SPARK—Solar Photovoltaic Adaptable Refrigeration Kit

Claudio Del Pero, Maddalena Buffoli, Luigi Piegari, Marta Dell'Ovo and Maria P. Vettori

Abstract In developing countries, especially in particularly critical areas such as tropical Africa, the state of health of the population is strongly influenced by infectious risk factors. High temperatures and humidity levels, in fact, contribute to the formation and proliferation of viruses and bacteria capable of spreading rapidly. For these reasons, the need to find low-cost and context-adaptable strategies capable of ensuring the correct preservation of food and medicine in areas where the electricity supply is not reliable is a priority for improving health and social conditions in developing countries. In such a context, the aim of this study was to develop a modular kit designed for the self-construction of a refrigeration system which is economically competitive with other products already developed for the same purpose. The refrigeration system is powered by solar photovoltaic energy and can be easily assembled in the required location of application, with particular reference to the context represented by Africa's tropical belt. The kit was designed and tested at the Politecnico di Milano University and the final prototype version was built in Cameroon.

Keywords Solar refrigeration · Photovoltaic (PV) refrigerator · Food preservation · Self-construction · Low-cost refrigerators

1 Introduction and Context Characterization

The unfair access to fundamental necessities, such as clean water, uncontaminated food, drugs, etc., strongly influences the well-being of a Country and is a cause of death (WHO 2018; Haver et al. 2013). Particularly, the most affected countries are those belonging to the tropical–equatorial belt of Africa and characterized by a low Human Development Index (Del Pero et al. 2015).

C. Del Pero (✉) · M. Buffoli · M. Dell'Ovo · M. P. Vettori
Architecture, Built Environment and Construction Engineering—ABC Department, Politecnico di Milano, Milan, Italy
e-mail: claudio.delpero@polimi.it

L. Piegari
Department of Electronics, Information and Bioengineering—DEIB, Politecnico di Milano, Milan, Italy

N. Aste et al. (eds.), *Innovative Models for Sustainable Development in Emerging African Countries*, Research for Development, https://doi.org/10.1007/978-3-030-33323-2_6

Their economic activity is mainly based on the primary sector, specifically on agriculture, but few preservation practices are adopted; in fact, more than the 30% of the production is discarded due to incorrect food storing practices (Haver et al. 2013). Among the main reasons, there is a lack of appropriate technology and a very limited access to energy, especially electricity, usually concentrated in major cities and restricted to less than 10% of the inhabitants. In this context, in fact, rural areas' settlements are the most affected by this problem (Rebecchi et al. 2016) since they are typically not served by the grid or with a very limited access only for a few hours per day (IMECHE 2014; Tassou et al. 2010). To overcome this issue, several stand-alone solutions for food preservation have been developed providing different innovative alternatives from which it is possible to choose the most suitable for the application context, such as those that are based on sorption refrigeration, using either fossil fuels or solar thermal collectors as a heat source (Somerton et al. 2009; Metcalf et al. 2011; N'tsoukpoe et al. 2014; Santori et al. 2014; Yildiz 2016). More recently, DC (Direct Current) PV (Photovoltaics) refrigeration has become a very interesting and affordable solution, mainly thanks to the reduced manufacturing cost of photovoltaic modules (Nemet 2006; Feldman et al. 2012).

Considering the importance of the topic and the increasing market demand, several commercial solutions are currently available (Ewert et al. 1998; Ewert and Bergeron III 2000; Kim and Ferreira 2008), but most of the products are characterized by high cost and certain limits:

- the use of batteries for energy storage in case of electric refrigeration;
- the implication of complex technical solutions given by the use of the absorption cycle coupled with solar thermal collectors;
- the manufacturing of the product in developed countries and the shipping as a ready-to-use system.

Given these premises, the aim of the present work is to describe a solar photovoltaic adaptable refrigeration kit (SPARK); it is an assembly kit of a stand-alone DC solar refrigerator powered by PV energy, suitable for food conservation in remote areas of countries in a state of protracted crisis (Critoph and Thompson 2002; Freni et al. 2008; Kanade et al. 2015). The project is the result of a study funded by the Politecnico di Milano (Polisocial Award competition) and developed in collaboration with African Center for Renewable Energies and Sustainable Technologies (ACREST), an NGO located in Cameroon, where the solution has been tested. In fact, the most suitable area selected for the application of the system is the tropical–equatorial belt of Africa (Fig. 1).

The work is organized in three sections: the methodology, aimed at presenting the phases of development; the results, to describe the product and the validation stage; and the conclusions.

Fig. 1 Application context of the project

2 Methodology

The proposed methodology is articulated in the following different phases.

PHASE 1: analysis of the state of the art and characterization of the context.

This phase examines in depth the framework of rural communities in tropical African countries, with a specific focus on the territorial/climatic/social/economic contexts and on the availability of local materials/technology; the aim is to create, in the following phases, a product that is truly useful, efficient and, above all, economically and technically feasible on a large scale. In particular, the focus of the research was on the village of Bangang in Cameroon (80,000 inhabitants), which was chosen as a representative application context.

PHASE 2: project preparation.

The information and analyses carried out are systematized according to the following macro-activities:

- optimization of commercially available and/or re-functionalized technical components that can be used in the specific context;
- development of a management and control system to ensure the correct functioning of all components;
- definition of sizing and self-construction criteria for the thermal envelope and energy storage system,
- system design + drafting of the guidelines for the final assembly of the kit.

In this phase, the prototype of the refrigeration kit was also assembled.

PHASE 3: project experimentation and validation.

The product was first experimented in laboratory conditions at the Politecnico di Milano and then was validated in Cameroon through an assisted self-construction activity. This phase also included the dissemination of the results with the support of local NGOs.

3 Results

After the consistent analysis of the state of the art aimed also at investigating existing practices and technologies (Del Pero et al. 2015), (Phase 1), the solar refrigerator powered by PV energy was designed in detail (Phase 2). With regards to its details, the system is characterized by the use of local materials and manpower, moreover it is modular, battery-free, and can be self-constructed on-site. The following features were defined as main requirements for the development phase:

- low-cost, in order to ensure the highest possible number of users guaranteed by the reduction in the shipping and manufacturing phase;
- high reliability, in fact the system is designed to be composed of reliable and durable components which can be easily repaired or substituted by the locals;
- high hygienic performance, guaranteed by the waterproof structure of the refrigerator, by a proper drain of the condensate and by specific guidelines on food preservation (Capolongo et al. 2012);
- modular structure: the basic module of the system (with a capacity of 250 L) can be easily coupled with other modules in order to create refrigerated volumes of different sizes;
- high thermal storage, by ensuring full operation without solar power for at least 72 h (Del Pero et al. 2018);
- reduced environmental impact, in order to minimize any kind of pollution during or at the end of its working life, in the proposed system all of the components can be re-used or recycled;
- active participation of local people in the manufacturing phase, to promote the economic benefits and improve technical knowledge (Capolongo et al. 2011). In detail, the system can be assembled without the participation of skilled workers

with specific expertise or technical equipment, in fact, the import of ready-to-use products from developed countries can reduce the level of local technical knowledge.

System Description

Based on the above-listed requirements, the precise definition of the technological configuration of the kit was carried out. In particular, the PV refrigerator is composed of the following main elements: A PV module, a DC compressor with a forced-air-cooled condenser, a roll-bond evaporator, a thermally-insulated envelope made with wood and thermal insulation, an ice storage, an expansion valve, and the control system. More in detail, the PV module generates DC electrical energy which powers the small-size DC compressor. The latter activates a refrigeration cycle, with a forced-air condenser and an evaporator placed inside the volume to be refrigerated. The cooling energy is used to freeze a mass of water (thermal storage) that allows the internal temperature to be maintained acceptably low both during the night and during any period with poor irradiance (full operation without solar power equal to 2–3 days) (Fig. 2).

The DC-powered compressor with variable input voltage was chosen with the specific purpose to avoid the use of inverters and batteries: in fact, the electronic unit of the compressor allows for direct coupling with PV modules. A pre-assembled product, typically used in the nautical field, was selected; it represents a product already well-tested under severe conditions. An air-forced condenser was preferred to a static one, because it ensures a good heat exchange even under conditions of high temperature and poor ventilation.

For the PV generator, a polycrystalline silicon PV module with high efficiency was selected. It is made of 60 polycrystalline silicon cells (156 mm × 156 mm) and is designed to work in the most difficult environmental and operating conditions.

For the evaporator side, a one-side-flat roll-bond heat exchanger was identified as the best choice, in order to ensure the maximum heat transfer surface and consequently improve the heat exchange. The component is made in aluminum and is suitable to work in direct contact with water (dimensions: 585 mm × 345 mm). It is in fact directly immersed in an aluminum or plastic tank placed inside the refrigerated volume and filled with water, to act as a thermal storage system.

The main function of the control system is to manage energy uses and to maintain the desired temperature level inside the insulated case, indicating also when it is possible to introduce food/beverages to be refrigerated in the system. Considering the specific configuration, the control system was specifically developed within the research project and supplied as a component within the assembly kit.

- The envelope of the refrigerators is manufactured on-site with local materials and skills and it is composed of:
- internal layer: local wood (0.9 mm) covered by a waterproof foil;
- thermal insulation: bamboo’s core (150 mm);
- external layer: bamboo (150 mm).

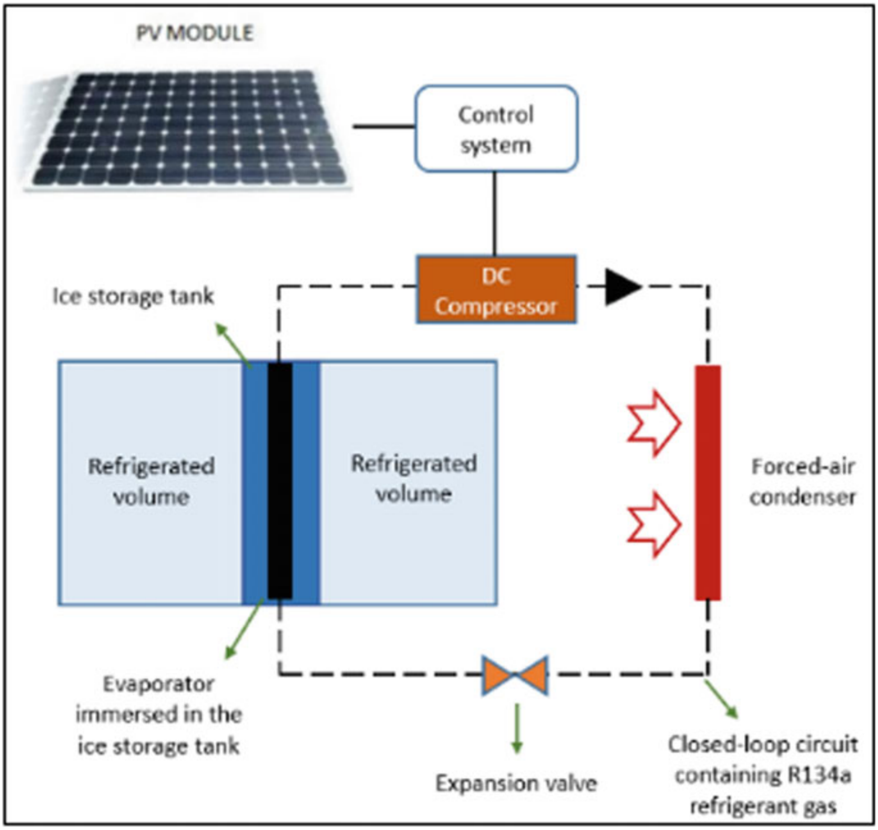

Fig. 2 System basic structure

The internal waterproof layer can be made of liquid-state plastic which can be applied like a varnish or by a more traditional plastic foil, while the bottom of the box is covered by an aluminum foil (1 mm). The box is lifted off the ground to stay dry and away from possible attacks by small animals. The upper side of the box is protected by a pressure cap and the leak-tightness is guaranteed by its own weight. According to the availability of local resources, it is possible to use other materials or construction techniques. The thermal transmittance of the described envelope is 0.3 W/m^{2}K (Fig. 3).

SPARK was first tested at the laboratory of the Politecnico di Milano in order to guarantee its efficiency and to stress its limits, resistance, and robustness (Del Pero et al. 2016).

In addition, to assess the energy performance of the system, a simplified energy model was developed. The model estimates the mean air temperature inside the refrigerator and the temperature of the water in the storage container, on the basis of the boundary conditions, assuming the initial conditions are known. The model is

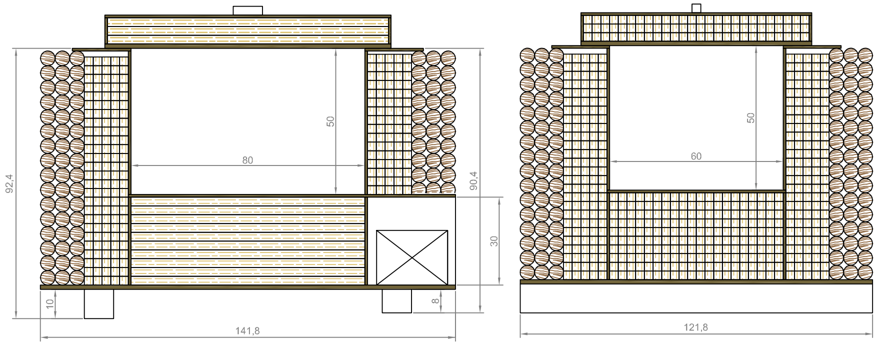

Fig. 3 Technical drawings of the system (upper: longitudinal section, below: transversal section)

based on the energy balances of the internal air and the whole refrigeration system, solved at any desired time step. The thermal inertia of the envelope is considered negligible, since it is realized with lightweight insulation materials.

By analyzing the obtained results from simulations and experimental activities, it was possible to state that:

- the average air temperature measured inside the refrigerator is always below 10 °C, even if a new thermal load is introduced in the course of the completely cloudy days, when the compressor is off. This result confirms the adequate design of the system;
- The error between the temperature calculated and that measured is, on average, lower than ±10% and can be mainly attributed to the impossibility to estimate precisely the heat transfer coefficient of the thermal load inside the refrigerator; this confirms that the developed energy model well describes the behavior of the system and can be used to assess its performances in different contexts.

The trial phase in laboratories lasted 6 months after which the validation phase was carried out within a real context. In detail, the Bangang village located in the northwestern section of Cameroon was selected for installation: there, in 2016, a 4-module (1000 L) solar refrigerator was built (Fig. 4).

As was already mentioned, local materials and man power have been used and involved in order to promote and support the internal economy. In fact, the population has broadly accepted the project and was enthusiastic about participating actively in its construction. This way, an overall cost of the materials and components needed to manufacture one module of the refrigerator (250 L) is assumed to be around 500 € (excluding VAT, shipment costs, and labor).

Such results can ensure a large penetration of the technology since it can be considered immediately affordable for food retailers and small communities.

The project is now facing the data collection phase to understand strengths and weaknesses of the proposal both under a technical point of view and under a social one, while also looking to see if the first signs of feedback from the field application are promising.

Fig. 4 View of the 4-module (1000 L) SPARK prototype built in Cameroon in 2016

4 Conclusions

In the present work, a solar refrigerator kit has been presented by describing its purpose, its technical components, and the benefits provided by its adoption in developing countries. The validation phase carried out both in laboratory conditions and on the field (Cameroon) confirmed a promising effectiveness and efficiency, and also if further improvements are possible. In addition, once again from an economic standpoint, the obtained manufacturing cost is promising, since the high use of local materials and man power helps to keep the refrigerator affordable compared to other similar market products.

Once the proposal has been fully validated and implemented, it would be possible to further test it in other geographical areas and social contexts in order to elaborate a scalability plan aimed at understanding the real replicability of SPARK and where it could be particularly effective. In fact, SPARK has a great potential to enhance food safety and, in particular, to reduce waste along the food supply chain of fish, meat, and several agricultural goods. Moreover, it could also be tested in healthcare facilities, e.g. for preserving vaccines. For now, before spreading its use across the medical field, it would be necessary and advisable to better stress the possible risks that arise from its adoption, which can be assessed in further stages of the research.

Acknowledgements The project was developed in collaboration with the African Center for Renewable Energies and Sustainable Technologies (ACREST), a non-governmental organization located in Cameroon.
The project was funded within the Polisocial Award competition.

References

Capolongo S, Battistella A, Buffoli M, Oppio A (2011) Healthy design for sustainable communities. Annali di igiene: medicina preventiva e di comunità 23(1):43–53

Capolongo S, Buffoli M, Riva MG, Tognolo C, Oppio A (2012) Hygiene and emergency: considerations and proposals for improving hygiene and health features of advanced medical post. Ann Ig 24(5):389–396

Critoph RE, Thompson K (2002) Solar energy for cooling and refrigeration. University of Warwick, Coventry, CV, UK

Del Pero C, Butera FM, Buffoli M, Piegari L, Capolongo L, Fattore M (2015) Feasibility study of a solar photovoltaic adaptable refrigeration kit for remote areas in developing countries. In: 2015 international conference on clean electrical power (ICCEP). IEEE, pp 701–708

Del Pero C, Butera F, Piegari L, Faifer M, Buffoli M, Monzani P (2016) Characterization and monitoring of a self-constructible photovoltaic-based refrigerator. Energies 9(9):749

Del Pero C, Aste N, Paksoy H, Haghighat F, Grillo S, Leonforte F (2018) Energy storage key performance indicators for building application. Sustain Cities Soc 40:54–65

Ewert MK, Bergeron III DJ (2000) Development of a battery-free solar refrigerator. Available online: https://ntrs.nasa.gov/search.jsp?R=20100042308. Accessed on 9 Sept 2016

Ewert MK, Agrella M, DeMonbrun D, Frahm J, Bergeron DJ, Berchowitz D (1998) Experimental evaluation of a solar PV refrigerator with thermoelectric, stirling and vapor compression heat pumps. In: Proceedings of solar, vol 98

Feldman D, Barbose G, Margolis R, Wiser R, Darghouth N, Goodrich A (2012) Photovoltaic (PV) pricing trends: historical, recent, and nearterm projections (No. LBNL-6019E). Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States)

Freni A, Maggio G, Vasta S, Santori G, Polonara F, Restuccia G (2008) Optimization of a solar-powered adsorptive ice-maker by a mathematical method. Sol Energy 82(11):965–976

Haver K, Harmer A, Taylor G, Latimore TK (2013) Evaluation of European Commission integrated approach of food security and nutrition in humanitarian context. European Commission Humanitarian Aid. http://ec.europa.eu/echo/files/evaluation/2013/food_security_and_nutrition.pdf

IMECHE (2014) A tank of cold: Cleantech Leapfrog to a more food secure world. Available online: https://www.imeche.org/docs/default-source/reports/a-tank-of-cold-cleantech-leapfrog-to-a-more-food-secure-world.pdf?sfvrsn=0. Accessed on 9 Sept 2016

Kanade AV, Kulkarni AV, Deshmukh DA (2015) Solar power adsorption ice maker system. Int Res J Eng Technol 2:477–486

Kim DS, Ferreira CI (2008) Solar refrigeration options—a state-of-the-art review. Int J Refrig 31(1):3–15

Metcalf SJ, Tamainot-Telto Z, Critoph RE (2011) Application of a compact sorption generator to solar refrigeration: Case study of Dakar (Senegal). Appl Therm Eng 31(14–15):2197–2204

N'Tsoukpoe KE, Yamegueu D, Bassole J (2014) Solar sorption refrigeration in Africa. Renew Sustain Energy Rev 35:318–335

Nemet GF (2006) Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy 34(17):3218–3232

Rebecchi A, Gola M, Kulkarni M, Lettieri E, Paoletti I, Capolongo S (2016) Healthcare for all in emerging countries: a preliminary investigation of facilities in Kolkata. India. Annali dell'Istituto superiore di sanita 52(1):88–97

Santori G, Santamaria S, Sapienza A, Brandani S, Freni A (2014) A stand-alone solar adsorption refrigerator for humanitarian aid. Sol Energy 100:172–178

Somerton CW, Aslam N, McPhail K, McPhee R, Rowland B, Tingwall E (2009) Vaccine refrigerator for developing nations. Michigan State University, East Lansing, MI, USA

Tassou SA, Lewis JS, Ge YT, Hadawey A, Chaer I (2010) A review of emerging technologies for food refrigeration applications. Appl Therm Eng 30(4):263–276

World Health Organization (2018) The state of food security and nutrition in the world 2018: building climate resilience for food security and nutrition. Food & Agriculture Org
Yildiz A (2016) Thermoeconomic analysis of diffusion absorption refrigeration systems. Appl Therm Eng 99:23–31