internally, then they utilize a vent to allow gas to escape. They contain liquid electrolyte that can spill and cause corrosion if tipped or punctured. For this reason they require maintenance, in the form of water, to routinely replenish lost electrolyte through the vents and they can only be installed upright. They cannot stand discharged conditions for large periods and continuous over-discharges.

- **Sealed batteries**: rather than submerging the plates in a liquid, the electrolyte is immobilized, gelled or absorbed in a material, allowing the battery to operate in any orientation without lacking. As all matter expands and contracts with heat, batteries are not truly sealed, but are "valve regulated", from here the name VRLA (valve regulated lead acid).

  Sealed construction eliminates periodic watering, corrosive acid fumes, and spills; then, requiring no maintenance, they are also called maintenance free batteries and they are more suitable for remote applications where regular maintenance is difficult, or enclosed locations where venting is an issue.

  Two categories can be distinct [69]:

  - *AGM* (Absorbent glass mat): to hold the electrolyte they feature fiberglass mesh; this leads to some advantages like faster charging and instant high currents on demand. They also can have over twice the cycle life of a conventional flooded product in the right application. Moreover, they are light, have a low self-discharge and have good performance at low temperatures. The principal drawback is the high price, in addition to have a low specific energy and a gradual decline of the capacity.
  - *GEL* batteries have the electrolyte permanently locked in a viscous gel state; because there is no liquid-type electrolyte, it will not leak out of the battery if tipped on its side. They have a superior deep discharge capacity and can deliver

over two to three times the cycle life of an AGM product in the right applications. Gel batteries can withstand deeper discharges than those of AGM, without damaging performance. However, due to the physical properties of the gelled electrolyte, Gel battery power declines faster than an AGM battery at low temperature conditions. These kind of batteries seem to be suitable for PV systems like the one analyzed in this work, but their high costs have to be considered. Their price ranges are even higher than AGM.

The level of maintenance required is another fundamental aspect of the decision: even if there would be one or two people dealing with the management and maintenance, a system that does not require excessive attention is better and has less risk of failure. In a context like fishing centers, distillated water is surely not easily attainable and finding it in the nearest cities may be difficult. This could lead to the usage of river water and incur permanent damage to the batteries, as it happened in other similar situations.
Because of this, flooded acid batteries are rejected, as they, more than any other, require this kind of maintenance.
Table 4-10 helps to comprehend whether AGM or Gel batteries should be favored:

Table 4-10 Advantages of gel and AGM battery design

KEY BATTERY BENEFITS	GEL	AGM
Premium maintenance-free design	Yes	Yes
Air transportable	Yes (most sizes)	Yes (many sizes)
Spillproof construction, won't leak if turned sideways	Yes	Yes
Minimizes terminal corrosion	Yes	Yes
Superior deep cycle life and resiliency to deep discharge damage	Yes (Best)	Yes (Good)
Operates at severe angle or on side (won't leak or spill)	Yes	Yes
Low to no gassing	Yes	Yes
Ideal for use around sensitive electronic equipment	Yes	Yes
Extended shelf life, low self-discharge rate	Yes	Yes
Enhanced recharging efficiency	Yes	Yes
Resistance to vibration	Yes	Yes
Delivers the best combination starting, cycling, and deep cycle service	Yes (Good)	Yes (Best)
Operation in cold temperatures	Yes (Good)	Yes (Best)
Cold engine cranking	Low	Yes

The following significant distinction is made to simplify the choice in question: AGM batteries excel for high current, high power applications and in extremely cold environments; they deliver a better dual-purpose solution for a combination of starting and accessory power.

Gel batteries are better suited for high-deep discharge applications and last longer; therefore, they will be the most appropriate batteries for the system studied.
Technical data are not referred to a specific commercial model: the sizing of battery array will be based just on the determination of total capacity needed. Here below there are all the technical features that will be considered in the simulation and that represent a generic gel battery utilized for similar contexts (Table 4-11):

Table 4-11 Technical data of a gel battery

Charging efficiency [%]	Discharging efficiency [%]	Self-discharge [%/month]	Maximum accepted DoD [% of the total capacity]	Price [€/Wh]
95	95	5	50	0,25

Inverter and charge controller

Inverter is an electronic device that converts direct current (DC) into alternate current (AC). It is necessary in a photovoltaic installation since the output of PV modules is direct current and normally the device supplied works with alternate current.
Inverters do not produce any power, the power is provided by the DC source, in most cases batteries. They have a high efficiency (around 95%) and each device has its characteristic power rating that indicates the power that will be available to the AC device and the power that will be needed from DC source.
Depending on the circuit design, inverters can produce different waves, among which the sine wave, and can adjust output voltage depending on the one of the device supplied.
Technical data used in the simulation are shown in table 4-12

Table 4-12 Technical data of two commercial inverters [70]

Model	Out power at 25°C [VA]	Out power at 25°C [W]	Peak power [W]	CC voltage [V]	AC voltage [V]	Efficiency [%]	Price [€]
Phoenics Inverter 24/3000	3000	2500	6000	24	230	94	1373
Phoenics Inverter 24/5000	5000	4500	10000	24	230	94	2162

The charge controller is an essential instrument for a correct functioning of a stand-alone photovoltaic system: it regulates rates of electricity flow from the generation source to the battery and the load, depending on needs and conditions [71]. It is definitively a vital component because it protects battery by preventing overcharging and avoiding overvoltage, both damaging for the battery. When the load is drawing power, the

controller allows the charge to flow from the generation source into the battery, the load, or both. It can also prevent deep discharging disconnecting cables when a fixed depth of discharge is reached in order to extend the battery's lifetime.
The cost of controllers generally depends on the ampere capacity at which the system operate and the monitoring features desired.
The following models reported in table 4-13 will characterize different possible solutions:

Table 4-13 Technical data of three commercial charge controllers [70]

Model	Maximum PV power [W]	Maximum PV open circuit voltage [V]	Battery voltage [V]	Rated charge current [A]	Efficiency [%]	Price [€]
BlueSolar MPPT 150/35	2000 (at 48V)	150	12/24 48	35	~ 100	330
BlueSolar MPPT 150/85	4850 (at 48V)	150	12/24 36/48	85	~ 100	730
BlueSolar MPPT 150/70	4000 (at 48V)	150	12/24 36/48	70	~ 100	650

4.2.3 Different system configurations

Before simulating the system operation it is necessary to define the energetic request in order to run the icemakers. The first stage consists in choosing the number and the type of icemakers to use in the system (see the models considered in the previous paragraph). By establishing the working hours for the icemakers it is possible to define a power curve.
The objective is to propone two possible configurations. The first configuration is characterized by an electrical storage while the second one has a cold storage.
For each configuration two different operation modes are defined. Each operation mode is characterized by different models and working timetable of icemakers.
The first part of this section will be dedicated to the configuration 1 (with the electric storage) while the second part will illustrate two alternatives of configuration 2 (with cold storage). The description of every configuration finishes with the definition of its power request.

Configuration 1

In the first system configuration, photovoltaic modules and battery array supply both icemakers. Icemakers operate in order to manage the coordination between ice demand and ice production and, to achieve this, icemakers must work at definite hours. Because during the whole year the ice is needed also in the early morning, the icemakers have to operate during the night in order to meet this need. Icemakers nocturnal operation is permitted by the energy supplied by batteries.

The first operation mode presented (***operation mode 1***) considers four Rosen1 icemakers that produce 60 kg of ice through a basic cycle of 6 hours. Their timetable of wet and dry season is represented in figure 4-5, while figure 4-6 shows the consequent power request.

	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WET SEASON	Rosen 1			off			on					off											on		
	Rosen 1			off			on					off											on		
	Rosen 1			off			on					off											on		
	Rosen 1					off			on					off											on
	PRODUCTION			180		60						180		60											
	REQUEST				150		75						150		75										
DRY SEASON	Rosen 1	off			on					off											on				
	Rosen 1					off				on					off										on
	Rosen 1					off						on					off								on
	Rosen 1					on					off														
	PRODUCTION	60				120				60	60				60		60								
	REQUEST		38				125				50	75				50		75							

Figure 4-5 Timetable of configuration 1, operation mode 1

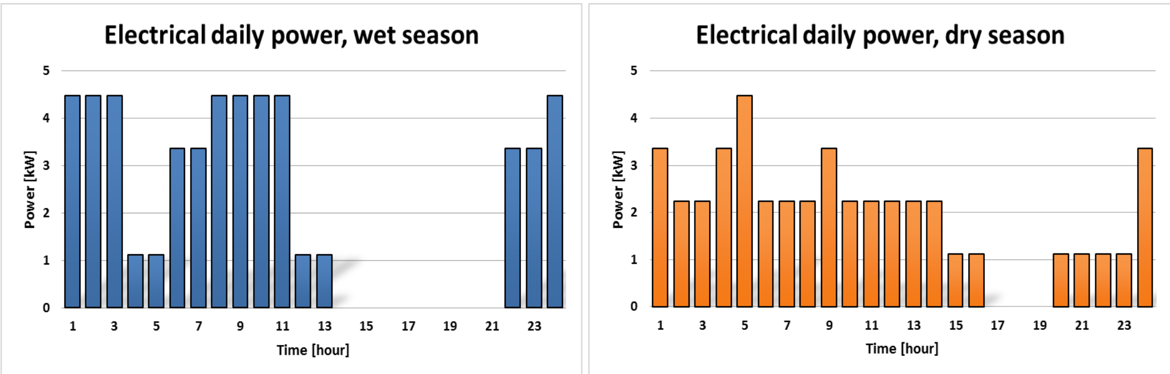


Figure 4-6 Electrical daily power of wet and dry season (Configuration 1, operation mode 1)

Electrical daily power curve does not correspond with solar irradiation curve, that has its peak between 11am and 2pm. Consequently, photovoltaic modules supply icemakers during the day and charge the batteries when energy production exceeds energy demand. The batteries will have to deliver the necessary current when solar source is not available, during cloudy hours and, in particular, during the night. This necessity supposes the installation of a high battery capacity.

The operation during the night reduces ice making efficiency losses caused by high temperatures and this represents a real and great advantage, as the monitoring of Chorreras icemaker proved.

A second combination of different icemakers (***operation mode 2***) is proposed. It features three machines, instead of four, of different brands: two Rosen1 and one U.S. ice machine that produces 126 kg of ice through a basic cycle of 6 hours.
Figures 4-7 and 4-8 represent respectively the timetable and the power curve of this operation mode.

	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WET SEASON	US ice machine			off			on					off											on		
	Rosen 1			off			on					off											on		
	Rosen 1					off			on					off											on
	PRODUCTION			186		60						186		60											
	REQUEST				150		75						150		75										
DRY SEASON	US ice machine			on											off										
	Rosen 1					off																			on
	Rosen 1					off													on					off	on
	PRODUCTION					120				126						126									60
	REQUEST		38				125				50	75				50		75							

Figure 4-7 Timetable of configuration 1, operation mode 2

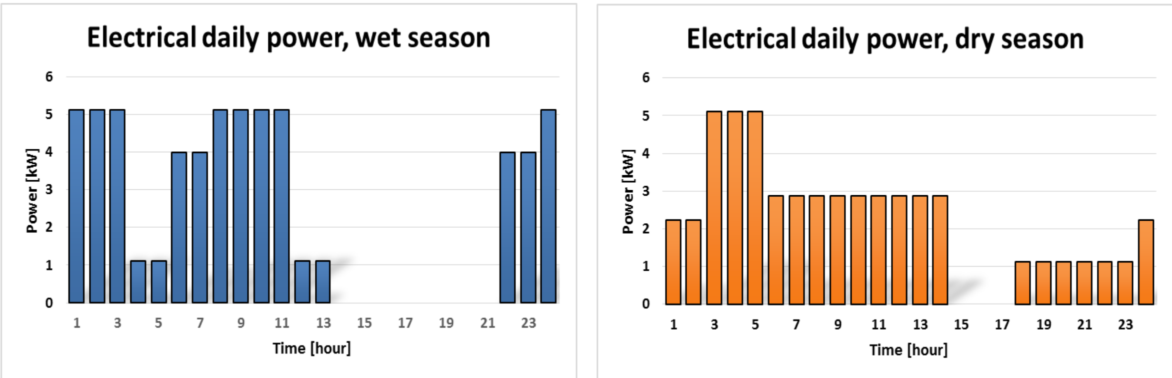


Figure 4-8 Electrical daily power of wet and dry season (Configuration 1, operation mode 2)

We consider the demand as satisfied if the ice is sold in less than two hours (starting from the moment of ice production). In this way thermal losses are neglected.
Comparing the two operations, some differences emerge: the combination of icemakers allows operation mode 1 to have a less expensive system, lower peak power and electrical production (in terms of kWh per day), that implies a cheaper photovoltaic system. On the other hand, operation mode 2 satisfies the entire daily ice request, while in the other case the icemakers produce 15 kg less per day than the necessary. Moreover, operation mode 2 has the advantage of having a more uniform power demand, a feature that supports battery performance.
It is practical to compare these two operation modes, since there will be an opportunity to determine if the last advantages described can go beyond economic benefits.

Configuration 2

The problem deriving from the nocturnal operation permitted the definition of other possible solutions. The principal negative aspect that could be avoided is the large battery size that the system requires to supply all the nocturnal requirements.

Consequently, the hypothesis of using a thermal storage instead of an electrical storage is considered. In this case the system uses all the available daily hours making icemakers run on the only photovoltaic output, if possible even during the hours with a weak solar radiation (in the early morning and in the late afternoon). The objective is to produce the total amount of ice necessary, storing it in a thermal storage and using it when required.

Batteries are also installed, but just for the purpose of supplying the power when photovoltaic modules are not able to manage it by themselves (in cloudy hours).

Depending on the type of thermal storage, two cases are distinguished.

Configuration 2S: it is characterized by an insulated container, where the produced ice is stored if fishermen and merchants does not need it. In case the production perfectly matches the request, the ice is not stored but directly sold. This container should minimize the thermal losses, because even at night temperatures are quite high. Afterwards, it should be placed in a shady area, for instance under a dedicated roofing.

The main success of this configuration could be the significant reduction of necessary battery capacity but this is feasible only if there is a concrete possibility of keeping ice at a temperature below 0°C. In order to achieve this, the container has to present an appropriate insulation: a calculation of thermal losses through insulated wall will be carried out to know ice temperature variation with insulation thickness.

Configuration 2F: a second possible configuration with thermal storage is proposed to avoid the issue of ice melting. Instead of an insulated container, a freezer that keeps the ice cold may be utilized: in this way, thermal loss is avoided and ice can be sold at -10°C. This configuration allows merchants and fishermen to utilize the ice for preserving fresh fish for more hours.

The freezer will be supplied directly by photovoltaic modules when possible and by batteries during the night or during cloudy hours. Besides this, the necessary battery capacity will be quite low, since the power amount requested for supplying the freezer is minimal.

Both configurations, 2S and 2F, have the same operation modes (operation mode 3 and 4). In this paragraph the additional energy required for freezer supply is not considered, then the power curve relative to the same operation mode is the same for configuration 2S and 2F.

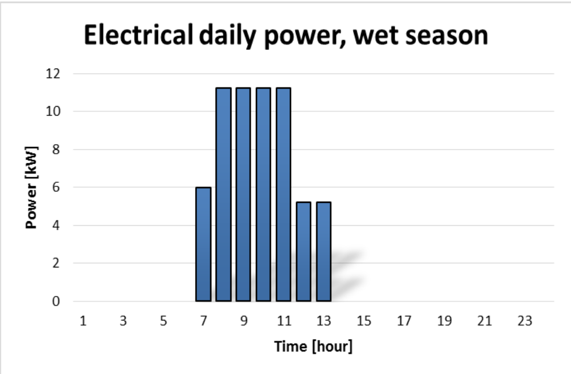
Operation mode 3 considers just two icemakers of two different brands: one GZ kooler that produces 200 kg of ice through a basic cycle of 4,8 hours and one Rosen2 that produces 250 kg of ice in 6 hours. With just two icemakers and a fixed ice request, there was not flexibility in the definition of the timetable.

In figure 4-9 icemakers timetable of configuration 2, operation mode 3 is presented.

	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WET SEASON	GZ kooler							on				off													
	Rosen 2								on					off											
	PRODUCTION											200		250											
	REQUEST				150		75						150		75										
DRY SEASON	GZ kooler												on				off								
	Rosen 2									on					off										
	PRODUCTION														250		200								
	REQUEST		38				125				50	75				50		75							

Figure 4-9 Timetable of configuration 2, operation mode 3

The consequent electrical daily power curve is shown in figure 4-10 :



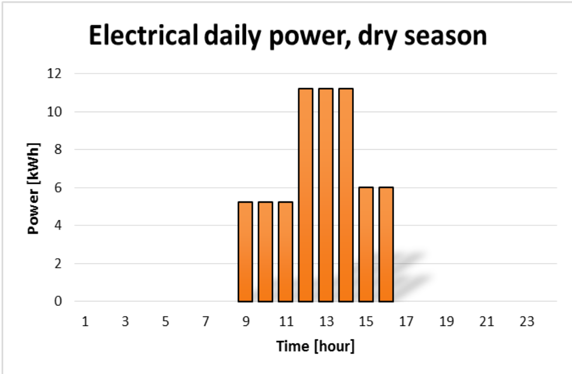


Figure 4-10 Electrical daily power of wet and dry season (Configuration 2, operation mode 3)

Operation mode 4 uses eight icemakers of the same brand. As in the operation 1 just Rosen1 are chosen and they produce 60 kg of ice in 6 hours. Because of the lower ice request of dry season, in that period just seven icemakers will operate.

The advantage of combining several icemakers is to create a power request that follows the solar irradiation curve perfectly, creating a clever timetable for ice making operations. Just one or two machines run in early morning and late afternoon, while the biggest part of the request is concentrated during solar peak hours, as figure 4-11 illustrates.

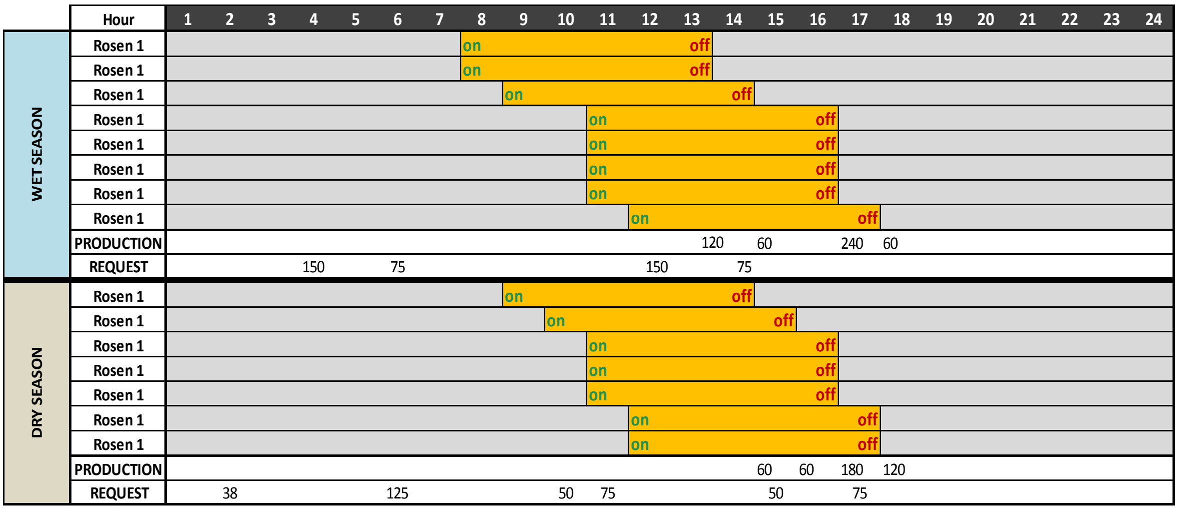


Figure 4-11 Timetable of configuration 2, operation mode 4

The characteristic power curve of this operation mode is illustrated in figure 4-12:

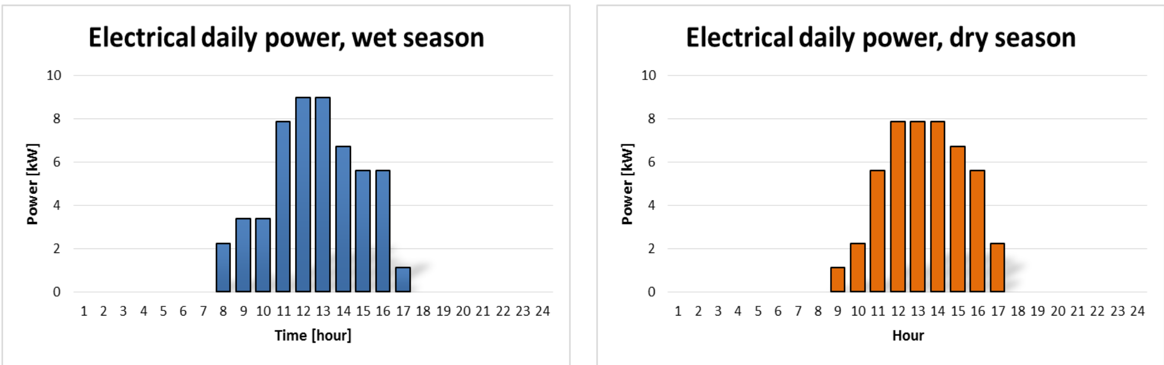


Figure 4-12 Electrical daily power of wet and dry season (Configuration 2, operation mode 4)

The comparison between a certain number of icemakers that have different basic cycles (in terms of time and quantity of ice produced) and different costs leads to some interesting comments: watching only icemakers costs, operation mode 3 results cheaper, but its peak power and daily energy production are higher than those of operation mode 4.

Table 4-14 summarizes the proposed possibilities and indicates icemakers cost, peak power and daily energy request of very operation mode relative to each configuration:

Table 4-14 Main features of the configurations

	Operation mode	Icemakers total cost [€]	Peak Power [kW]	Daily energy request [kWh/d]	
				Wet season	Dry season
Electrical storage	1	8552	4,5	54	47
	2	14006	5,1	61	55
Thermal storage	3	12840	11,2	61	61
	4	17104	8,9	54	47

Economic evaluation

We now evaluate in economic terms all the configurations described in the previous paragraph. This analysis also defines the economic indexes later used to assess the simulation results.
One of the most important parameter the choice of the suitable system is based on is the Net Present Cost (NPC). It represents the economic value of the system during its entire lifetime, since it considers also operation and maintenance and replacements costs, in addition to the investment. Considering only the initial capital for a comparison would be wrong, as many information about future costs of the different configurations would be lost.
Assuming a system lifetime of 25 years, NPC is calculated with the following formula:

$$NPC = \sum_{i=0}^{25} \frac{FF_i}{k_i} - \frac{SV_{25}}{k_{25}} \qquad \text{Equation 4-6}$$

where

- k is the discount factor: $k = (1 + r)^i$, with r (discount rate) assumed equal to 3,5%[7].
- SV is the salvage value, utilized just for the last year. It represents the economic value that all the components have at the last year of the system life and, for every component, is evaluated like:

$$SV = P \times \frac{y_{left}}{y_{tot}} \qquad \text{Equation 4-7}$$

with
P= component price
y_{left}= left years of operation
y_{tot}= component lifetime

- FF_i are the yearly financial flows:

$$FF = C_{inv} + C_{O\&M} + C_{rep} \qquad \text{Equation 4-8}$$

In the equation the components costs are:
  - C_{inv} = investment cost
  - $C_{O\&M}$ = operation and maintenance costs
  - C_{rep} = replacement costs

[7] The discount rate considers inflation, interest and risk rate. It is common to use a value of 3 to 5 percent when evaluating social programs [78]

We now focus on these three costs, specifying how they are made up for every type of configuration.

Investment cost

Depending on the configuration and the relative operation mode, investment cost arrives from different singular component prices, which have different values.

In all cases, it consists of icemakers contribute and the ones of inverter and charge controller. Moreover, costs of photovoltaic system and batteries have to be considered, but they will depend on the sizes calculated by the code; for now we know just how the price varies with the size: in the case of batteries, we have 0,25 €/Wh, while photovoltaic array has a price of 0,67 €/Wp, at which an installation cost of 30% will be added.

Here below, for every case, a list of the costs varying with the configuration is reported:

Configuration 1, operation mode 1:

- 4 Rosen1 icemakers → 8552 €
- 1 Victron inverter (5 kVA) → 2162 €
- 1 Victron charge controller (4850W) →730 €

Configuration 1, operation mode 2:

- 1 Rosen1 icemaker + 2 US ice machines → 14006 €
- 2 Victron inverter (3 kVA each)→ 2746 €
- 2 charge controller → 980 €

Configuration 2, operation mode 3:

- 1 GZ Kooler and 1 Rosen2 icemakers → 12840 €
- 2 Victron inverter (5 KVA) + 1 Victron inverter (3 KVA each) → 5697 €
- 2 Victron charge controller (4850 W each) + 1 (2000 W) → 1790 €

Configuration 2, operation mode 4:

- 8 Rosen1 icemakers → 17104 €
- 2 Victron inverter (5 KVA) → 4324 €
- 2 Victron charge controller (4850 W each) → 1460 €

Other investment costs arrive from the freezer in the case of configuration 2F (748 €) [72] and from the insulation in the case of configuration 2A (85 €/m^3) [73].

Operation & maintenance costs

O&M costs are considered a percentage of total costs of every component, independently on the type of configuration:

- Photovoltaic modules: 20 €/kW per year
- Batteries: 7% of total cost
- Inverter: 10% of total cost

- Icemakers: 5% of total cost

Besides all of these components, also the salaries contribute to O&M costs: to make the system work correctly, at least one person has to manage and control it, making the appropriate maintenance. The number of people needed varies according to the type of configuration: the system that utilizes an electric storage and has a nocturnal operation needs just one person, that deals with water replenishment of icemakers and with photovoltaic modules' cleaning. On the contrary, configuration 2, both with a thermal storage and a freezer, necessitates two persons because of the major task of managing ice storage.
According to World Bank evaluations [48], a normal Mozambican salary is about 100 € per month, then configuration 1 will presents an annual salary cost of 1200 €, while configuration 2, 2400 € .

Replacement costs
Replacement cost of a single component has the same value of its initial cost, actualized at the replacement year. For the calculation of NPC, elements' replacements were based on their respective lifetimes, took from technical data:

- Icemakers: 8 years
- Batteries: 5 years
- Inverter: 10 years
- Photovoltaic system and charge controller: 20 years

In this paragraph, different elements that will compose the system are described; the intention is to introduce their typical features and to classify every component according to existing typologies present in the market, in order to be able to choose the best ones.

4.2.4 Simulation modeling

The model proposed in this work aims to simulate the operation of each configuration, in order to establish the optimal sizing of the entire system and to acquire some data that allow defining the most appropriate configuration.
The simulation has been made with a Matlab code that replicates the operation of each component of the system hour by hour in a typical year, that is based on typical meteorological year data. This code has the objective of calculating, given hourly inputs, total energy production and total energy supplied to the icemakers, with their relative time trends.

Here below (Figure 4-13) we illustrate the available and necessary inputs for the simulation and the most significant expected outputs. In the following, they are described in more detail.

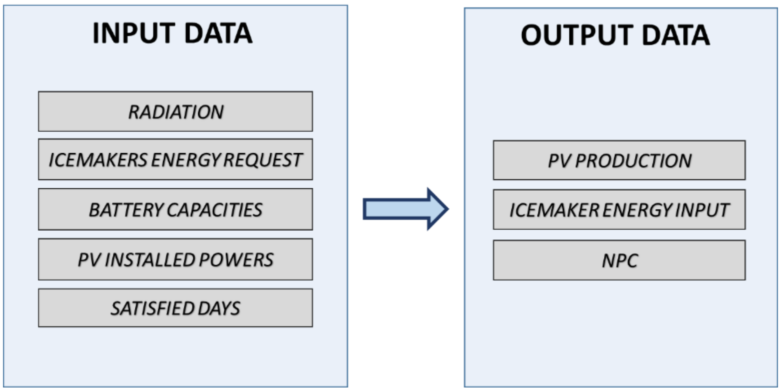


Figure 4-13 Input and output data of the Matlab code

INPUTS

- **Radiation data:** data are obtained from Meteonorm, a software that contains worldwide weather data based on historical reports (the standard is 1991-2010 for solar irradiation).
  Given the geographic coordinates of Mopeia (latitude -18,02°; longitude 35,68°), the software interpolates data of the three nearest localities where weather information are known, extracting those of the desired area.
  Through Meteonorm features, the calculation of the best panels inclination has been possible: a north-facing surface tilted at 20° results the one that receives the highest amount of irradiation during the considered period, thus radiation data are referred to this tilt angle.
  All hourly data entering in the code are expressed in energy [Wh/m^2].
  Figure 4-14 displays the global irradiance, resulting from Meteonorm, on a surface tilted at 20°C:

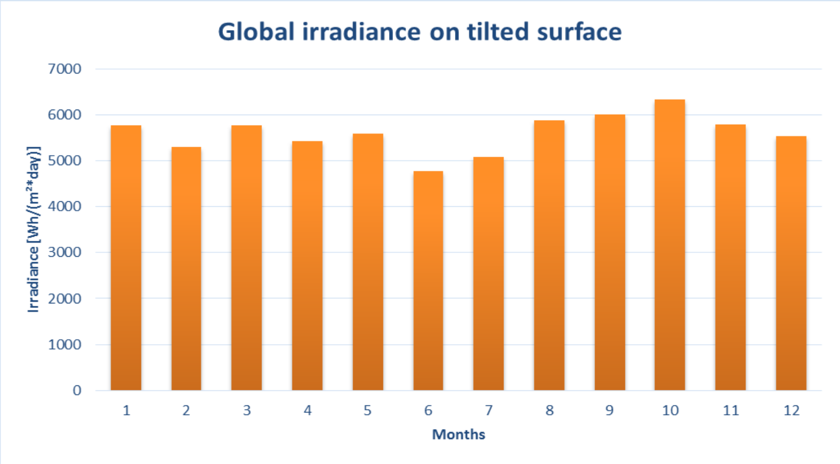


Figure 4-14 Global irradiance on tilted surface, Zambezia

Besides solar irradiation, Meteonorm provides hourly **air temperature**, that is necessary to calculate ice melting and the losses of PV module efficiency.

- **Icemakers energy request:** it is the energetic input that icemakers need hour-by-hour [Wh]. As defined before, it is constant in the days belonging to the same season.
- **Range of PV installed power:** depending on the configuration simulated, power installed can vary from 15 kWp to 50 kWp, with a step of 0,5 kW. For every values of this range the code calculates the PV production and the icemakers energy input.
- **Range of battery capacity:** depending on the configuration simulated, battery capacity can vary from 5 kWh to 90 kWh, with a step of 1 kWh. Among these values the code finds the suitable battery capacity relative to every photovoltaic installed power.
- **Number of days in which the request is satisfied:** they are expressed as percentage over one year. They are necessary because, as explained in the following, the code bases all the calculations on the minimum number of days in which the entire system must guarantee the requested energy. Days where the request is satisfied are called “satisfied days”.

OUTPUTS

- The first evaluation of the model is the hourly **energy production** of photovoltaic system. In following steps, its final use is determined, depending on icemaker request and on the state of charge of the battery.
- Once known the PV production and energy stored in batteries, the real **energy supplied to the icemaker** is calculated.

- The code returns also an economic parameter, the Net Present Cost (**NPC**), that has a key role for the comparison of the different solutions under investigation.

The next paragraphs describes the logic of functioning of every component and the general structure of the code.

Photovoltaic modules

The electrical energy (E_{pv}) produced by the photovoltaic array is calculated by taking as input the solar energy that hits 1 m² of surface tilted at 20° in 1 hour (H_t):

$$E_{pv} = H_t \cdot \eta_{cell} \cdot \eta_{BOS} \cdot S$$ Equation 4-9

Surface S is derived from the installed power (P_{inst}), and is obtained by the following relation:

$$S = P_{inst}/P_{mod} \cdot S_{mod}$$ Equation 4-10

E_{pv} takes into account the performance of the photovoltaic system, but it still does not consider other aspects that may influence it negatively. Meteonorm provides the temperature of a generic surface tilted at a desired angle, so surface cells temperature can be calculated and this allows taking into consideration performance losses due to high temperatures. As mentioned in chapter 4.2.2, we use a factor of -0,43%/°C.
In addition to this, also a decrease of performance caused by modules' fouling has been considered. This parameters makes the simulation more realistic, since in the context at issue the modules could be cleaned rarely.

Batteries

For every hour, three values concerning battery bank are calculated: energy input (E_{in}^h), energy output(E_{out}^h) and energy stored(E_s^{h-1}).
Energy input is due to photovoltaic production, but only when it has already matched icemakers demand. In this case, energy E_{in}^h entering into the storage is lower than energy arriving from PV panels, as the process of charging brings to some losses. If battery is already charged, there is no energy input.
Energy output E_{out}^h depends on icemakers request and photovoltaic production, and takes into consideration losses due to battery discharge and inverter operation. Moreover, it has a well-defined limit: the control is set in order to avoid a depth of discharge higher than 50%. Therefore, when this value is reached, extracting energy from the battery is no longer allowed.

At the end of every hour, stored energy (E_s^h) is computed on the basis of the input and output energy of the same hour (respectively E_{in}^h and E_{out}^h), and the energy stored at the previous hour (E_s^{h-1}), as the following relation shows.

$$E_s^h = E_{in}^h - E_{out}^h + E_s^{h-1}$$

Equation 4-11

Icemakers

As shown in the previous paragraph, different icemakers work to produce a specific quantity of ice in one day according to specific operation strategies: such amount of ice is then used to calculate one of the inputs of the code, the total energy request.

All the icemakers are simulated in the code as a unique icemaker that produces all the ice, working at partial levels.

The demand is satisfied just when the entire energy request is matched.

Another note about icemakers operation: as seen before, there are basic cycles that last some hours and need continuous supply. Thus, for example, if one basic cycle lasts 6 hours but the forth hour is not fully satisfied, the operation is considered interrupted and the entire cycle not counted.

Therefore, we define the day as “satisfied” when icemakers are supplied at full load during the whole operating cycle. This is a conservative hypothesis, but the objective of the simulation is to verify if the proposed installation can supply hour by hour the request, respecting quantities and time restrictions.

General logic of the code

The code simulates the operation of different configurations through different functions, which have different input values, but the same logic: we start now to explain this logic, illustrating how the code works to obtain the desired outputs.

Figure 4-15 displays the main function of the code, composed of different sub-functions described in the following:

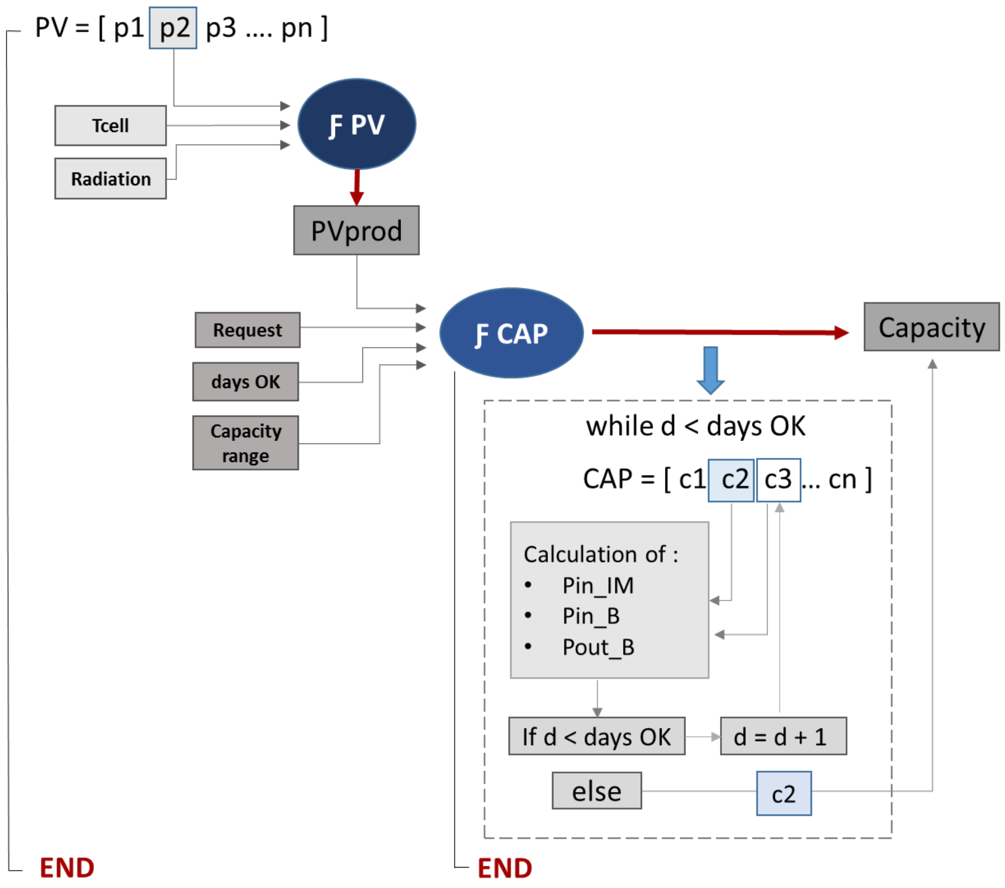


Figure 4-15 Code's main function

The main function analyzes each value of installed PV power, repeating the same computation for each one.

The first step is the calculation of the power produced by photovoltaic modules, through the function "PV". This constitutes one of the inputs of the function "CAP": this function, starting from a specific photovoltaic power, is able to find the minimum battery capacity that matches the request, satisfying a given number of days (expressed as "days OK").

Function "CAP" begins running with the first possible value of battery capacity: this is used to calculate the total energy input of icemakers and the numbers of satisfied days. If this number is lower than "days OK", the function will repeat the same computation taking the next battery capacity, until it finds the definitive value.

We now illustrate the operational logic that defines energy flows in photovoltaic modules, battery and icemakers.

In the optimal conditions (Figure 4-16), photovoltaic modules produce enough power to supply icemakers at full load, and the remaining part of electricity produced is used to charge the batteries. If these are already fully charged, extra energy is lost. Indeed, the

charge controller stops the charge of the battery when this is almost full, avoiding overcharge.
The power produced by the PV array is considered sufficient to supply the icemakers, if it considers also the losses that the inverter will cause.

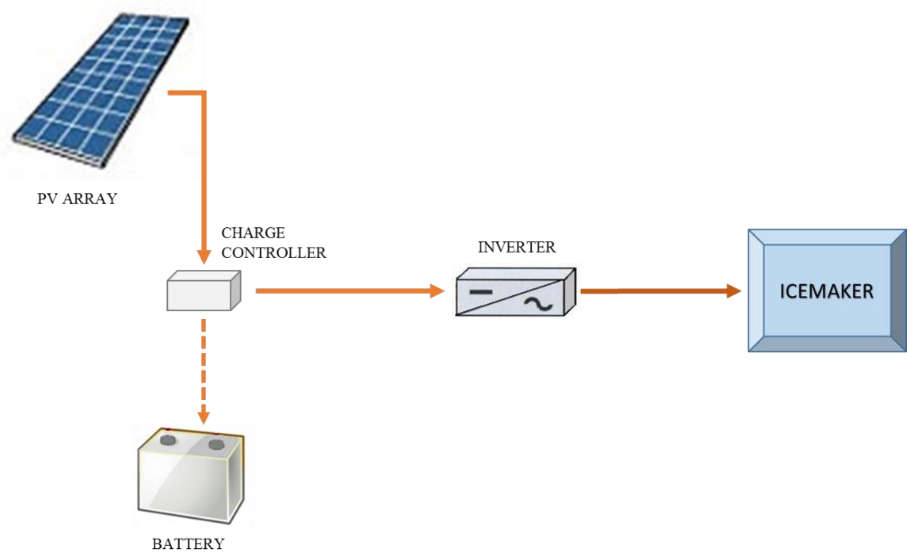


Figure 4-16 Energy flows in case of sufficient photovoltaic power

If power produced by photovoltaic array is not sufficient, the battery bank supplies the lacking power to icemakers. Photovoltaic panels have always the priority: we resort to battery only to fill the unmet demand gap generated by insufficient power from the PV array This constitutes the basic function of batteries, as figure 4-17 illustrates:

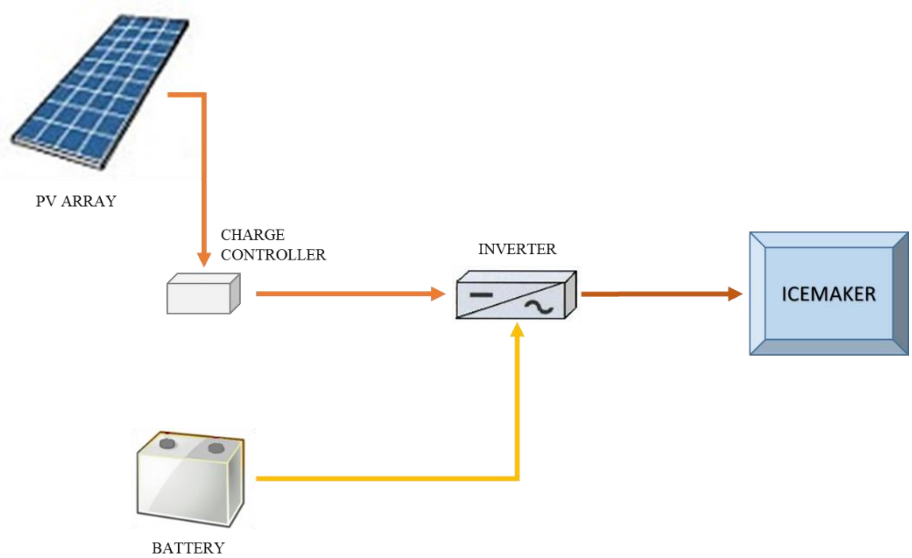


Figure 4-17 Energy flows in case of insufficient photovoltaic power

Another possible scenario occurs when photovoltaic and battery array together cannot satisfy the load. For simplicity, an "hourly available energy" (E_a^h) is defined: it is the sum of the energy coming from photovoltaic modules (E_{pv}^h) and that stored in the battery(E_s^{h-1}). It includes the losses caused by inverter and the ones deriving from the discharge of the battery.

$$E_a^h = ((E_s^{h-1} - E_{min}) \times \eta_d + E_{pv}^h) \times \eta_{inv} \qquad \text{Equation 4-12}$$

where
η_d= discharge efficiency of the battery;
η_{inv} = inverter efficiency;
E_{min} = minimum energy that can be stored in the battery (50% of the total capacity);

This is necessary to reproduce more faithfully the real operation of icemakers: even if they really do not work at partial levels, it can happen that the available power is enough to make some of them work at full load, leaving the others turned off. This allows calculating the satisfied request as the ratio between the energy effectively supplied to icemakers and the total requested load, in terms of energy (kWh) instead of days.
When battery and photovoltaic together are not sufficient to supply the total power, the system operates in the following way: different numbers of individual icemakers can work simultaneously and this allows defining different possible levels of request (pL^h) that can be satisfied. In this way, the system will supply as more machines as possible, guaranteeing full single loads.
In order to clarify this operation mode, we report an example. If available energy is sufficient to supply just three machines instead of five, the E_a^h could arrive from photovoltaic array or from the storage. In the first option, if there is some remaining energy, it is used to charge the battery.

Figures 4-18 and 4-19 summarize how the function "CAP" calculates energy flows:

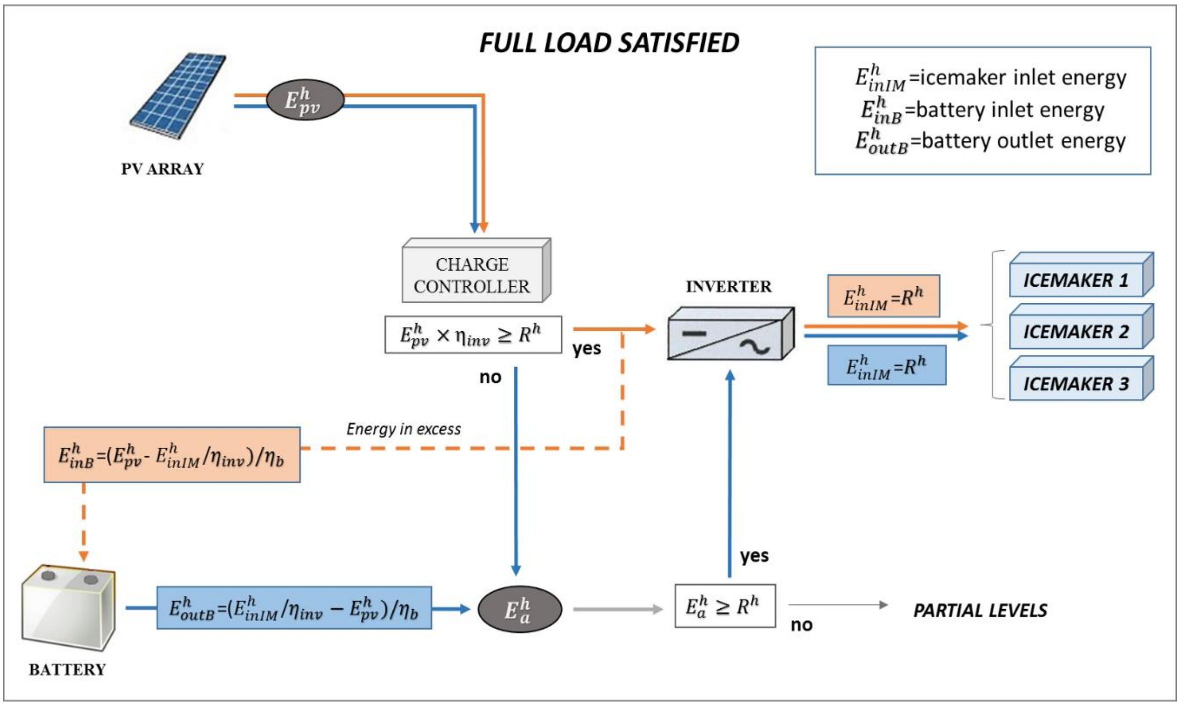


Figure 4-18 Function CAP, full load satisfied

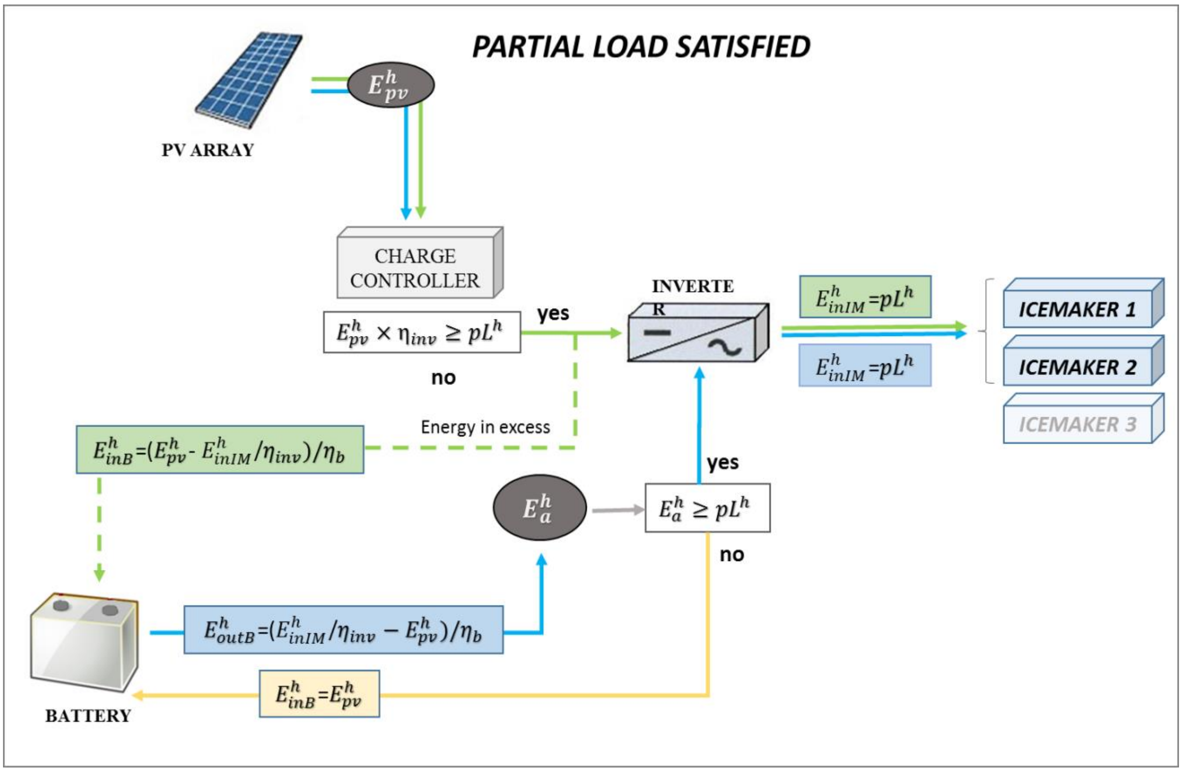


Figure 4-19 Function CAP, partial load satisfied

Every function, has this operational logic, based on the maximization of the use of photovoltaic installation. In the next part, the differences in the structure of the code for the different configurations are explained.

Configuration 1

This configuration is the one that better follows the operational logic just described: its only objective is defining the flows concerning photovoltaic modules, battery bank and icemakers and it does not present peculiarities with respect to the operation explained above.

In this case, icemakers operate also during the night and the code follows the previous logic: irradiation is absent and photovoltaic array does not produce any power, so all the energy supplying the icemakers comes from battery bank.

This leads to a high storage capacity, as the battery has to match the entire nocturnal load.

Configuration 2S

Configuration 2 uses batteries with the scope of assuring a continuous supply during cloudy periods, since icemakers operate just in daily hours, when radiation is enough to produce all the energy needed.

The peculiarity of the code that simulates this second configuration is the function that computes the melting of the ice stored in the insulated container.

In particular, the function evaluates ice temperature at the beginning and at the end of every hour, in order to know at which temperature the ice is sold to merchants or fishermen. This is possible by knowing the quantity of stored ice, the air temperature and some features of the insulated container, as shown in figure 4-20

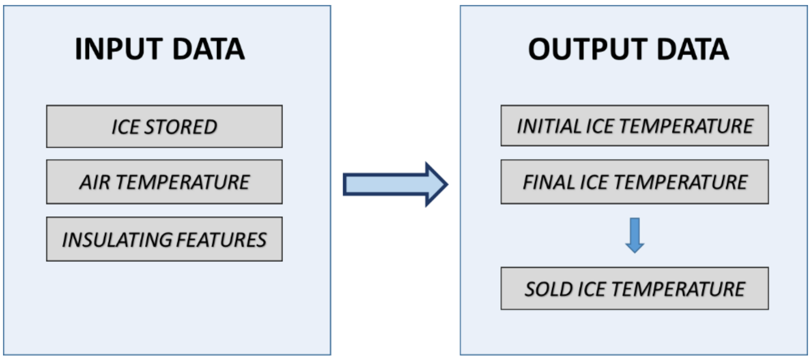


Figure 4-20 Input and output data of the function that calculates ice melting

A focus on the inputs of this function is necessary to explain how they have been calculated or where they derive from.

INPUTS

- **Stored ice** is evaluated by means of a vector that indicates which days of the year are satisfied. In this way, if a day is satisfied, we know exactly when and how much ice is produced. Being known also the request of ice, stored ice at hour 'h' can be calculated as:

$$Ice_{stored}^{h} = Ice_{stored}^{h-1} + Ice_{produced}^{h} - Ice_{requested}^{h} \quad \text{Equation 4-13}$$

- Hourly **air temperature** is a key factor for the evaluation of thermal losses. This parameter has an important influence also during the night, since the mean of nocturnal temperatures is quite high, even in absence of solar irradiation.
  Another essential parameter is the convective heat transfer coefficient: assuming natural convection, h = 25 $W/m^2 K$ has been considered a reasonable value [55].
- **Insulating data** include conductive heat transfer coefficient of the insulating material (k) and container dimensions. The most significant is the thickness: changing the input value of the thickness of the insulating layer, alterations of ice temperature are observed and the optimal value can be determined.
  The material chosen for the insulation is expanded polystyrene, that presents a conductive heat transfer coefficient (k) of 0,036 $W/m\,K$.[55]
  For simplicity, a cubic container is supposed, with an internal volume of 1m³; depending on the thickness, a total external area is calculated.

OUTPUTS

The main output is the temperature at which ice is sold ($T_{ice\_sold}^{h}$). Different cases are possible:

- if there is a coincidence between the production and the demand and the quantity of ice just produced is as much as the quantity requested, the ice is immediately sold. In this case sold ice temperature is the same of produced ice temperature ($T_{prod} =$ -10°C);
- if there is a coincidence between the production and the demand but the ice produced is not enough, the remaining needed quantity of ice comes by the storage. Sold ice temperature stays between the produced ice temperature, ($T_{prod} =$ -10°C), and the ice temperature in the storage at the end of the previous hour ($T_{ice_{stored}}^{h-1}$). In detail, the temperature of the sold ice is calculated as the weighted average temperature, as expressed above:

$$T^{h}_{ice\_sold} = \frac{m^{h}_{ice_{produced}} \times (T_{prod}) + (m^{h}_{ice_{requested}} - m^{h}_{ice_{produced}}) \times T^{h-1}_{ice_{stored}}}{m^{h}_{ice\_requested}}$$ Equation 4-14

If at the moment in which ice is required there is no production, the ice will be taken from the storage, at the final temperature of the previous hour.
We now clarify how initial and final temperatures of preserved ice are estimated.
First of all, the process of ice melting considers just the phenomena of convection and conduction, excluding irradiation: the period in which melting occurs is when the last machines finish working, that is in the late afternoon. Furthermore, if the ice storage is placed in a shady area, as previously mentioned, solar irradiation influence is minimized.
The two coefficients of heat transfer mentioned above permit to define a total resistance, which consider both conduction and convection. From literature [55], it is calculated with the following equation:

$$R_{tot} = \frac{t}{A_k \times k} + \frac{1}{A_h \times h}$$ Equation 4-15

where:
A_k= area of conductive heat transfer (arithmetic mean of internal and external area) [m²];
A_h= area of convective heat transfer (external area, in contact with the atmosphere) [m²];
t = thickness [m]

Knowing the total resistance, and assuming a temperature of internal walls equal to that of the ice, it is possible to calculate the power loss through insulated walls [55], as shown in the following relation.

$$Q = \frac{(T_{air} - T_{internal\_wall})}{R_{tot}} \quad [\mathrm{W}]$$ Equation 4-16

Q represents the hourly average power entering into the container, that makes the ice melting. This permits to know the energy lost during one hour (E [J]).
Different cases are distinguished to estimate the **initial temperature** of the ice at the hour 'h':

- If a part of ice produced is stored into the storage, containing already other ice, initial temperature is between -10°C and the temperature of ice stored from the previous hour. The calculation is done similarly to the case of the sold ice, in which mass weights have been considered.
- If at hour 'h' no ice remains stored and there is remaining produced ice, all of this is stored and, consequently, the initial temperature is be -10°C

- If there is no ice production at hour ‘h’, or all the ice produced is sold, initial temperature is the same of the final one of the previous hour.

Therefore, for every hour, the code calculates initial temperature of stored ice and energy losses. At this point, before passing to the successive hour, final ice temperature is determinate through the following equation [55].

$$T_f^h = \frac{(E^h + m_{stored}^h \times c_p \times T_i^h)}{m_{stored}^h \times c_p} \; [°C] \qquad \text{Equation 4-17}$$

Figure 4-21 is a schematic description of what has been explained and it should help to understand how ice temperatures are calculated in the different cases.

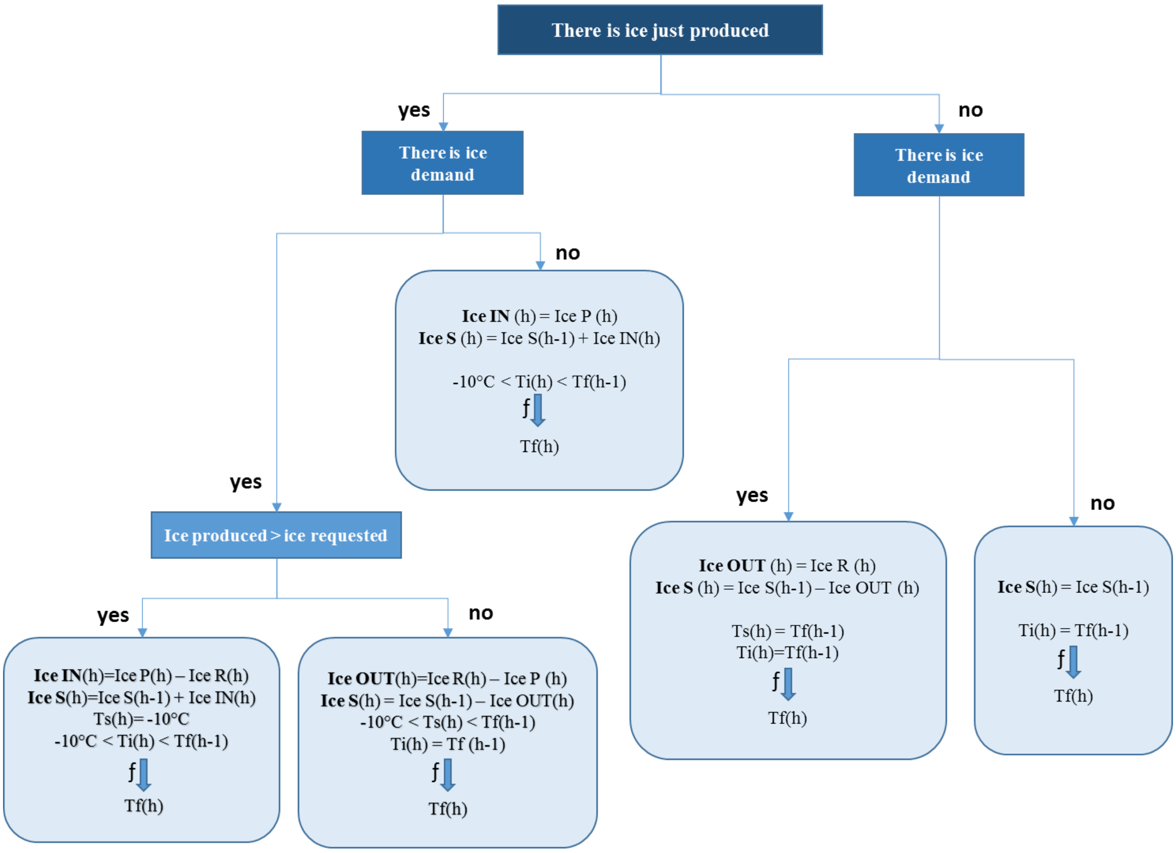


Figure 4-21 Schematic of ice temperature calculation

Configuration 2F

This configuration does not present the function just descripted above, as the system is thought in order to maintain the ice stored at a temperature of -10°C through a freezer. This, requiring an electrical supply, makes the daily request change: in this case, the input data “energy request” of the main function “PV” is the sum of the energy requested by icemakers and the freezer.

Technical data of the freezer are referred to a commercial model [72], of which we know:

- material of insulating: cyclopentane
- insulating thickness: 0,08 m
- conductive heat transfer coefficient of cyclopentane: 0,02 $W/m\ K$
- COP = 2;

As before, the total resistance is:

$$R_{tot} = \frac{t}{A_k \times k} + \frac{1}{A_h \times h} \quad \text{Equation 4-18}$$

Internal surface is calculated assuming a side of 1 m and *h* has the same value of the one used before (25 $W/m^2\ K$).
Having hourly air temperature and a constant temperature of ice stored of -10°C (T_{ice}), the power needed (P_c) to keep the ice at -10°C is calculated through the following relation [55]:

$$P_c = \frac{T_{air} - (T_{ice})}{R_{tot}} \quad \text{Equation 4-19}$$

Knowing the COP of the freezer and taking a safety factor (*sf*) of 1,2, inlet electrical power will be calculated as [6]:

$$P_{el\_f} = sf \cdot \frac{P_c}{COP} \quad \text{Equation 4-20}$$

The electrical power supplying the freezer, plus the icemakers energy request, generates the new "energy demand" input of the basic function.

The presented Matlab code, at this point, allows starting the simulation of all the configurations considered. Using few inputs it is possible to obtain different results for every operation mode. These results show the advantages and drawbacks of every system simulated, making a critical comparison between them possible.
In the next paragraph, obtained results are shown and the criteria applied for the selection of the most appropriate solution is described.

4.3 Results

Before analyzing the numeric results of the simulations done, we report some outcomes of the code that will permit to understand in the detail how the single components of the system operate. Depending on the requirements, annual, monthly or daily variations of different parameters will be shown. In order to clarify the system operation, a critic analysis of results is presented.

4.3.1 Simulation results and discussion

A net difference of the trend of energy stored between configuration 1 and 2 is expected, as in the first case the battery has to supply an important amount of the energy, while in configuration 2 batteries are used just as a backup.

The underlying graphics illustrate the energy trend stored in the batteries, for every operation mode, in the worst month (all the cases refer to the same number of satisfied days).

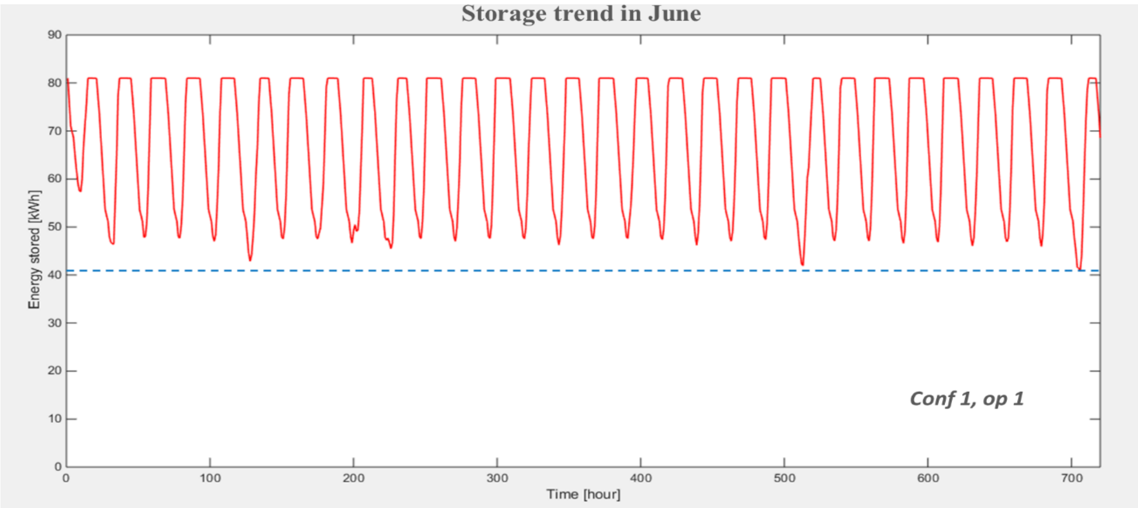


Figure 4-22 Storage trend in June (Configuration 1, operation mode 1)

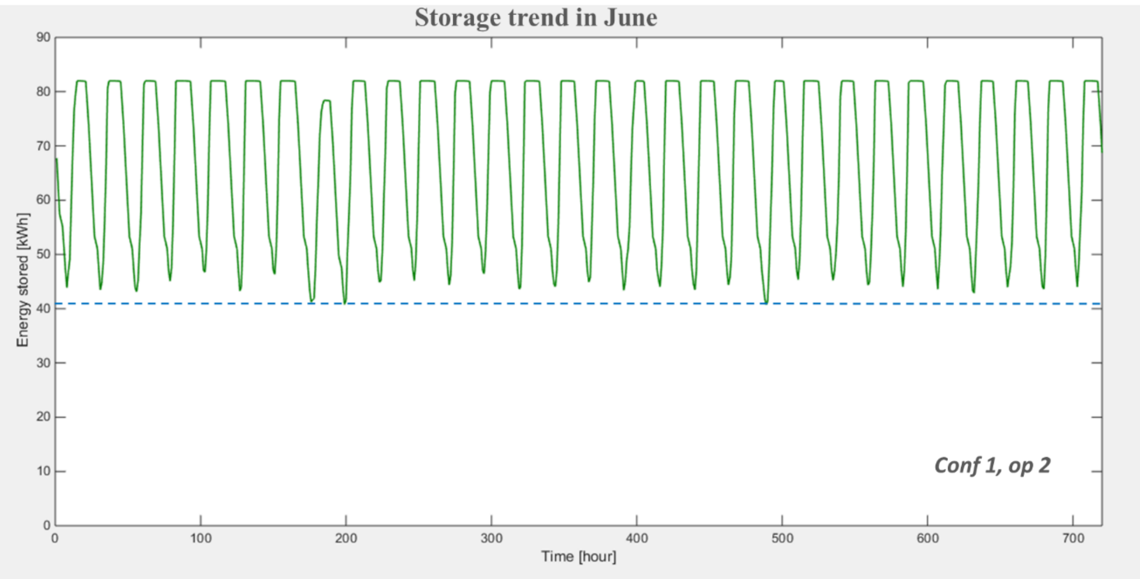


Figure 4-23 Storage trend in June (Configuration 1, operation mode 2)

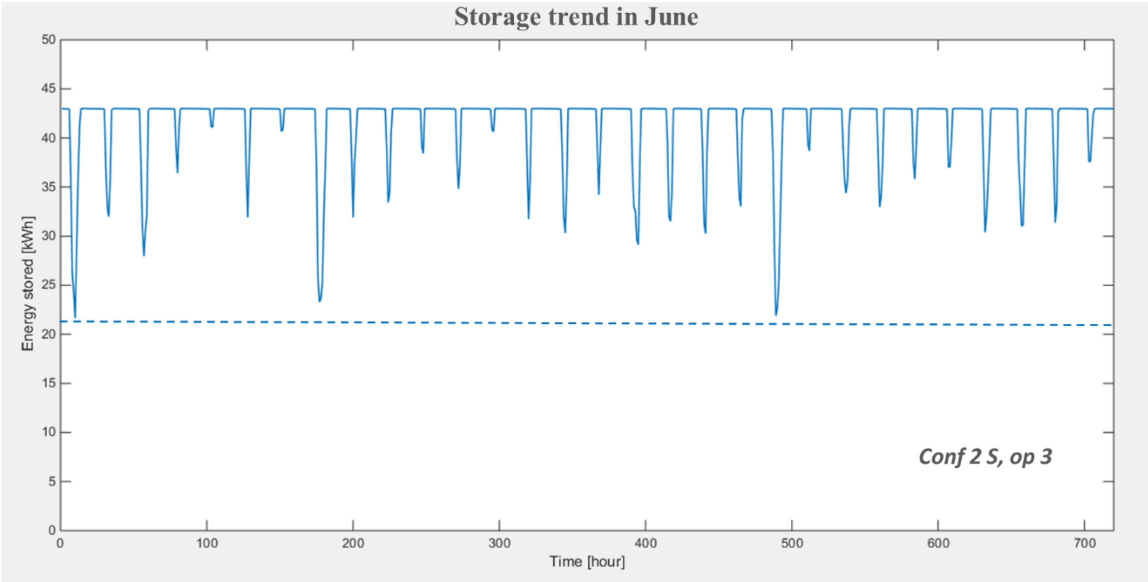


Figure 4-24 Storage trend in June (Configuration 1, operation mode 3)

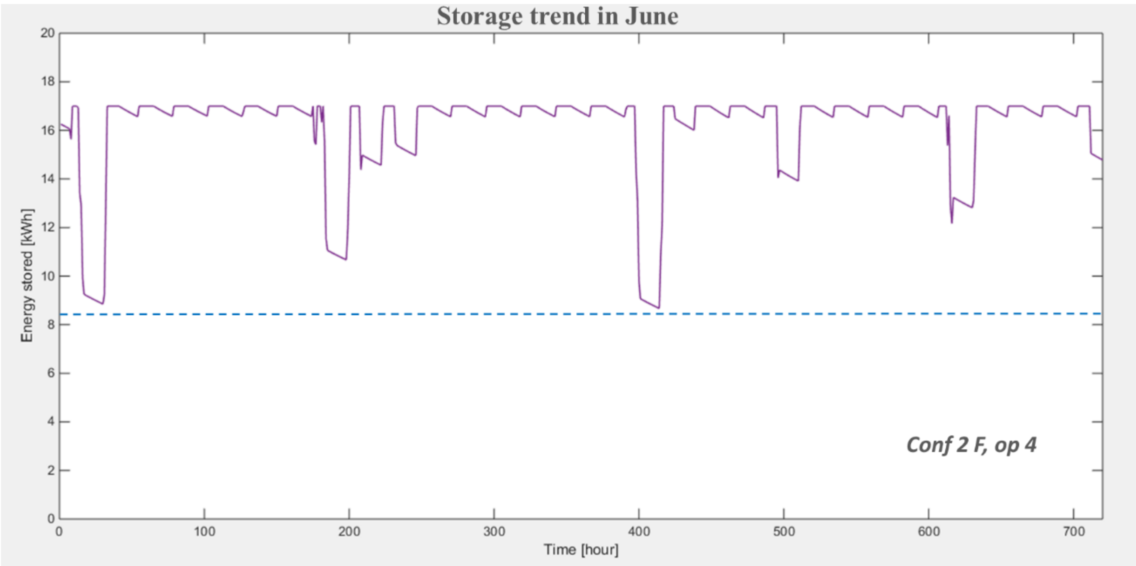


Figure 4-25 Storage trend in June (Configuration 1, operation mode 4)

For each operation, the dotted line delimits the minimum possible level of charge of the battery, that is always a 50% of the total capacity.

There is a clear difference distinguishing batteries in configuration 1 and 2: in the first case, the system uses almost the totality of the available stored energy every day. The battery bank is sized to be able to supply the entire nocturnal request, leaving a backup for cloudy hours. Thus, batteries in configuration 1 are almost completely charged and discharged every day, arriving to the minimum state of charge in cloudy periods.

On the contrary, in the configuration 2 the system uses just a low percentage of the total capacity of the batteries, since they only function as a backup. The installation is designed to satisfy a given number of days, so the battery must be sized to guarantee the necessary energy in case of cloudy days (that in the graphics coincide with the peaks).
Also between operation modes 3 and 4 we notice some differences: in the last case, the battery seems to be useful just when irradiance is absent, giving a very low contribution for some hours. On the other hand, in operation mode 3, even if the storage is not fully used, more energy from the batteries is necessary. This is because of the difference of energy demand distribution during the day, as figure 4-26 and 4-27 show.

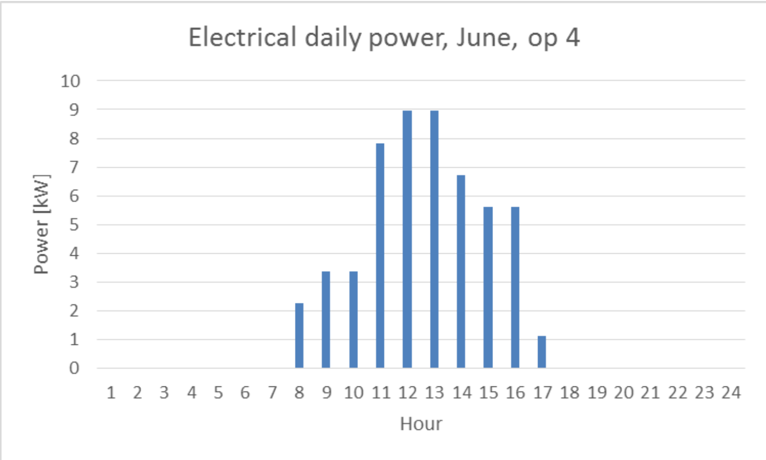


Figure 4-26 Electrical daily power in June. Operation mode 4

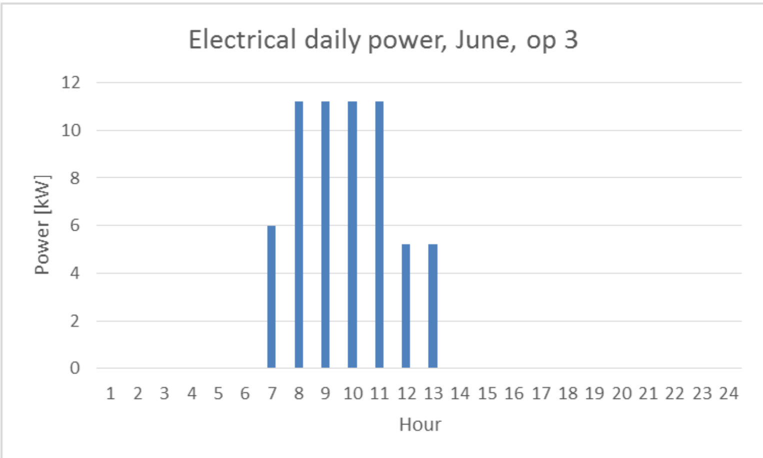


Figure 4-27 Electrical daily power in June. Operation mode 3

Operation mode 4 adheres more closely to solar radiation trend, as it presents a low demand during the first hours of the morning and in the late afternoon. This type of distribution permits an improved use of photovoltaic modules: if clouds are absent, PV panels can supply the icemakers without the aid of the battery, even during hours of low radiation.

Instead, operation mode 3 has a uniform and concentrated demand: at 7 a.m. 6 kW is necessary, while from 8 a.m. the system has to provide about 11 kW. The elevated request of the morning is the cause of the greater utilization of the battery in respect to the previous case.
To better understand the behavior of the storage (for operation mode 3), the graph below (Figure 4-28) represents the hourly energy stored in six days of June

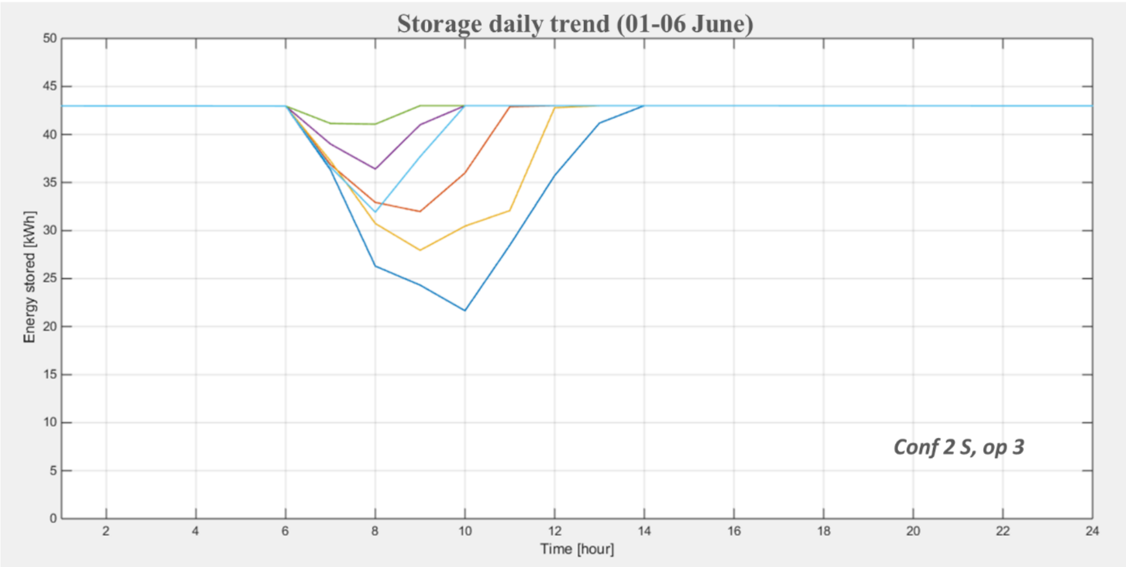


Figure 4-28 Storage daily trend, June (Configuration 2S, operation mode 3)

Independent of weather conditions, batteries support is always necessary during the first hours of operation. Then, if the day presents good solar radiation, energy to icemakers may be supplied by photovoltaic modules alone, since they finish operating in the early afternoon when radiation reaches its maximum value.
Average depths of discharge of every case are reported in table 4.15:

Table 4-15 Average depths of discharge of different configurations

Configuration	***Battery capacity [kWh]***	***Avarage min storage [kWh]***	***Avarage depth of discharge [%]***
1, operation 1	81	48	40,7
1, operation 2	82	47	42,7
2S, operation 3	43	37,9	11,9
2F, operation 4	17	15,3	10,0

Different depths of discharge may bring about some alterations of life cycle of the batteries: configuration 2 uses about 10% of the total capacity of the storage, when this could be discharged up to a 50%. This detail reveals potential problematic: a life cycle of 5

years will be used for economic evaluations for each configuration and, at a final stage, we will review if this approximation is acceptable.
Additional interpretation of numeric results: battery bank in configuration 2 may seem over-sized, because only a low percentage of the capacity is used. Given a fixed number of satisfied days, reducing battery capacity would mean markedly increasing photovoltaic module surface to also match the morning request. As we will see later, this could be a possible solution but it would be much more expensive.
System in operation mode 4 can afford to use a very low amount of stored energy, because during sunny days the high photovoltaic installed power (illustrated in figure 4-29) can supply the load unaided.

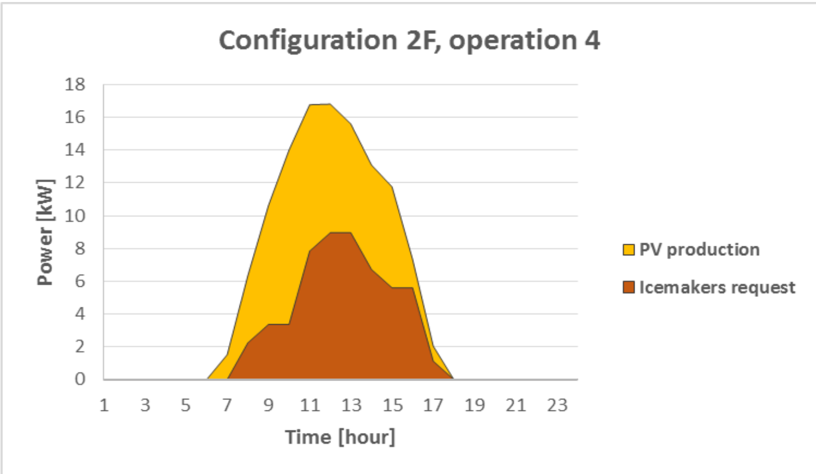


Figure 4-29 Photovoltaic production and icemakers request (Configuration 2F, operation mode 4)

Photovoltaic production displayed in the graph above refers to a day in June, the least favorable month. Even in this situation, the amount of extra energy produced by PV modules is quite elevated and can even double the request. This surplus is utilized to charge the batteries, but, in any case, a large part of it remains unused. The oversizing of the photovoltaic system is essential to facilitate use of the low radiation in the morning and late afternoon. Indeed, in the figure we can see how the request is quite close to the PV production curve at the extremes.

A third element of the system merits particular attention: the icemaker.
From the code outcome, that will be analyzed at a later stage, we know exactly how many and which days are satisfied. Nevertheless, these results only show the total volume of energy intake into the icemakers, without specifying its source. By knowing the photovoltaic production and the state of charge of the battery, the contributions of the two different sources are defined, as illustrated in figures 4-30 and 4-31 for configuration 2F operation mode 4.

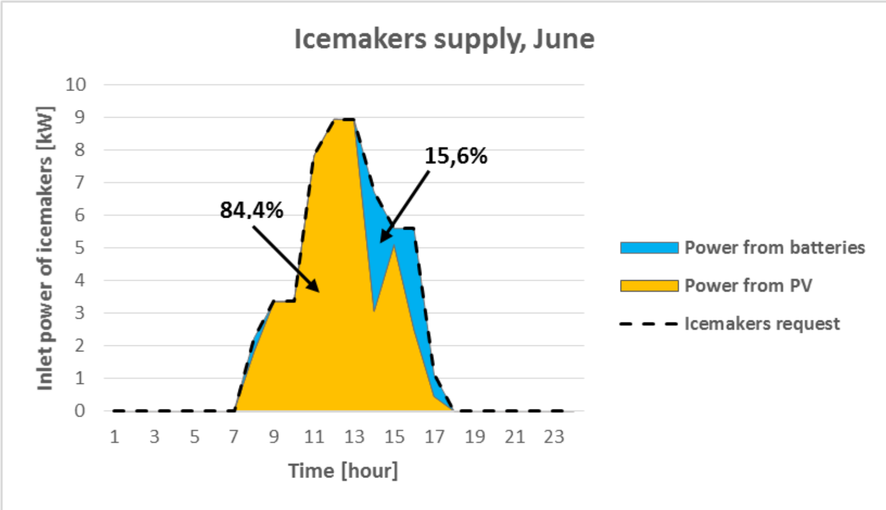


Figure 4-30 Contributes of PV and battery array for icemakers supply. Day 01/06 (Configuration 2F, operation mode 4)

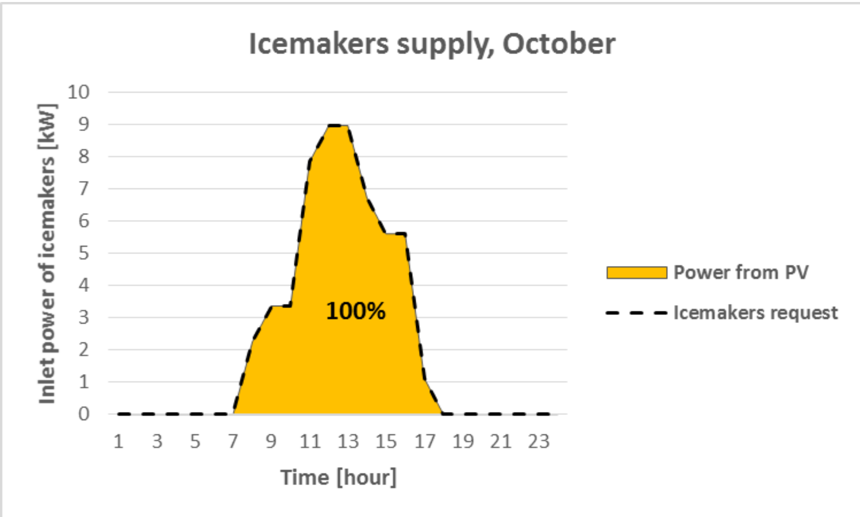


Figure 4-31 Contributes of PV and battery array for icemakers supply. Day 17/10. (Configuration 2F, operation mode 4)

The graphs show that, in this operation mode, the batteries have a low contribute in supplying the icemakers, because of their backup function. In configuration 1 the contribution of the two sources are quite distinct: as the icemakers operate principally during the night, batteries are the chief contributors. While during daytime, photovoltaic modules should self-sufficiently support the demand.

In the following graphs (Figures 4-32 and 4-33) it is clear how energy demand is supplied (the same days as previously are considered).

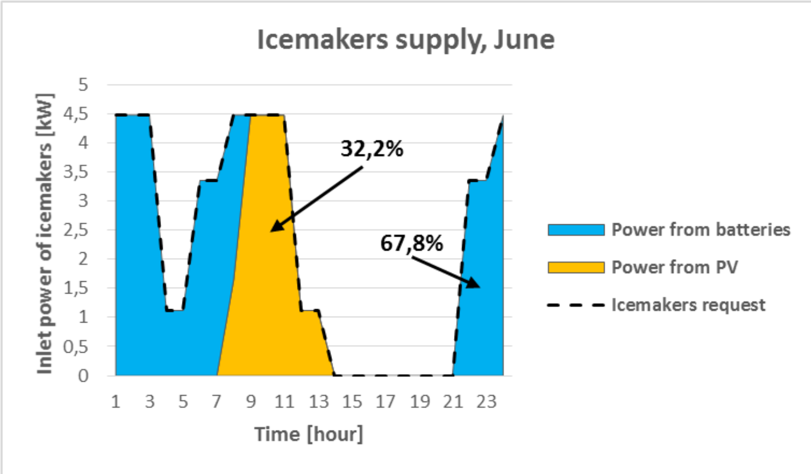


Figure 4-32 Contribute of PV and battery array for icemakers supply. Day 01/06 (Configuration 1, operation mode 1)

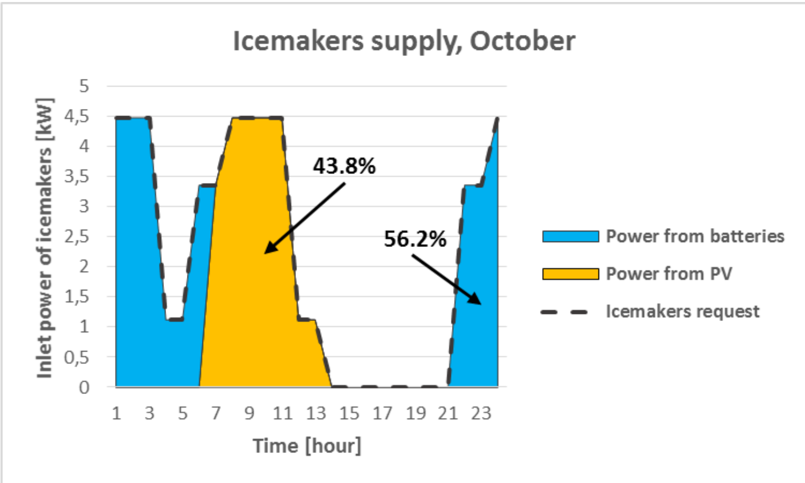


Figure 4-33 Contribute of PV and battery array for icemakers supply. Day 17/10. (Configuration 1, operation mode 1)

In June, the photovoltaic system is able to supply energy to the icemakers unaided from 9a.m., while in October, solar radiation is similarly adequate from 7a.m. Therefore, in both cases, energy stored in the batteries is not used after these first hours.

We now focus our attention on the particular case of insulated storage. Before determining the size of the system, it is necessary to define the thickness of the insulated container in configuration 2S, in order to fix a value that will be used in the next simulations.
Ice temperature does not depend on the size of the system and the combination of photovoltaic and battery array: the number of satisfied days is the only parameter which influences ice melting, due to air temperature variations from day to day.
Here we analyze two operation modes that match the entire annual request, with a random combination of photovoltaic power and battery capacity.

First, the code simulated ice melting with different values of insulating thickness: the following graph (Figure 4-34) reports the maximum ice temperature reached over one year in the case of different insulations.

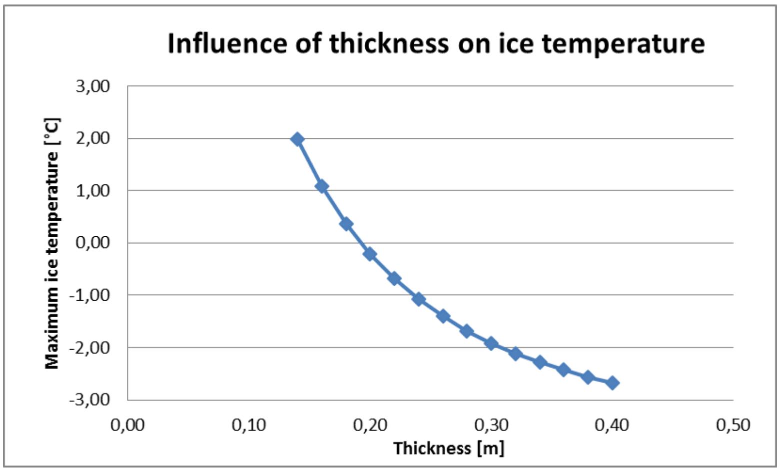


Figure 4-34 Influence of thickness on ice temperature

It can be noticed that ice temperature never goes up 0°C with a thickness of at least 20cm. 0°C is the maximum admissible temperature that ice can reach: over 0°C ice begins melting and the insulating can be considered inappropriate, given the conservation problems illustrated before.

For a more accurate analysis, hourly ice temperatures deriving from an insulating thickness of 20 cm have been extrapolated in the warmer month. Figures 4-35 and 4-36 refer to October, that presents both seasons, and display average temperatures of ice when this is sold to fishermen and merchants, in the case of operation modes 3 and 4.

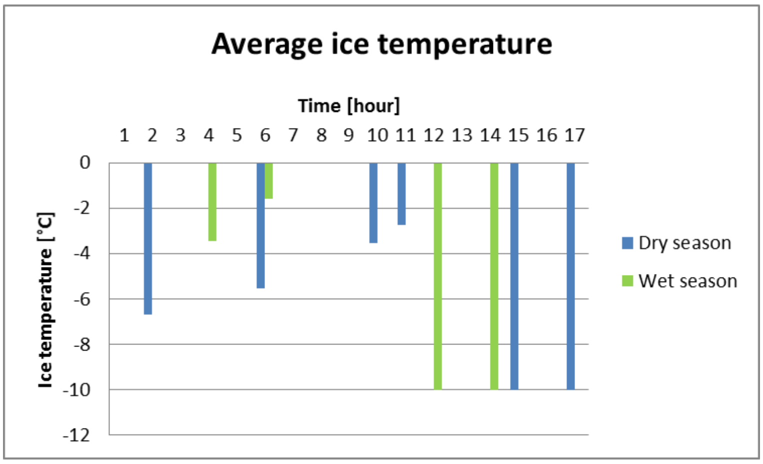


Figure 4-35 Average ice temperature in October with a thickness of 20cm (Configuration 2S, operation mode 3)

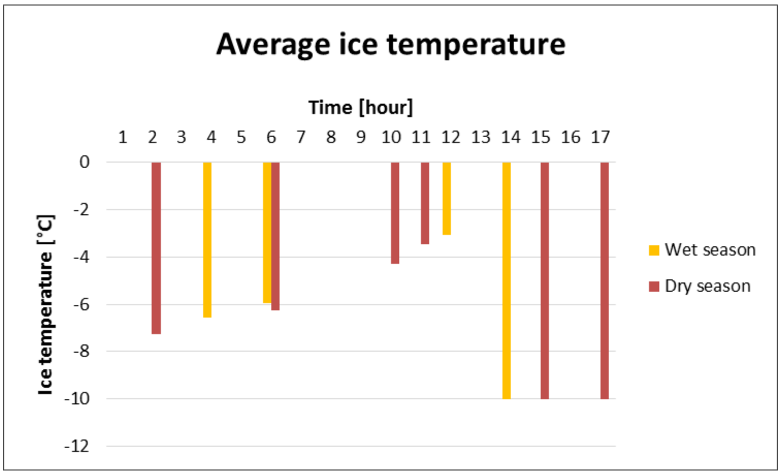


Figure 4-36 Average ice temperature in October with a thickness of 20cm (Configuration 2S, operation 4)

Differences between the operation modes are due to a diverse ice production, in terms of quantity of ice and icemakers timetable.
The ice stored in a container with a thickness of 20 cm, even in the most critical month, has almost always a temperature above -2°C. This is the reason that led to the selection of this value for each of the remaining simulations.

4.3.2 Decision-making process to select the appropriate configuration

All the simulations have been done starting from a minimum percentage of satisfied days of 70%, arriving to a 100% with a maximum step of 5%. An inferior limit of 70% seemed reasonable, given the fact that the model simulates a system that satisfies just a 25% of the total original load.
For every percentage of satisfied days, the code finds the best combination of photovoltaic installed power and battery capacity: each cycle takes a PV power and returns the minimum capacity storage needed for reaching the imposed number of days.
This has been done for every configuration and its relative operation mode; each one of these situations implies 7 simulations (from 70% to 100%).
In order to select the appropriate configuration we defined some selection criteria, of which one is based on the Analytic Hierarchy Process (AHP).

<u>Basic selection criteria: unit cost of ice</u>
Having finished all the simulations, it is necessary to extract just one combination of photovoltaic-batteries among all those referring to an equivalent satisfied percentage. The choice was made selecting for each case the combination with the lowest NPC.

In this way, we can gather together all the combinations with the minor NPC, each one of a specific percentage. Here there is an example of collected results of configuration 2F, operation mode 4 (Table 4-16).

Table 4-16 Combinations matching different satisfied percentage (configuration 2F, operation mode 4)

% days ok	*PV power [kW]*	*Capacity [kWh]*	*Capital cost [€]*	*Ice production [kg/yr]*	*Energy surplus [kWh/yr]*	*% unsatisfied annual kWh*	*NPC*	*PV production [kWh/yr]*	*Unit cost [€/kg]*
100	32	42	62008	166980	73,6	0,00	186074	48294	0,0427
95	31,5	17	55323	158700	72,1	0,63	155386	47495	0,0379
90	23	20	48669	150420	39,8	1,79	147729	34724	0,0379
87	26	11	49032	145200	52,1	2,19	140894	39513	0,0376
85	21,5	15	46113	141600	35,2	2,87	139738	32728	0,0382
83	23,5	9	46355	139860	43,3	3,51	135181	35522	0,0375
80	19,5	10	43121	133800	29,1	4,74	131083	29535	0,0380
77	20	7	42806	129660	31,2	5,99	128142	30333	0,0384
75	21	6	43427	127800	35	6,11	127065	31930	0,0392
70	18,5	6	41250	117300	25,9	7,82	124954	27938	0,0414

Besides to NPC, there are other information about every combination that will be useful in the next decisional steps. For the moment, we use just unit cost for the comparison.

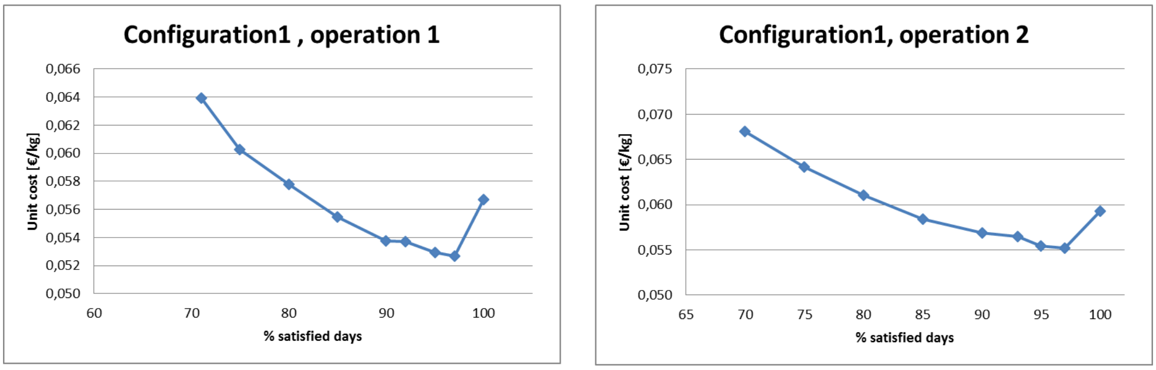


Figure 4-37 Unit cost trend with a variable percentage of satisfied days (Configuration 1, operation modes 1 and 2)

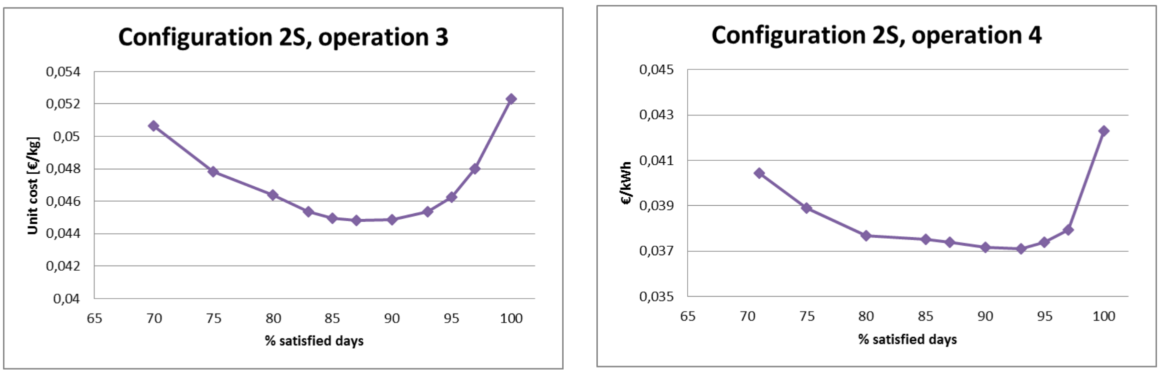


Figure 4-38 Unit cost trend with a variable percentage of satisfied days (Configuration 2S, operation modes 3 and 4)

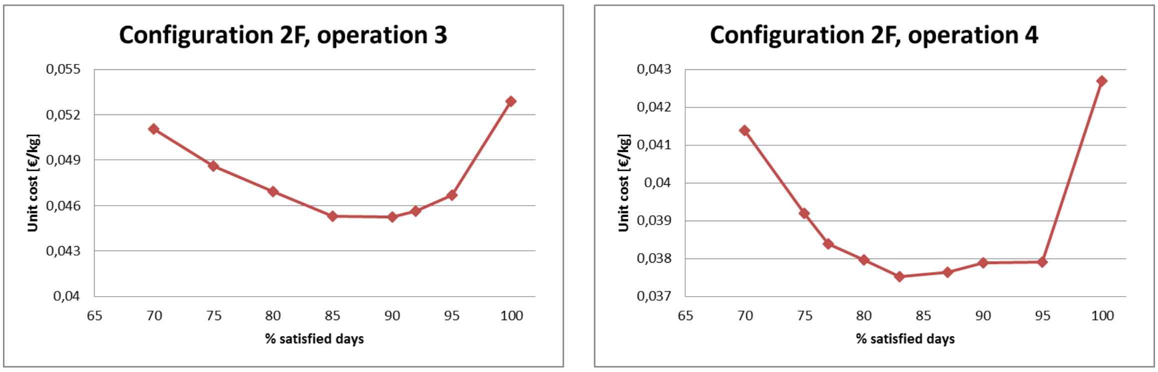


Figure 4-39 Unit cost trend with a variable percentage of satisfied days (Configuration 2F, operation modes 3 and 4)

The unit cost represents the price of 1 kg of ice taking into consideration the present net cost, in order to define the real cost of the system, looking at the entire lifetime and not just at the investment cost. For this reason, it is one of the best parameters to utilize for critic analysis.

From the graphs, it can be noted that, for all the cases, unit cost value has its minimum point in the same interval and in particular the minimum corresponds to a 90% of satisfied days in the case of configuration 2 and to a 97% in configuration 1.

This observation leads to taking all the solutions that satisfy the same percentage of days: the one that better represents a medium value is 95%. This means comparing solutions (now 6) that present many different features but have at least one communal value.

The combinations matching the 95% of the request and their relative unit costs are illustrated in figure 4-40.

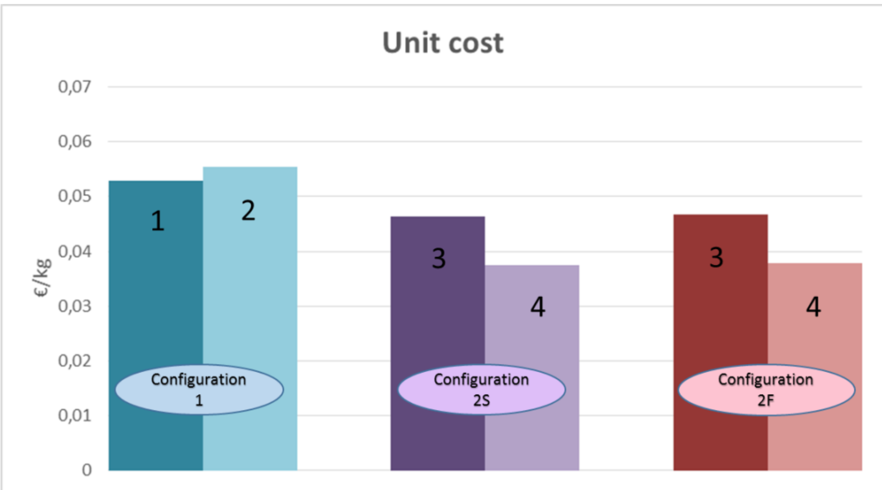


Figure 4-40 Unit costs of the combinations matching 95% of the request

Among the proposed combinations, the ones having the lower unit cost are:

Table 4-17 Main features of the configurations having the lowest unit cost

	PV power [kWp]	Battery capacity [kWh]	Capital cost [€]	Ice production [kg/yr]	Energy surplus [kWh/yr]	% unsatisfied annual energy	NPC	PV production [kWh/yr]	Unit cost [€/kg]
Conf 1, op 1	28,5	81	56518	151192	58,1	0,71	210950	43105	0,053
Conf 2S, op 4	28,5	19	52610	158640	61,7	0,71	153214	43105	0,037
Conf 2F, op 4	31,5	17	55323	158700	72,1	0,63	155386	47495	0,038

All three solutions have equivalent satisfied days, but this does not mean that they have to present the same ice production and unsatisfied annual kWh: ice production depends on the way in which satisfied days are distributed between the wet and dry season, because the ice request varies with the period of the year. Instead, the calculation of unsatisfied energy is the actual energy that the system is unable to supply to the icemakers, taking into account that a day considered "not satisfied" has some hours in which the machines are operating.

Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) has been used to identify an optimum technical solution for this particular case.

The Analytic Hierarchy Process consists on the identification of a goal and the following hierarchical definition of the criteria for selecting the best solution, among a set of alternatives, to achieve the goal. The importance of each criterion with respect to the others is evaluated through "weights" and each alternative on the base of the criteria is evaluated through "judgements". The AHP has several methods to define weights and judgements, among which a direct evaluation (giving value from 1 to 10) or an indirect evaluation through a comparison.

Here AHP has been implemented by means of the SuperDecisions software[74], that uses a prioritization process based on deriving priorities and relative weights of selection criteria by making judgments on pairs of elements.

The decision elements are arranged in a hierarchic decision structure from the goal to the criteria to the alternative to select, as can be seen in figure 4-41.

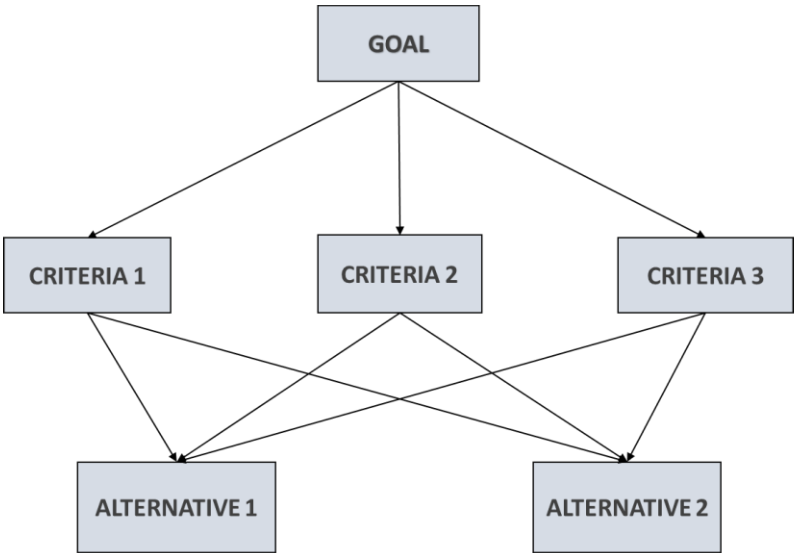


Figure 4-41 Hierarchic decision structure of SuperDecisions software

For the choice of the best solution, we considered two different GOALs: economic and energetic goal. The economic goal is having a relative affordable system, this means meanly to have low unit and capital cost. The energetic one corresponds to having a system with a low energy surplus and a good behavior in case of worse radiation.
In order to choose the solution able to reach the goal, different criteria are defined:

- **Capital cost**: alongside NPC, which is aimed at commercial evaluation over the entire lifetime, an investment cost is a top parameter of choice, since the initial budget may be limited.
- **Energy surplus**: it represents the annual average energy produced in one day by photovoltaic that remains when icemakers are already supplied and the battery is completely charged.
- **Unit cost**: as illustrated before, it indicates the cost of making 1 kg of ice, taking into account the costs that consider the entire life cycle of the system.
- **Ice temperature**: temperature at which the ice is sold. Because in the case of configuration 2S the ice temperature varies depending on the selling hour, we use a temperature range, where the maximum value is the maximum temperature reached in the year.
- **System robustness**: this parameter helps to know how the system could work in different cases of solar irradiation. More simulations were carried out (two for each configuration) varying at a 15% (in positive and negative) the hourly irradiation in order to find the new percentage of satisfied days and to compare it with the old value. For the definition of this criteria value, results of negative irradiance variations will be principally considered, as we are interested in observing the operation of the system with worse weather conditions.

- **Impact**: it practically represents the total space necessary to install the system. Square meters of photovoltaic panels, the number of batteries and icemakers and the presence of a storage and/or a freezer were considered.
- **Management**: the three different systems need different attention and maintenance: the more PV panels, the more work to clear them; the more icemakers, the more time required to fill and manage them. Furthermore, a system with ice storage will necessitate someone to supervise it.
- **Reliability**: looking at the number of elements composing the system, it shows how reliable the total system is. These elements are inverters and icemakers, the ones with a lower individual reliability. For instance, if the system consists of only two icemakers, when one is damaged half the load is not matched, while, if more icemakers are present, a lower fraction of the load remains unsatisfied. This is the logic behind authentic needs and expectations, even if the total reliability decreases with a high number of components.
- **Environmental impact**: this parameter only takes into account the number of batteries. They are considered extremely harmful to the environment because in many contexts, like the one in Mozambique, often occurs that batteries are simply thrown away, without being appropriately recycled,

The best solution will be selected between three alternatives obtained from the three solution with the lowest unit cost. They are configuration 1 (operation1), configuration 2S (operation4) and configuration 2F (operation4).
The three alternatives and their main features are summarized in table 4-18.

Table 4-18 Helpful data for alternatives' judgements definition

	Capital cost [€]	Energy surplus [kWh/yr]	Unit cost [€/kg]	Tice [°C]	Ice storage	Photovoltaic modules [m^2]	Battery capacity [kWh]	Number of icemakers	Satisfied days [%]	
									Irradiance variation of -15%	Irradiance variation of +15%
Conf 1, op 1	56518	58,1	0,053	-10	no	180	81	4	89,9	97,3
Conf 2S, op 4	52610	61,7	0,037	from -10 to -3	yes	180	19	8	91,2	96,4
Conf 2F, op 4	55323	72,1	0,038	-10	yes	199	17	8	91,5	97,0

An interesting observation comes from the results concerning the satisfied days: configuration 2 reacts slightly better to the deteriorating of the radiation, while configuration 1 has a larger difference between the new percentage of satisfied days and the previous one. In the configuration 1, icemakers operate by night and batteries are sized to be fully charged in the late afternoon and fully discharged at the end of every night. Thus, with the same photovoltaic surface, if radiation decreases, modules cannot bring batteries to a full charge state. On the other hand, the capacity of backup batteries

in configuration 2 is used less, so, even if batteries are not fully charged, they can supply the entire load.
Before giving numerical values to weights, it is necessary to explain how they have been defined: we have chosen the specific value of each weight taking into account the professional opinion of the CeLIM contact and the lesson learnt by the review described above.
Needs expressed by CeLIM expert concern overall investment and quality of ice sold, while similar prototypes described let emerge the importance of other parameters, like maintenance. In Chorreras, for example, an irregular maintenance (irregular cleaning of icemaker water pipes, that became calcified because of the large content of carbonate in the water) caused a net drop off of ice production. In addition, one must consider the cooperative nature of the hypothetical realization of the project, that urges one to reflect simultaneously on three main aspects: economic, environmental and social sustainability. Thus, impact, management and environmental impact are quite relevant for the choice of the best solution.
However, our opinion has had a relevant impact on the choice, thus it is impossible to avoid a subjective nature of the selection.
For each goal we have evaluated the criteria weights through values from 1 to 10 (higher the number, higher the importance of the criterion), reported in table 4-19.

Table 4-19 Criteria weights of each goal

	Capital cost	Energy surplus	Unit cost	Ice temperature	System robustness	Impact	Management	Reliability	Environmental impact
ENERGETIC GOAL	2	8	1	7	10	4	4	5	5
ECONOMIC GOAL	8	2	10	7	1	4	4	5	5

Both goals present the same importance referred to impact, management, reliability and environmental impact, while differing in the others. Economic goal aims to give a high importance to unit cost and capital cost; on the other hand, the alternative way considers system solidity and energy surplus more decisive.
Ice temperature has a significant relevance for both: as illustrated before, the problem of ice melting during transportation cannot be solved. Providing ice at low temperature, fresh fishes can last longer and merchants may arrive to the market without melted ice and spoiled fish.
Every alternative is evaluated through judgement. Values from 1 to 10 are used: the higher the numbers, the better the configuration with respect to the criterion it is referred to.
The values used are reported in table 4-20.

Table 4-20 Alternatives' judgments

	Capital cost	Energy surplus	Unit cost	Ice temperature	System robustness	Impact	Management	Reliability	Environmental impact
Conf 1, op 1	6	8	6	9	5	9	9	5	3
Conf 2S, op 4	8	7	9	5	8	6	5	8	8
Conf 2F, op 4	7	5	9	9	8	5	5	7	8

It is worth to notice that for the alternative judgement based on the impact criterion, the number of icemakers and the presence of a storage have more influence than other elements. Thus the batteries, despite their several problems, have a low influence on the weight of this criterion.

Using the software it is possible to calculate the most appropriate solution by using weights and judgements. Here below the main screen of SuperDecisions (Figure 4-42).

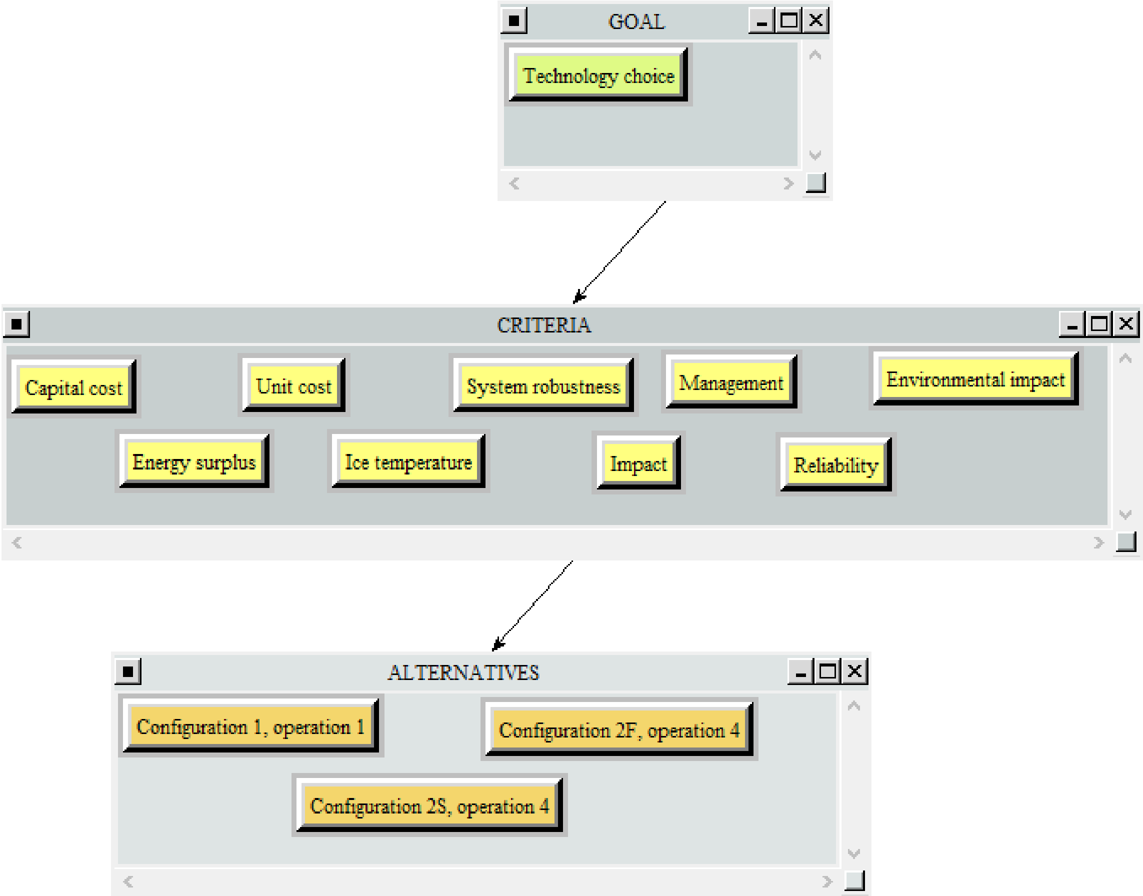


Figure 4-42 Main screen of SuperDecisions

Depending on the goal, different results have been obtained:

- **Energetic goal**: system with insulated storage emerged as the best solution. Here below the normalized results obtained by the software (Figure 4-43).

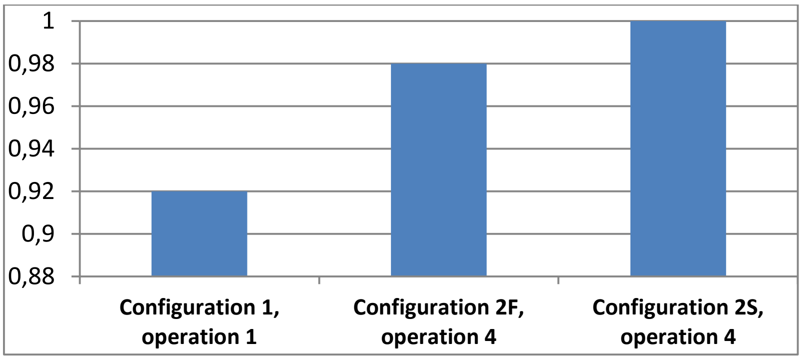


Figure 4-43 SuperDecisions' results, energetic goal

Table 4-21 helps to clarify the reason: configuration 2S produces a smaller amount of useless daily energy than configuration 2F and this leads to discarding the option with the freezer. As concerns system robustness, configuration 2 results much more robust than configuration 1. These differences characterizing the most influencing parameters found in the choice of configuration **2S, operation 4**, even if the configuration 2F has the advantage of providing colder ice.

Table 4-21 Focus on energy surplus and system robustness criteria

	Energy surplus	System robustness
Conf 1, op 1	8	5
Conf 2S, op 4	**7**	**8**
Conf 2F, op 4	5	8
ENERGETIC GOAL	8	10

- **Economic goal**: configuration with freezer seems to be the most appropriate system. (Figure 4-44)

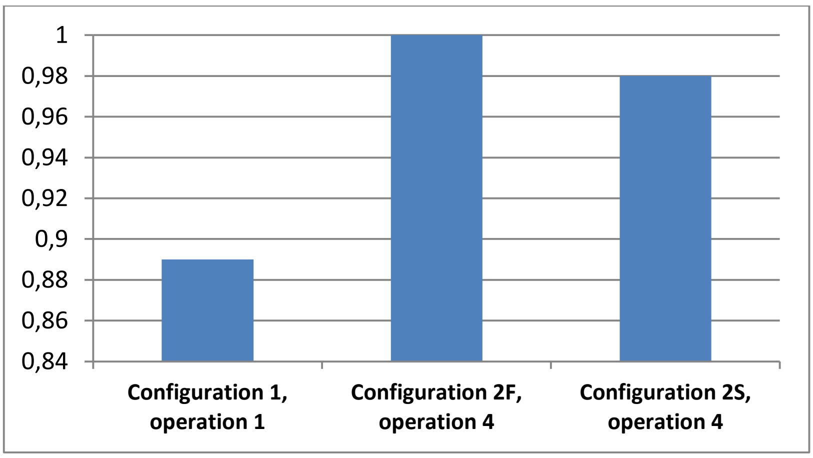


Figure 4-44 SuperDecisions' results, economic goal

Values reported in table 4-22 show that a system with insulated storage has the same unit cost and a lower capital cost than configuration 2F. Considering just these two characteristics, that are the ones with the highest weights, the previous winning solution seems to be the best again. The principal factor that makes configuration 2F better than configuration 2S is ice temperature: economical differences are so minimal that the decision is based principally on ice temperature, so the system that keeps the ice at -10°C emerges as the most convenient.

Table 4-22 Focus on capital cost, unit cost and ice temperature criteria

	Capital cost	Unit cost	Ice temperature
Conf 1, op 1	6	6	9
Conf 2S, op 4	8	9	5
Conf 2F, op 4	**7**	**9**	**9**
ECONOMIC GOAL	8	10	7

Summarizing, there are two possible solutions, based on different criteria choice, illustrated in table 4-23:

Table 4-23 Technical and economic features of the selected configurations

	PV power [kWp]	Total PV surface [m²]	Battery capacity [kWh]	Number of IM	Number of inverters	Storage	Max ice production [kg/day]	Max energy request [kWh/day]	Energy surplus [kWh/day]	NPC [€]	Unit cost [€/kg]	Capital cost [€]
ENERGETIC GOAL	28,5	179,6	19	8	2	Insulated container	480	53,8	61,7	153214	0,037	52610
ECONOMIC GOAL	31,5	198,5	17	8	2	Freezer	480	53,8	72,1	155386	0,038	55323

4.3.3 Model validation

In order to validate the model and consequently the obtained results, we simulated the same system using the software Homer Energy. It is a computer model that simplifies the task of designing hybrid renewable microgrids, whether remote or attached to a larger grid. The software evaluates the economic and technical feasibility of a large number of technology options, taking into account variations in technology costs and energy resources availability.

Figure 4-45 reports the results obtained by the software Homer Energy for the configuration 2S operation mode 4.

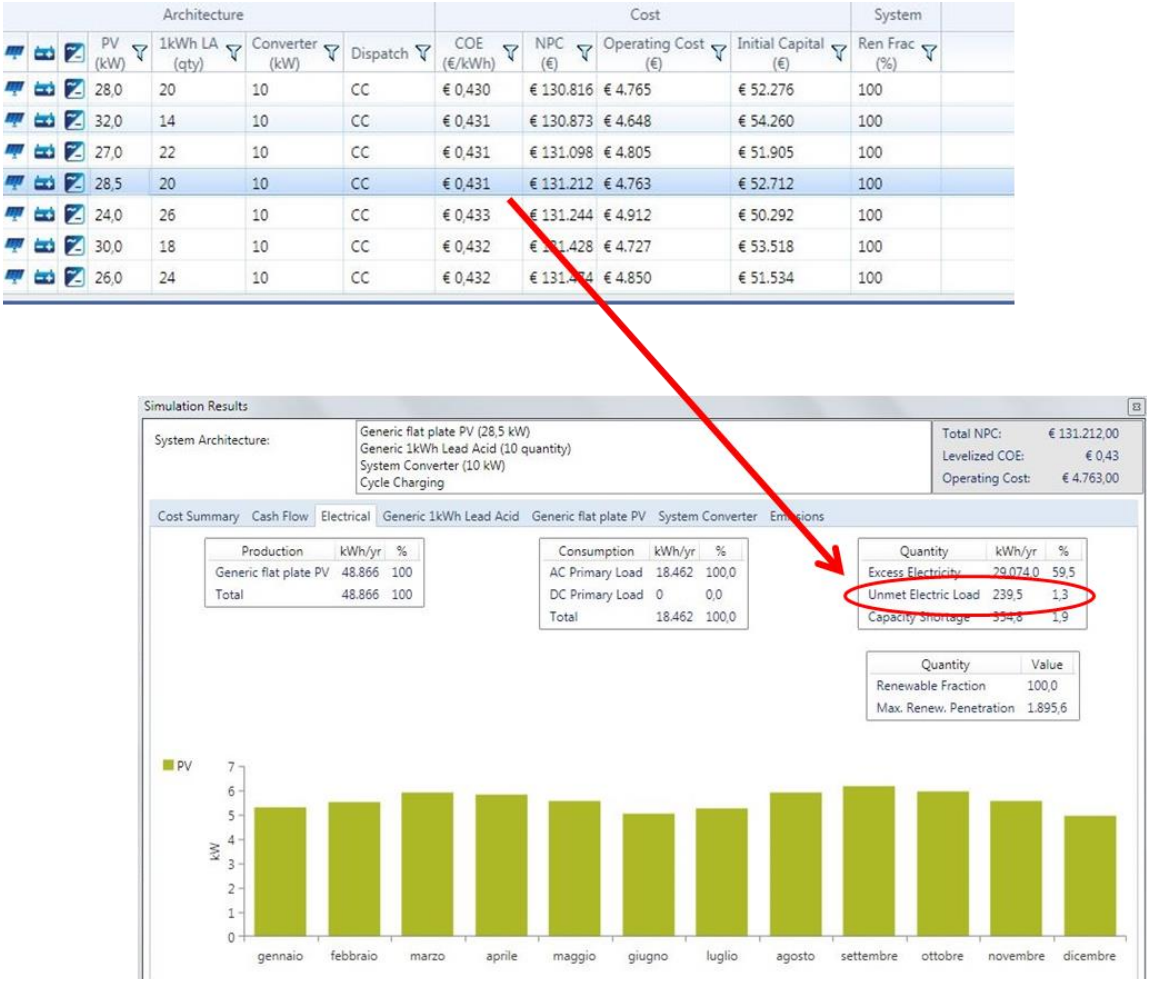


Figure 4-45 Homer's results

The highlighted configuration is the one that better reproduce the one of our model, differing just from the battery capacity. This difference is due to the different method utilized by the software to calculate the battery size: it considers some strings connected in parallel, while we considered directly the total battery capacity. Another difference that reflects on the results is the method used to calculate the matched load: the software, unlike our model, does not consider partial loads, but it attempts to ensure the entire primary load. Being based on a specific set percentage of a maximum annual unmet request the software computes all the possible configurations that satisfy this constraint. This difference brings to have a higher percentage of unmet electric load (Homer value: 1,3% vs our model value: 0,63%).

For this specific simulation the main limitation of the software is that it does not consider the costs of components representing the load (in this case the icemakers) for the system economic analysis. It was possible to consider the fixed capital and O&M costs of the icemakers, but not the replacement cost. This lack brings to a different NPC (Homer value: 131212 € vs our model value: 153214 €). In order to have a further validation, we calculated the NPC using the same components and method of the software obtaining a

very similar result (131047 €). The very low difference is attributed to a different accuracy of the discount rate.
Therefore, the model can be considered validated, since the software returns a configuration that is characterized by an annual energetic load matched (in terms of kWh) very similar to that resulting from our model, with the same combination of photovoltaic power and battery capacity.

4.3.4 Economic analysis

Thanks to the simulation results and the adopted selection criteria, two final configurations emerge as possible solutions. We do not want to arrive at defining a unique and definitive one, but we aim to analyze them in a more critical way, in order to show some aspects, principally commercial, that could lead to the choice of one of them.
The most important of these economic aspects are:
- Net Present Cost
- Net Present Value (NPV): it is the sum of the present values of incoming (or benefit) and outgoing (cost) flows over the lifetime of the system, in this case 25 years.

$$NPV = \sum_{i=0}^{25} \frac{R_i}{(1+r)^i}$$ Equation 4-21

i: year of cash flow;
R_i: net cash flow (cash inflow – cash outflow) at year i;
r: discount rate.

- Pay Back Time (PBT): it is the necessary period of time to recover the money spent in the investment.

NPV and PBT depend on the selling price of the ice. The choice of the price that fishermen and merchants will pay for the ice in fishing centers needs a clarification.
It is known, from the answers to questionnaires, that ice in the markets is sold at 0,10 €/kg, while fishermen would be willing to pay 0,06 €/kg for the ice produced in fishing centers. We evaluate the two selected configurations by an economic analysis that shows how different selling prices could change the scenario.
Table 4-25 shows in detail how the three economic values have been calculated (just the case of configuration 2S, operation mode 4, is reported). O&M and replacement costs of every component are reported in table 4-24 for a better comprehension of the following economic calculations.

Table 4-24 O&M costs and replacement costs (Configuration 2S, operation mode 4)

O&M costs [€/yr]					Replacement costs [€]					***Sale price [€/kg]***
PV [20€/kW]	Battery (7%)	IM (5%)	Inverter (10%)	Salary	PV	Battery	IM cost	Inverter	Charge Controller	
570	332,5	855,2	432,4	1200	19095	4750	17104	4324	1460	0,1

Table 4-25 Calculation process for NPC, NPV and PBT definition

Year	*Investment cost [€]*	*O&M costs [€]*	*Repl. costs [€]*	*Salary [€]*	*k*	*Actualized total costs [€]*	*Profits [€]*	*Actualized Profits [€]*	*Net profits [€]*	*Cumulative net profits [€]*
0	52610	0	0	0	1,000	52610	0	0	-52610	-52610
1	0	2190	0	1200	0,966	3275	15864	15328	12052	-40558
2	0	2190	0	1200	0,934	3165	15864	14809	11645	-28913
3	0	2190	0	1200	0,902	3058	15864	14308	11251	-17662
4	0	2190	0	1200	0,871	2954	15864	13825	10870	-6792
5	0	2190	4750	1200	0,842	6854	15864	13357	6503	-289
6	0	2190	0	1200	0,814	2758	15864	12905	10148	9859
7	0	2190	0	1200	0,786	2665	15864	12469	9804	19663
8	0	2190	17104	1200	0,759	15563	15864	12047	-3516	16147
9	0	2190	0	1200	0,734	2487	15864	11640	9152	25299
10	0	2190	9074	1200	0,709	8836	15864	11246	2410	27710
11	0	2190	0	1200	0,685	2322	15864	10866	8544	36254
12	0	2190	0	1200	0,662	2244	15864	10499	8255	44509
13	0	2190	0	1200	0,639	2168	15864	10144	7976	52485
14	0	2190	0	1200	0,618	2094	15864	9800	7706	60191
15	0	2190	4750	1200	0,597	4859	15864	9469	4610	64801
16	0	2190	17104	1200	0,577	11819	15864	9149	-2670	62131
17	0	2190	0	1200	0,557	1889	15864	8839	6951	69081
18	0	2190	0	1200	0,538	1825	15864	8541	6715	75797
19	0	2190	0	1200	0,520	1763	15864	8252	6488	82285
20	0	2190	29629	1200	0,503	16594	15864	7973	-8622	73664
21	0	2190	0	1200	0,486	1646	15864	7703	6057	79721
22	0	2190	0	1200	0,469	1590	15864	7443	5852	85573
23	0	2190	0	1200	0,453	1537	15864	7191	5654	91227
24	0	2190	17104	1200	0,438	8976	15864	6948	-2028	89199
25	0	2190	4750	1200	0,423	-12336	15864	6713	19049	108248
Salvage value	37294				***NPC***	153214		***NPV***		108248

The following graph (Figure 4-46), based on the values reported in the previous table, represents the trend of the cumulative net profits, resulting in a very low pay back time:

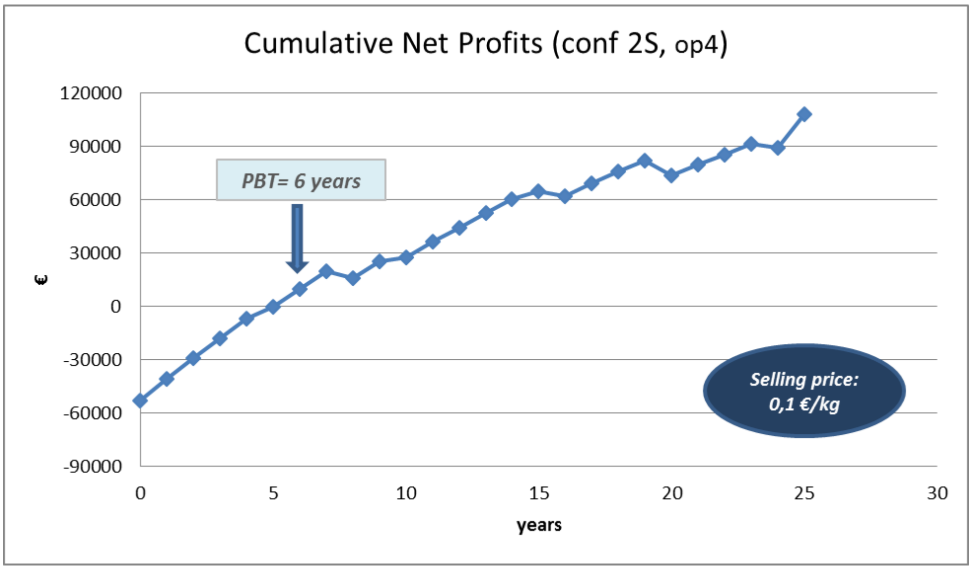


Figure 4-46 Cumulative net profits with a selling price of 0,1 €/kg (Configuration 2S, operation mode 4)

We calculated NPV and PBT on the basis of different sale prices for both the considered system configurations (2S and 2F). Results are reported in the graphs below:

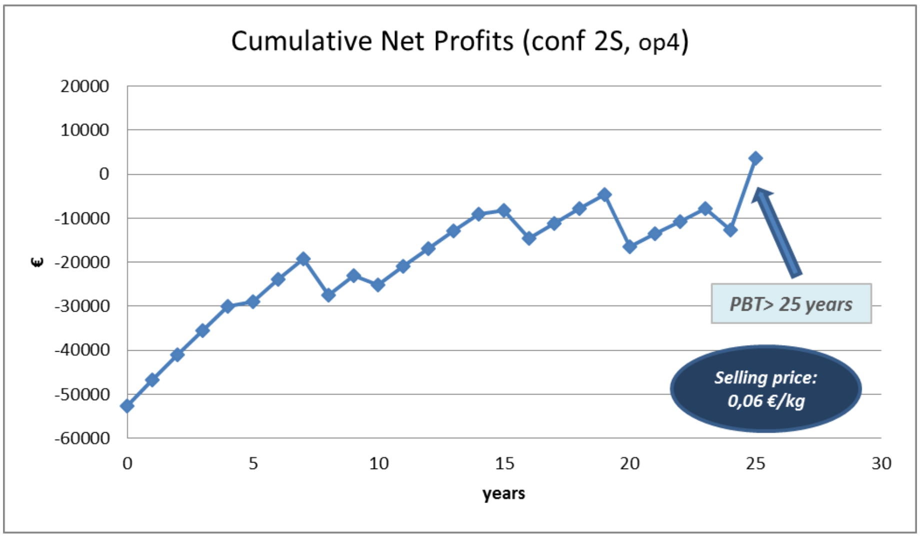


Figure 4-47 Cumulative net profits with a selling price of 0,06 €/kg (Configuration 2S, operation mode 4)

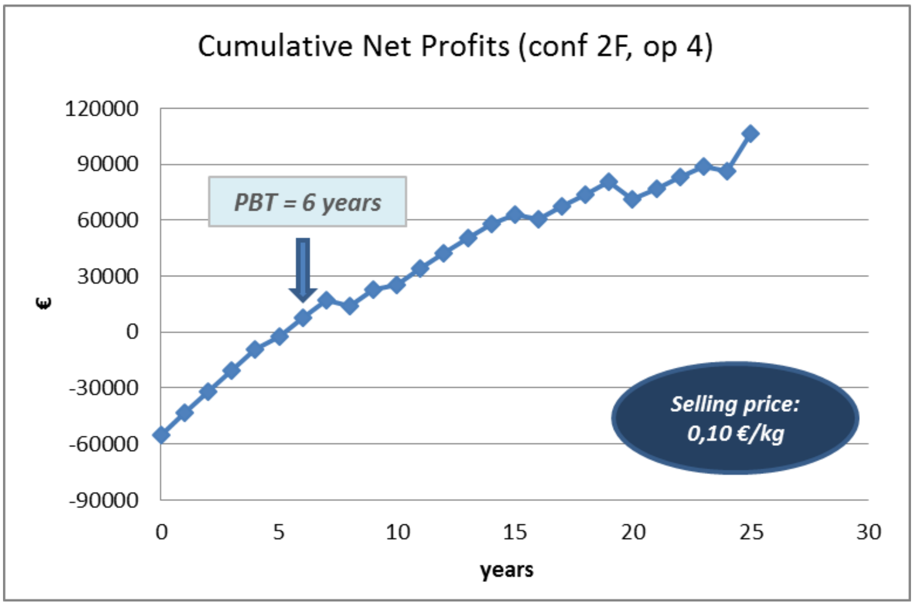


Figure 4-48 Cumulative net profits with a selling price of 0,1 €/kg (Configuration 2F, operation mode 4)

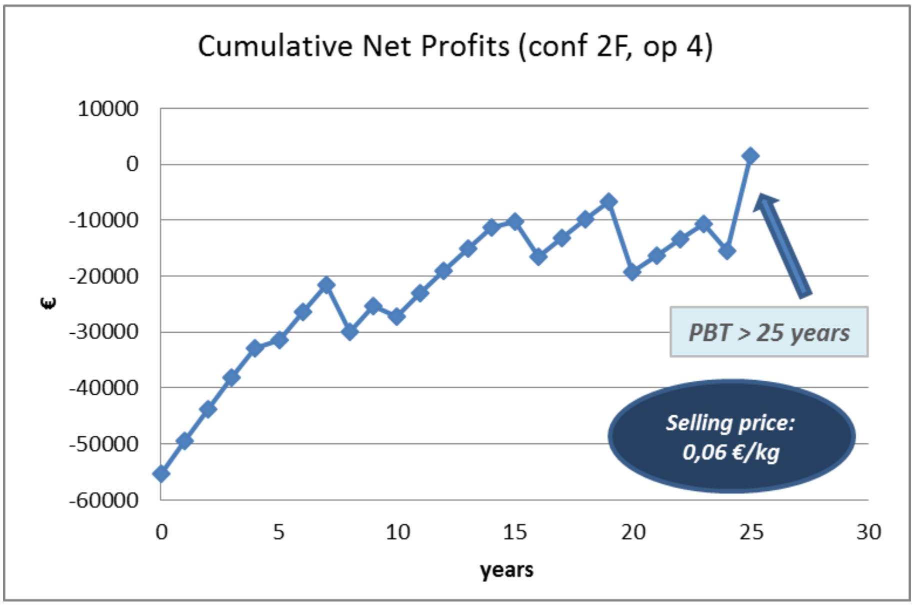


Figure 4-49 Cumulative net profits with a selling price of 0,06 €/kg (Configuration 2F, operation mode 4)

The graphs show a net difference between the case in which ice is sold at the price that fishermen would be willing to pay and the one in which the price is maintained in line with the one of the markets. If the price of the ice is 0,06 €/kg, PBT results to be very high (higher than 25 years for both), while with a selling price of 0,10 €/kg the PBT is low for both system configurations (6 years). This last option would permit to realize an economical system just if all the ice produced is sold and fishermen and merchants can afford it.

This leads us to calculate the economic results on the base of an ice price of 0,08 €/kg. Figures 4-50 and 4-51 display such case for both the configurations:

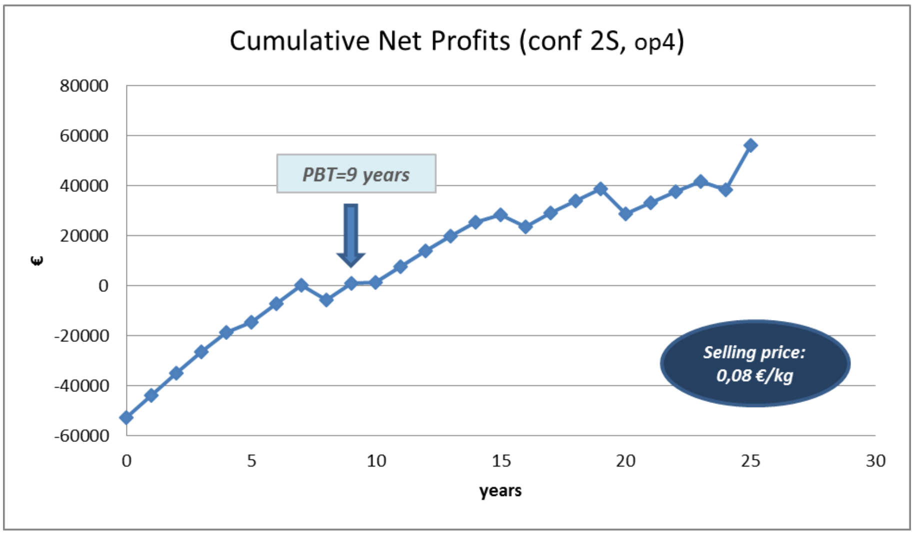


Figure 4-50 Cumulative net profits with a selling price of 0,08 €/kg (Configuration 2S, operation mode 4)

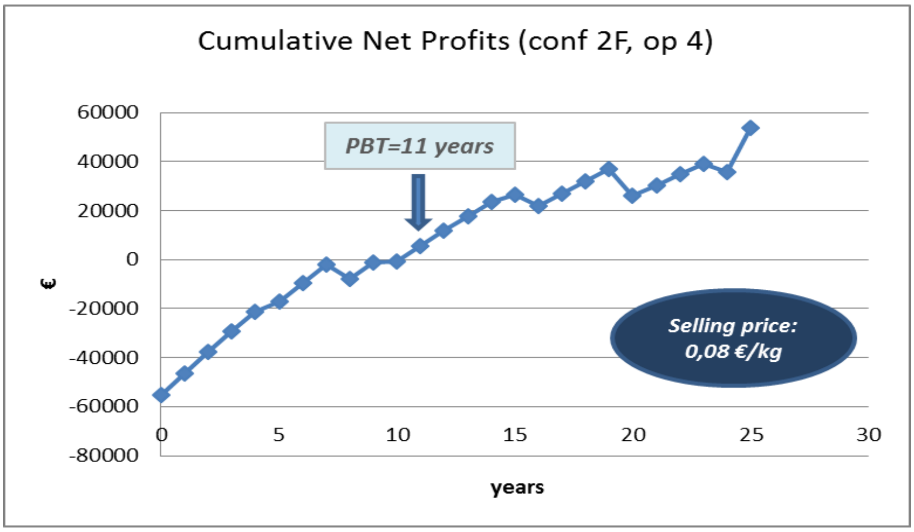


Figure 4-51 Cumulative net profits with a selling price of 0,08 €/kg (Configuration 2F, operation mode 4)

Table 4-26 reports the values of NPC, NPV and PBT of configuration 2S and 2F, related to the three considered selling prices:

Table 4-26 NPC, NPV and PBT of configurations 2S and 2F (operation mode 4) with different selling prices

		NPC	NPV	PBT
Sale price: 0,06 €/kg	Conf 2S, op 4	153214	3663	>25
	Conf 2F, op 4	155386	1551	>25
Sale price: 0,08 €/kg	Conf 2S, op 4	153214	55956	9
	Conf 2F, op 4	155386	53863	11
Sale price: 0,10 €/kg	Conf 2S, op 4	153214	108248	6
	Conf 2F, op 4	155386	106175	6

Sensitivity analysis of economic parameters

A sensitivity analysis consists of varying one value in the model by a given amount, in order to examine the impact of the change on the model's results.
In the economic analysis of the simulated systems some values that may be subjected to variations have been used. The discount rate and the price of the elements that compose the system are those that most of all may change in a significant way.
As regards the discount rate, for the calculation of NPC and NPV, an initial value of 3,5% has been taken. This value may vary considerably, as it depends on different parameters subject to frequent fluctuations, like inflation, interest and risk rate.
A value of discount rate of 3,5% was taken because we assume a favorable financing justified from the cooperation objectives if CeLIM cannot finance entirely the project. Moreover, we consider a free risk rate (even if the project has a certain risk) because a cooperative action does not aim to make profit.
The value of the discount rate was varied between 2% and 15%, with a step of 0,5%, in order to assess the resulting variation of NPC, NPV and PBT in our model output.
Here we report just the sensitivity analysis concerning one of the various simulated configurations: the one with insulated storage (conf 2S, op 4), and an ice selling price of 0,08 €/kg.
Figure 4-52 shows the variation of NPC and NPV.

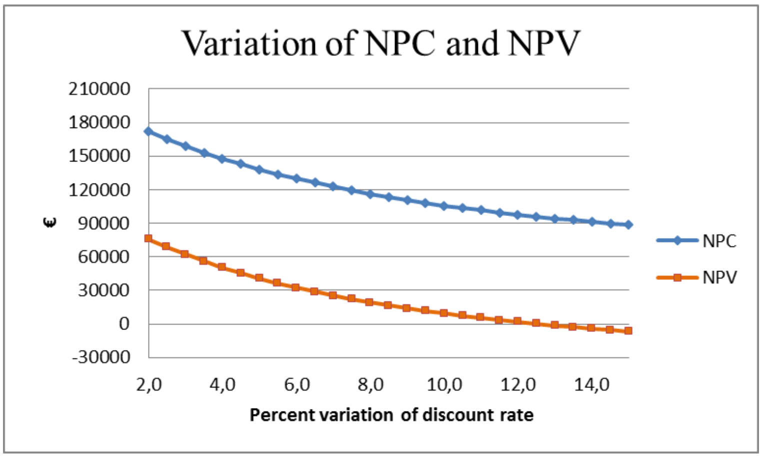


Figure 4-52 NPC and NPV with variable discount rate (Configuration 2S, operation mode 4)

Higher discount rates imply lower values of actualized costs and net profits. In this particular case, NPV reaches negative values at a discount rate of nearly 12,5%; this is the reason why the exact calculation of PBT (shown in figure 4-53) with a discount rate higher than 12,5% is not possible (we only know that it is higher than 25 years).

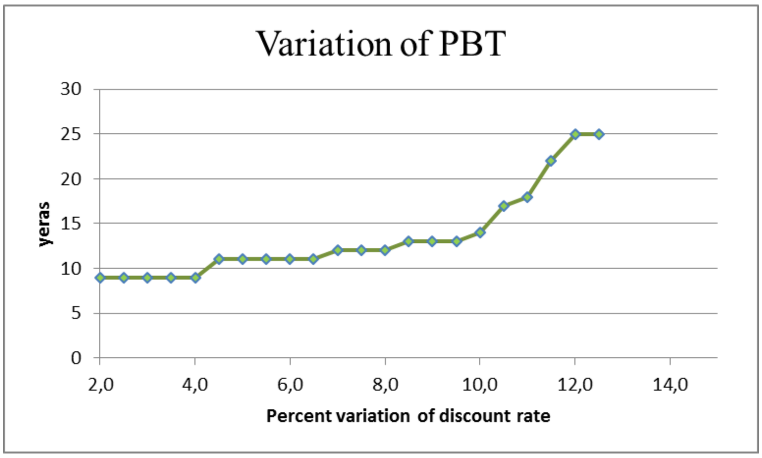


Figure 4-53 PBT with variable discount rate (Configuration 2S, operation mode 4)

A further sensitivity analysis has been carried out on varying different components price. Data on component costs are referred to commercial models produced and sold by European or American companies. Indeed these costs may vary significantly in different contexts and markets.

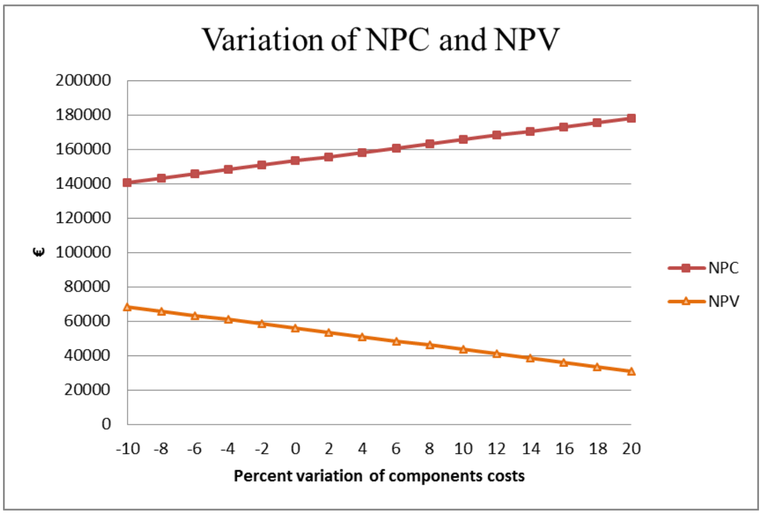


Figure 4-54 NPC and NPV with variable components costs (Configuration 2S, operation mode 4)

Figure 4-54 shows how NPC increases with higher components costs, while NPV decreases. Even with a variation of components costs of 20%, NPV remains positive (around 30000 €), with a PBT of 13 years: this means that possible high variations of the price of the components may not change significantly the economic results.

4.3.5 System evaluation

Through the decision-making process, two configurations have been selected as the most appropriate, one that better meets energetic requirements and another more convenient in an economic view.

- Configuration 2S-operation mode 4 turn out to be the most suitable system according with the energetic criterion. A photovoltaic array of 28,5 kW supplies 8 icemakers during the day and the produced ice is stored in an insulated container until it is sold. A battery bank of 19 kWh allows a continue power supply during cloudy days. This system has a good robustness and produces a lower amount of excess energy than the other configurations.
- Configuration 2F-operation mode 4 is the best solution considering the economic criterion. It has the same icemakers of the other configuration, but these are supplied by a photovoltaic array of 31,5 kW and have a battery backup of 17 kWh. The ice, produced during daily hours, is stored in a freezer powered by photovoltaic modules or by batteries. It is lightly more expensive than the other one but it ensures a constant temperature of sold ice at -10°C.

The economic analysis, followed by the sensitivity analysis, has demonstrated the feasibility of these solutions: with a selling price of ice of 8 c€/kg (a compromise between fishermen willing and market standard) a satisfactory Pay Back Time is obtained. PBT could be even lower if we consider the batteries' behavior of the configurations with thermal storage: the low average depth of discharge may increase batteries lifetime and consequently the cost of a real system may be lower than what we evaluated with a conservative hypothesis (batteries lifetime of 5 years).

Given the specific requests and needs expressed by CeLIM, we consider that the configuration with the freezer as storage (conf 2F, op 4) is the best solution. The higher cost can be justified by the higher "quality" of ice supply (-10°C) which allows an appropriate fresh fish preservation in case of hot days and long travel times.

As a first real application, a possibility could be installing the system in just one of the several fishing centers, meeting the fishermen requirements by selling the ice at 6 c€/kg. Despite the disadvantage of having a very high payback time, this choice may permit to know the real impact of the technology in the specific context at a social and economic level. In case of positive acceptance of the community, the project could be replicated in some other fishing centers and the selling price of ice could be increased to make the project economically sustainable.

We must not forget that the proposed system presents a high excess in electricity production. To avoid an excessive waste of energy in a context where the energy access is limited, a possible solution could be to use the energy surplus for charging or supplying some devices, as mobile phones or rechargeable batteries.

We now have the final configuration that better meets the identified needs. At this point, a more specific evaluation of the proposed system is done by means of some typical indicators, reported in table 4-27.

Table 4-27 Indicators for system evaluation

Daily quantity of ice produced per m^2 of PV module [kg/m^2 day]	*Daily quantity of ice produced per PV installed power [kg/kW_p day]*	*LCOE[8] [€/kWh]*
2,4	15,2	0,41

The daily quantity of ice produced per m^2 of photovoltaic module is quite low with respect to Chorreras and Dresden prototypes (respectively 3,7 kg/m^2 day and 7,9 kg/m^2 day). This is due to the choice of polycrystalline modules and the oversizing of the photovoltaic system, necessary to make the icemakers operate in the early morning and in the late afternoon, when the solar radiation is weak. Consequently, also the daily quantity of ice produced per photovoltaic installed power results lower than the two prototypes' values (Chorreras produces in one day 31,3 kg of ice per kWp, while Dresden produces in one day 58,8 kg of ice per kWp).
LCOE shows a high cost of electricity production compared to a standard value of grid-connected photovoltaic systems that is in the range 0,09 - 0,19 €/kWh [75]. This is a reasonable result as stand-alone systems are usually more expensive than grid-connected systems. Values reported for grid-connected systems are calculated considering the produced energy that corresponds to consumed energy. In order to make a reasonable comparison we calculate the system LCOE considering the only consumed energy, given also the large amount of excess energy.

---

[8] The LCOE (Levelized Cost Of Energy) represents the per-kilowatthour cost (in real dollars) of building and operating a generating plant over an assumed financial life and duty cycle. Key inputs to calculating LCOE include capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type. [79]

5. Conclusions

This study aims at selecting the most appropriate cooling technology for a specific case, where food preservation emerges as a significant issue. This selection has been supported by the review of relevant refrigeration technologies. The optimization of the system configuration, which is based on the selected technology, is achieved by simulating the yearly operation of the whole system, thanks to a numerical model specifically developed and implemented in Matlab.

The review is focused on specific systems realized for stand-alone applications powered by solar energy and aimed principally at food preservation. Both refrigerators and icemakers, based on a vapor compression or sorption cycle, have been reported and compared: icemakers are more suitable for the preservation of food that has to be kept at a specific temperature range (above 0°C), while refrigerators are employed for a wider set of food. Evaporative cooling is used for fruits and vegetables preservation given the temperature range it can guarantee. The choice of the most suitable thermodynamic cycle comes principally from the necessary amount of ice or from the required volume that needs to be to refrigerate and from the temperatures desired.

The first activity of the study, focused on the specific case proposed by CeLIM, an Italian NGO, has been the analysis of the context: it results that fresh fish preservation is a critical issue for the fishermen on Zambesi River. Through some questionnaires, submitted to the stakeholders, and a study about standard conditions for fish preservation, ice blocks turns out to be the best means for fish preservation and, consequently, icemakers are the best technology. The second stage of the study has been the system design: given the high amount of requested ice, vapor compression icemakers have been chosen and a photovoltaic system has been selected to provide the necessary electricity. As the system will be installed in a stand-alone context the use of batteries is necessary to make it reliable.

Different configurations with different operation modes and type of storage have been simulated and optimized by means of a numerical model implemented in Matlab: the optimization consists in selecting the minimum battery capacity, for a given range of photovoltaic installed power, to match a specific percentage of the annual request. Once sized the photovoltaic array and the battery bank, a series of selection criteria has been considered and two configurations emerged as the most suitable for the local context.

The analysis of the model results and a decision making process permitted to select the most appropriate system configuration and the operation mode for Mozambican fishing centers. Eight icemakers work in daily hours powered by the only photovoltaic power, a battery bank supplies the necessary energy in cloudy hours and the ice produced is stored in a freezer in order to guarantee a temperature of -10°C when it is sold. This proposal may represent a starting point for improving fish conservation in the specific case at issue, and may be a reference point for other similar situations. Given the relevance of the fish preservation problem and the economic feasibility of the project, it is considerably worthwhile to realize a pilot project in one fishing center.

The necessity of a reliable and affordable stand-alone system for cooling purposes in rural contexts is strong and real. The researches concerning this field are several but despite a great deal of efforts lots of areas are still characterized by food preservation problem. This work may represent a little contribution for further developments.

APPENDIX A

Information exchanges with representatives of CeLIM

Organizzazione di un centro di pesca

1. In che orari lavorano i pescatori?

   Risposta: Nos centros de pesca visitados no âmbito do Macro-Diagnóstico no Distrito de Morrumbala, os pescadores deram a conhecer que o horário das actividades é de 2 turnos, Diurno e Nocturno. No período diurno, os pescadores embarcam as 7:00h e desembarcam as 15, e Nocturno embarcam as 17:00h e desembarcam 7:00h do dia seguinte, dependendo da produção, chegam a desembarcar mais cedo ou mais tarde.
   Traduzione: 2 turni: diurno dalle 6-7 am fin verso le 3 pm; notturno verso le 5-6 pm fino al mattino seguente, verso le 6-7 am.

2. A che ora e quanto spesso passano i commercianti per portare il pesce in città? (con le risposte alle domande 1 e 2 ci aspettiamo di capire per quanto tempo il pesce fresco debba essere conservato dal momento della pesca all'arrivo del commerciante)

   R: Os únicos comerciantes que levam pescado fresco para comercialização a grandes distancias sao os de Pinda que saem de Morrumbala pelas 04 horas e chegam no CP as 07 horas tendo na mesma hora apos a compra voltam de bicicletas e motas. Sao muito frequentes no periodo de manha. Quanto aos outros mercados somente levam pescado seco ou fumado.
   Trad: i commercianti di Morrumbala sono soliti partire verso le 4 di mattina dalla cittadina di Morrumbala per arrivare verso le 7 ai centri di pesca nella zona di Pinda (alcuni hanno moto e portano ghiacciaie con sé, altri hanno biciclette). Il pesce fresco a Morrumbala comincia ad arrivare ed esser venduto verso le 10 del mattino. Nella zona di Mopeia é facile veder arrivare i commercianti con pesce fresco nel pomeriggio, verso le 5, dunque probabilmente comprano pesce nel CP verso le 3 del pomeriggio.

3. Quanti pescatori lavorano sulla singola barca? Con quanto pesce rientra normalmente ogni barca?

   R: Quanto ao número dos tripulantes em cada almadia, depende do tipo de arte por eles utilizado, no caso de *Kokotha* (Rede de Arrasto), a tripulação

pode ser de Dez (10) no máximo e no mínimo seis (6), se for *Khumba* (Rede de Emalhar) são dois (2) tripulantes, Txáve (Tarrafa) também dois (2) tripulantes e Khonga (Gaiola) apenas um (1) tripulante.
E quanto a quantidade média de peixe capturado em cada faina pode ser de 50Kg de Peixe fresco.
Trad: il numero di pescatori dipende dal tipo di reti usate e varia da un mínimo di 1 a un massimo di 10. Si possono attingere 50 kg di pesce in media.

4. Ogni centro di pesca ha un sistema di accumulo e di affumicazione comune a tutti i pescatori o ciascuno ha il proprio? Nel caso di un accumulo comune, quanto tempo resta il pesce senza essere conservato al fresco (prima di essere affumicato)?

   R: A forma de processamento é individual mas com ajudantes, nenhum processador junta com outro. Quando está para ser fumado, o peixe é aberto ao meio e eviscerado, depois é estendido por um período. Então, Desde a captura até o início da Fumagem ou Salgagem leva duas (2) a três (3) horas de tempo.
   Trad: la lavorazione é individuale (con aiutanti), non esiste un sistema di accumulo comune. I pescatori non mettono insieme il pesce. Un'altra distinzione riguarda pescatori/trasformatori: parliamo quasi sempre di 2 gruppi distinti. I commercianti di pesce (salato, affumicato) possono trattare da soli il pescato per poi portarlo sul mercato giá lavorato. Il pescatore può lavorare il pescato ma lo fa più che altro per una questione di sussistenza famigliare, meno per vendita. Il suo obiettivo é pescare e consegnare la maggior parte del pesce al commerciante che aspetta.
   Di solito passano 2-3 ore prima che il pesce venga aperto per essere lavorato.

5. Hanno già esperienza per la condivisione di spazi per la conservazione del pesce? Nel caso di una soluzione tecnologica utilizzabile da tutti, potrebbero crearsi dei conflitti tra i vari pescatori?

   R: Pelo apurado durante o Macro-Diagnóstico, em quase todos Centros não existem associações, o que faz com que cada processador possua o seu próprio fumeiro praticando as actividades individualmente. Mas fizeram conhecer que no caso de existência de um qualquer tipo de apoio, eles estão disposto em trabalhar em grupos.
   Trad: nel lavoro di indagine a Morrumbala si é constatato che in tutti i centri di pesca non esistono associazioni o cooperative e ogni gruppetto di trasformatori dispone del suo forno per l'affumicazione o della sua stuoia per

seccare il pesce. In ogni caso i commercianti/trasformatori hanno manifestato interesse in eventuali sistemi migliorati dimostrativi per la trasformazione in comune.

6. Ci sono differenze organizzative e di gestione tra i diversi centri di pesca (dato che si trovano in due diversi distretti)?

   R: Nas condições acima referidas, de não existência de associações, todos Centros de Pesca possuem uma forma de organização, digamos Padrão, existência de Um (1) Txeia e Um (1) Vice, ou seja Um (1) Chefe dos Pescadores e Um Adjunto (1).
   Trad: in assenza di associazioni, tutti i CP hanno una forma organizzativa molto simile, esiste un capo entro e un vice.

7. Ammesso che l'affumicazione sia l'unica soluzione ora in uso per la conservazione del pesce, tale sistema da chi viene gestito? Se comune, è un servizio a pagamento?

   R: Este sistema é gerido individualmente visto que cada processador faz o seu negocio para o sustento da sua família, como seu emprego onde consegue algo para sua renda.
   Trad: non è l'unica (aggiungo io) esiste anche l'essicazione. Il sistema di lavorazione del pesce é gestito da singole persone o da gruppetti di persone composti al massimo da 2-4 persone (che condividono eventualmente un forno in comune).

Organizzazione della connessione tra i centri di pesca

1. Ogni centro di pesca è autonomo o è in contatto con gli altri centri di pesca dello stesso distretto? (ovvero, magari un centro di pesca relativamente piccolo usa l'affumicatoio di un centro adiacente, oppure ognuno ha il proprio)

   R: Quanto aos fumeiros usados para o processamento, cada centro é independente, ou seja nenhum CP usa o fumeiro de um outro CP.
   Trad: centri vicini possono essere in contatto, esistono centri che stanno a 1 km uno dall'altro e che per esempio condividono lo spazio di pesca (fiume o lagune). Difficilmente vengono condivisi gli affumicatoi, di solito ogni centro ha il suo.

2. Quanto distano i centri di pesca l'uno dall'altro? (per capire se è possibile pensare ad un centro comune per la conservazione).

   R: A distância depende da localização dos CP ou dos centros de desembarque, variando de 300 metros a 1 km ate 10km ou mais.
   Trad: le distanze variano molto, da 300 m fino a 10 km o piu…
   Aggiungo io: diciamo che in ogni distretto possiamo distinguere delle zone che potrebbero raggruppare i centri di pesca piu o meno vicini. Ad esempio nel distretto di Morrumbala potremmo parlare di almeno 4 zone di pesca con una ventina di CP circa, in media 5 CP per zona. Nel distretto di Mopeia potremmo distinguere 5 zone di pesca con diversi CP. Poi, nel testo di progetto parliamo di 4 consigli comunitari di pesca, 2 per distretto: in teoria un CCP può riunire pescatori e trasformatori di piu zone. Se volessimo fare qualche azione dimostrativa potrebbe aver senso lavorare nei principali CP dei 4 CCP (che verranno definiti in corso di progetto, a breve).

Organizzazione della rete di commercio

1. Dove si trovano i principali mercati? Quanto distano dai centri di pesca?

   R: Os principais mercados destes centros de pesca situa- se nos distritos de Mocuba, Milange e Malawi que distam cerca de 100 a 200km…
   Trad. Per quanto riguarda il pesce secco e affumicato possiamo parlare di mercati più lontani (Quelimane, Mocuba, Cuamba, Milange, Malawi). Per il pesce fresco, i mercati princiapli sono Morrumbala e Mopeia, le due sedi di distretto. Mponha per esempio dista circa 35 km da Morrumbala, mentre le zone di pesca intorno a Mopeia distano da 2-3 km a una ventina. Un altro punto di vendita del pesce fresco é la localitá di Chimuara, sullo Zambezi e dista 5-10 km dai centri di pesca di quella zona (Noere, Braz, Nhacatundo). Nella zona di Posto Chire, lontana più di 100 km da Morrumbala, il mercato principale diventa il vicino Malawi.

2. Quanto tempo impiega un commerciante per andare da uno o più centri di pesca ai relativi mercati?

   R: Levam entre dois a três dias de viagem para chegar aos mercados
   Trad: il trasporto può anche durare dei giorni (2-7) quando si tratta di portare del pesce secco o affumicato in bicicletta (per esempio da Mopeia a Milange si fanno quasi 300 km in bici) con un carico di pesce da 60-80 kg. Nel caso di pesce fresco il commerciante può usare una motocicletta e metterci 1-2 ore di

tempo o una bici qualora il mercato sia abbastanza vicino e metterci anche in questo caso 1-3 ore.

3. Relativamente a ciò, in che condizioni sono le strade? (con le risposte alle precedenti domande vorremmo capire se possa essere utile avere una macchina che produca ghiaccio in tutti/alcuni centri di pesca per la conservazione del pesce durante il trasporto)

   R: Dipende dalle zone e dai centri di pesca, in ogni caso sempre sterrate e non tutte percorribili in auto. Durante la stagione delle piogge é ancor più difficile raggiungere molti centri di pesca sia in auto che in moto.

4. Normalmente con che mezzi viene trasportato il pesce fino al mercato?

   R: Bicicletta (qualcuno con moto), pulmini quando ci sono e quando il mercato si trova distante (es: Quelimane, Mocuba da Mopeia o da Morrumbala). Il pesce secco è trasportato in grossi imballaggi fatti con cartone o in sacchi di rafia.

5. In che modo esattamente il pesce viene conservato durante il trasporto? (es in un recipiente contenente del ghiaccio).

   R: Cesti, sacchi, scatole di cartone, ghiacciaie o contenitori di polistirolo (con ghiaccio) per il pesce fresco.

Ulteriori informazioni

1. Oltre al fatto che operate da molto tempo nei distretti di Morrumbala e Mopeia, c'è un altro motivo per cui avete deciso di concentrarvi su queste due località?

   R: direi che sono due distretti con un economia fortemente dipendente dalla pesca. La pesca é insieme all'agricoltura l'attivitá economica principale per il distretto di Mopeia, probabilmente la prima tenuto conto anche del volume di commercio di pesce che si genera. Il pesce secco o affumicato di Mopeia viene portato fino a 500 km di distanza!
   Parliamo di un'area comunque molto vasta, difficile anche da esplorare, lungo i bacini di due fiumi importantissimi come Zambesi e Shire.

2. Le piene e le alluvioni sono fenomeni frequenti nel corso dell'anno? Il loro impatto è tale da danneggiare le strutture dei centri di pesca e da impedire i lavoro dei pescatori?

   R: Durante a época chuvosa que geralmente tem culminado com o aumento de nível de água nos principais rios (Zambeze e Chire) e causam alagamentos nos Centros de Pesca, tem causado danos materiais consideráveis, como a destruição dos acampamentos onde tem sido processado e conservado o peixe, que acaba condicionando a actividade de processamento, mas em contra-partida a produção pesqueira aumenta.
   Trad: le piene sono cicliche, generalmente ogni 5 anni si registra almeno un'inondazione sopra la media. A volte vengono colpiti e distrutti magazzini e accampamenti dove viene conservato il pesce. Va però anche detto che l'acqua esondata genera un ricambio e un arricchimento anche a livello di fauna ittica con effetti favorevoli per la pesca nei mesi successivi alla piena.

3. Di quanto aumenterebbe il valore del pesce fresco (in termini di denaro) rispetto a quello affumicato? Senza questa soluzione, i pescatori perdono parte della loro raccolta a causa della cattiva conservazione?

   R: O Peixe fresco é mais nutritivo em relação ao Fumado ou Salgado-Seco, pois conserva todos nutrientes que o Salgado ou Fumado, mas nos mercados, quanto aos preços, o peixe fumado custa mais em relação ao fresco. Por exemplo o fumado pode custar a 175,00mt/kg, e o fresco 70,00mt/kg, e também um (1) peixe fumado pode custar até 30,00mt e um (1) fresco até 20,00mt, dependendo do tamanho.
   A não observância "que pode ser por várias razões" da principal forma de processamento (Fumagem) praticado em todos Centros, pode levar uma perda do produto até 50%.
   Trad: si può arrivare a un 50% di perdita di prodotto se non si osservano norme adeguate di lavorazione del pesce. In media comunque nel passaggio pesce fresco-pesce trasformato, si perde tra il 3 e il 5% del prodotto.
   Il pesce fresco é certamente più apprezzato ma meno reperibile a causa della distanza dei CP dai mercati e a causa di difficoltà di conservazione (mancanza di ghiaccio).
   Nei mercati il pesce affumicato costa di più rispetto al pesce fresco (a causa dei vari costi nell'intera filiera, dal fiume al mercato finale). Per esempio il pesce affumicato può costare 170 mt al kg (circa 4 euro al kg) mentre il fresco costare

intorno ai 70-100 mt. Un pesce secco può costare 30 mt (75 cent) e un pesce fresco 20 mt (50 cent).
Aggiungo io: il pesce fresco guadagna valore quando arriva nei mercati principali dove la domanda é maggiore (ad esempio in cittá come Mopeia, Morrumbala o Quelimane). La tilapia ha molto più valore rispetto al pesce gatto, é molto meno reperibile sui banchi del mercato e ha una domanda alta ovunque (finisce in fretta).

4. In che modo le autorità locali tradizionali hanno espresso la problematica della conservazione?

   R: A seconda dei vari livelli di autorità, dal più lontano al più vicino concretamente al centro di pesca, la problematica e stata presentata in modo differente. L'amministratore ha colto l`occasione per avanzare la richiesta di integrare al mercato già esistente a Morrumbala, una parte per la vendita del ghiaccio, dove appunto i commercianti di pesce possano comprarlo per trasportare pesce fresco. I rappresentanti dei centri di pesca vivono il problema per primi. Riescono a processare e fumare il pesce nei tempi giusti ma per il pesce fresco il problema è strutturale: in alcuni centri non arriva l`elettricità, non hanno coleman (ghiacciaie), non hanno ghiaccio e le vie d`accesso richiedono ore di bicicletta per raggiungere il mercato più vicino.

5. Quali sono approssimativamente le condizioni climatiche in termini di temperatura e precipitazioni? (in modo da confrontarli con i dati che recupereremo sul web).

   R: Piogge iniziano di solito verso metà ottobre e finiscono a fine marzo-metá aprile. Le temperature sono elevate più o meno nello stesso periodo con valori medi sopra i 30 gradi. Nella valle dei fiumi shire e Zambesi da novembre a marzo siamo quasi sempre intorno ai 35 gradi come temperatura media giornaliera. L'inverno è mite e va da giugno ad agosto (inverso della nostra estate) con temperature che si attestano tra i 22 e i 26 gradi. Le minime invernali possono arrivare a 12-13 gradi.
   Morrumbala é a 400 m slm ed ha decisamente temperature medie più fredde rispetto a Mopeia e Quelimane.
   Nei mesi di giugno e luglio é normale l'arrivo di una piccola stagione delle piogge.

APPENDIX B

Questionnaire

1. In quale periodo fai i turni di pesca notturni?
   - ☐ Quando fa troppo caldo (da ottobre a marzo circa)
   - ☐ Quando si pesca di più (specificare quando _________________________)
   - ☐ Mai
   - ✓ **Sempre**
   - ☐ Altro _________________________

2. Ci sono giorni in cui alcuni pescatori pescano di giorno ed altri la sera?
   - ✓ **Si**
   - ☐ No

3. Ci sono dei giorni in cui non ci sono pescatori al centro di pesca?
   - ☐ No, c'è sempre qualcuno che pesca
   - ✓ **Si, c'è un giorno di riposo**
   - ☐ Altro _________________________

4. Durante un turno quante uscite fai?
   - Durante la stagione secca
     - ☐ 1
     - ✓ **2**
     - ☐ Più di 2
   - Durante la stagione delle piogge
     - ✓ **1**
     - ☐ 2
     - ☐ Più di 2

5. Quanto dura la singola uscita?
   - Durante la stagione secca
     - ☐ Almeno 2h
     - ☐ 2h-4h
     - ✓ **4h-6h**
     - ☐ Più di 6h
   - Durante la stagione delle piogge
     - ✓ **Almeno 2h**
     - ☐ 2h-4h
     - ☐ 4h-6h
     - ☐ Più di 6h

6. Se fai più di 1 uscita, una volta tornato a terra:
   - ✓ **Vendi subito il pesce ai commercianti**
   - ☐ Lo accumuli in una cesta senza trattarlo
   - ☐ Lo tratti (o lo fai trattare da qualcun'altro)

7. Quanti kg di pesce rientrano dopo ogni uscita di una singola barca?

- Durante la stagione secca
  - ✓ **Meno di 30kg**
  - ☐ 30-50kg
  - ☐ 50-70kg
  - ☐ Più di 70kg (____________)

- Durante la stagione delle piogge
  - ☐ Meno di 30kg
  - ✓ **30-50kg**
  - ☐ 50-70kg
  - ☐ Più di 70kg (____________)

8. Oltre a te, quante persone ci sono sulla barca?
   - ✓ **Nessuna**
   - ☐ 1-3
   - ☐ 4-6
   - ☐ Più di 6

9. Il guadagno derivante dalla vendita del pesce viene diviso equamente tra i pescatori della stessa barca?
   - ☐ Si
   - ✓ **No, esiste una specie di gerarchia** (è chiarito che i pescatori affittano la barca e quindi una minima parte del loro guadagno è usata a tale scopo)
   - ☐ No per altri motivi (specificare____)

10. A quanto vendi il pesce ai commercianti?

    _________12 PESCI (=1 KG) A 20 MT [circa 0,53 euro]__________________

11. Ti sarebbe utile del ghiaccio da portare sulla barca ad ogni uscita?
    - ✓ **Si, molto**
    - ☐ Si, ma non è indispensabile
    - ☐ No

12. Se si, quanto saresti disposto a pagarlo?

    _________5 KG DI GHIACCIO A 10 MT [circa 0,27 euro]___________

APPENDIX C

Homer Software

The HOMER Micropower Optimization Model is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micropower systems and to facilitate the comparison of power generation technologies across a wide range of applications. HOMER models a power system's physical behaviour and its life-cycle cost, which is the total cost of installing and operating the system over its life span. HOMER allows the modeller to compare many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs.

HOMER can model grid-connected and off-grid micropower systems serving electric and thermal loads, and comprising any combination of photovoltaic (PV) modules, wind turbines, small hydro, biomass power, reciprocating engine generators, microturbines, fuel cells, batteries, and hydrogen storage. HOMER performs three principal tasks: simulation, optimization, and sensitivity analysis.

The simulation process serves two purposes. First, it determines whether the system is feasible. HOMER considers the system to be feasible if it can adequately serve the loads and satisfies any other constraints imposed by the user. Second, it estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its lifetime. HOMER steps through the year one hour at a time, calculating the available renewable power, comparing it to the electric load, and deciding what to do with surplus renewable power in times of excess, or how best to generate additional power in times of deficit. When it has completed one year's worth of calculations, HOMER determines whether the system satisfies the constraints imposed by the user on such quantities as the fraction of the total electrical demand served the proportion of power generated by renewable sources, or the emissions of certain pollutants. HOMER simulates how the system operates over one year and assumes that the key simulation results for that year (such as fuel consumption, battery throughput, and surplus power production) are representative of every other year in the project lifetime, it does not consider changes over time, such as load growth or the deterioration of component performance with aging. The quantity HOMER uses to represent the life cycle cost of the system is the total net present cost (NPC). This single value includes all costs and revenues that occur within the project lifetime, with future cash flows discounted to the present.

The optimization process determines the best possible system configuration. In HOMER, the best possible, or optimal, system configuration is the one that satisfies the user specified constraints at the lowest total net present cost. Finding the optimal system configuration may involve deciding on the mix of components that the system should contain, the size or quantity of each component, and the dispatch strategy the system should use. In the optimization process, HOMER simulates many different system configurations, discards the infeasible ones (those that do not satisfy the user-specified constraints), ranks the feasible ones according to total net present cost, and presents the feasible one with the lowest total net present cost as the optimal system configuration.

A sensitivity analysis reveals how sensitive the outputs are to changes in the inputs. In a sensitivity analysis, the HOMER user enters a range of values for a single input variable. One of the primary uses of sensitivity analysis is in dealing with uncertainty. If a system designer is unsure of the value of a particular variable, he or she can enter several values covering the likely range and see how the results vary across that range.

Bibliography

[1] J. Gustavsson, C. Cederberg, and U. Sonesson, *Global food losses and f o o d waste*. 2011.

[2] “http://www.unep.org/wed/2013/quickfacts/.” .

[3] University of Nottingham, “The Impact of Reducing Food Loss in the Global Cold Chain,” no. September, pp. 1–27, 2014.

[4] Insitution of Mechanical Engineers (IMechE), “A TANK OF COLD : CLEANTECH LEAPFROG TO A MORE FOOD SECURE WORLD .,” 2014.

[5] “http://www.iea.org/.” .

[6] S. K. Wang, *Handbook of Air Conditioning and Refrigeration*. 2000, p. 1232.

[7] P. . Macchi,E; Campanari,S.;Silva, *La climatizzazione a gas e ad azionamento termico*. 2012.

[8] “http://www.apep.uci.edu/der/buildingintegration/2/Technologies/WasteHeatRecovery.aspx.” .

[9] A. K. . Keith, E.H.; Reinhard, R.; Sanford, *Absorption Chillers and Heat Pumps*. 1996.

[10] P. Srikhirin, S. Aphornratana, and S. Chungpaibulpatana, “A review of absorption refrigeration technologies,” *Renew. Sustain. Energy Rev.*, vol. 5, pp. 343–372, 2000.

[11] B. K. Wang and E. a Vineyard, “Adsorption Refrigeration,” *Ashrae*, no. September, 2011.

[12] Y. Fan, L. Luo, and B. Souyri, “Review of solar sorption refrigeration technologies: Development and applications,” *Renew. Sustain. Energy Rev.*, vol. 11, pp. 1758–1775, 2007.

[13] L. W. Wang, R. Z. Wang, and R. G. Oliveira, “A review on adsorption working pairs for refrigeration,” *Renew. Sustain. Energy Rev.*, vol. 13, pp. 518–534, 2009.

[14] Marcello Aprile, “Teaching material of the course ‘Ingegneria dei processi solari termici’, Politecnico d Milano.” .

[15] J. Paynter, “Evaporative Cooling,” *Archit. Sci. Rev.*, vol. 7, no. 871954, pp. 110–113, 1964.

[16] A. Cota and R. Foster, “Photovoltaics for Rural Development in Latin America : A Quarter Century of Lessons Learned.”

[17] R. Foster, L. Estrada, M. Romero, M. Ross, and C. Hanley, “Performance and Reliability of a PV Hybrid Ice-Making System,” pp. 1–9, 2001.

[18] ILK Dresden Institute, “PV-Ice Maker,” 2004.

[19] P. J. Axaopoulos and M. P. Theodoridis, “Design and experimental performance of a PV Ice-maker without battery,” *Sol. Energy*, vol. 83, no. 8, pp. 1360–1369, 2009.

[20] C. Erickson, “Rural milk preservation with the ISAAC solar icemaker,” *Energy Sustain. Dev.*, vol. 13, no. 4, pp. 287–291, 2009.

[21] D. Erickson, “Solar Icemaker in Maruata, Mexico,” *The American solar energy socitey, Solat today*, pp. 21–23, 1994.

[22] K. Sheinkopf, “Solar Icemaker in a Mexican Fishing Village,” 1997.

[23] M. D. Staicovici, “An autonomous solar ammonia-water refrigeration system,” *Sol. Energy*, vol. 36, no. 2, pp. 115–124, 1986.

[24] N. Clavell, “Development of a low cost, low power consumption system for manufacturing ozonised fluid ice for fishing via absorption system,” 2007.

[25] M. Li, C. J. Sun, R. Z. Wang, and W. D. Cai, “Development of no valve solar ice maker,” *Appl. Therm. Eng.*, vol. 24, pp. 865–872, 2004.

[26] N. M. Khattab, “A novel solar-powered adsorption refrigeration module,” *Appl. Therm. Eng.*, vol. 24, pp. 2747–2760, 2004.

[27] NASA’s Johnson Space Center, “Company Licenses NASA Technology for Battery- Free Solar Powered Refrigeration Systems.”

[28] “http://www.who.int/immunization_standards/en/.” .

[29] “http://practicalaction.org/.” .

[30] O. Iso, “Solar Photovoltaic,” vol. 44, no. 871954, pp. 3–4, 2005.

[31] SolarChill, “Refrigerators and Vaccine Coolers Powered by the Sun.”

[32] M. K. Ewert, “Solar-Powered Refrigeration System,” 2002.

[33] M. Hammad and S. Habali, “Design and performance study of a solar energy powered vaccine cabinet,” *Appl. Therm. Eng.*, vol. 20, pp. 1785–1798, 2000.

[34] I. Pilatowsky, W. Rivera, and J. R. Romero, “Performance evaluation of a monomethylamine-water solar absorption refrigeration system for milk cooling purposes,” *Appl. Therm. Eng.*, vol. 24, pp. 1103–1115, 2004.

[35] F. Z. Sierra, R. Best, and F. a. Holland, “Experiments on an absorption refrigeration system powered by a solar pond,” *Heat Recover. Syst. CHP*, vol. 13, no. 5, pp. 401–408, 1993.

[36] E. E. Anyanwu and C. I. Ezekwe, “Design, construction and test run of a solid adsorption solar refrigerator using activated carbon/methanol, as adsorbent/adsorbate pair,” *Energy Convers. Manag.*, vol. 44, pp. 2879–2892, 2003.

[37] F. Buchter, P. Dind, and M. Pons, “An experimental solar-powered adsorptive refrigerator tested in Burkina-Faso,” *Int. J. Refrig.*, vol. 26, pp. 79–86, 2003.

[38] F. Lemmini and a. Errougani, “Building and experimentation of a solar powered adsorption refrigerator,” *Renew. Energy*, vol. 30, pp. 1989–2003, 2005.

[39] F. Lemmini and A. Errougani, “Experimentation of a solar adsorption refrigerator in Morocco,” *Renew. Energy*, vol. 32, pp. 2629–2641, 2007.

[40] N. Stenkjaer, “Cooling in Developing Countries.” .

[41] “http://www.davidweatherhead.com/project_12.html.” .

[42] “http://www.oliverpoyntz.com/zeer1.html.” .

[43] “http://www.emilycummins.co.uk/about.” .

[44] R. E. Critoph and K. Thompson, “Solar energy for cooling and refrigeration,” *EC BREC/WREN Proc. Eur. Semin. ’Renewable Energy - A Strateg. Sustain. Dev. IBMER, Warsaw, 17-19th November, 1997*, pp. 47–57, 1997.

[45] S. a. Kalogirou, *Solar thermal collectors and applications*, vol. 30. 2004, pp. 231–295.

[46] “http://hdr.undp.org/en/countries/profiles/MOZ.” .

[47] “http://en.wikipedia.org/wiki/Mozambique.” .

[48] “http://data.worldbank.org/indicator.” .

[49] Fao, *Review of the state of world marine capture fisheries management: Indian Ocean.* 2005.

[50] “http://www.eia.gov/countries/country-data.cfm?fips=mz.” .

[51] “http://www.africaneconomicoutlook.org/en/countries/southern-africa/mozambique/.” .

[52] CeLIM, “‘Promozione della pesca fluviale di piccola scala nei distretti di Mopeia e Morrumbala - Mozambico’, Modello di documento di progetto.” .

[53] FAO; Fisheries and Aquaculture Department, “Preservation techniques.”

[54] “http://www.fao.org/docrep/006/y5013e/y5013e07.htm.” .

[55] T.L. Bergman; A.S. Lavine; F.P.Incropera; V.P. Dewitt, *Fundamentals of heat and mass transfer*. .

[56] “http://meteonorm.com/.” .

[57] “http://www.nordon.com.au/.” .

[58] “http://www.snowell-icemachine.com/.” .

[59] “http://gzkoller.en.made-in-china.com/.” .

[60] “http://www.usicemachine.com/.” .

[61] “http://www.minus40.co.za/.” .

[62] “http://www.snowkey.com/.” .

[63] “http://www.rosen.com/.” .

[64] E. & S. group P.Silva, “Fotovoltaico - La tecnologia,” 2013.

[65] “http://www.q-cells.it.” .

[66] W. U. of technology J. B. M. Martinez, “Batteries in PV Systems,” *Pract. Handb. Photovoltaics*, pp. 721–776, 2012.

[67] N. A. P. S. Solar Store, “Battery information.”

[68] “http://www.victronenergy.com/.” .

[69] E. and A. W. EAST PENN, “Valve-Regulated Lead_acid (VRLA): Gelled Electrolyte (Gel) and Absorbed Glass Mat (AGM) Batteries.”

[70] “http://www.victronenergy.it/.” .

[71] U.S. Department of Energy., “Charge Controllers for Stand-Alone Systems.” .

[72] “http://www.ycitalia.com/it/congelatori-a-pozzetto/3225-congelatore-a-pozzetto-2055x715x903cf700.html.” .

[73] “http://www.plastifoam.it/.” .

[74] “http://www.superdecisions.com/.” .

[75] E.Colombo and S.Bologna, *Renewable Energy for Unleashing Sustainable Development*, vol. 23. 2013, pp. 19–25.

[76] W. A. Duffie, J.A. ; Beckman, *Solar Engineering of Thermal Processes*. .

[77] WHO, “Guideline on the international packaging and shipping of vaccines,” *World Health Organization*. p. 30, 2005.

[78] "http://cbkb.org/toolkit/discounting/." .

[79] EIA, "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2014," no. April, pp. 1–12, 2014.