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Storing surplus solar energy in low temperature thermal storage for refrigeration applications

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ABSTRACT

In this paper a thermodynamic analysis of a concept approach based on a possible form of load management for photovoltaic energy is presented. By using the surplus electricity for driving a compression chiller it is possible to load a low temperature thermal storage. This cold storage can be used to cover the cooling demand of domestic refrigerator and freezers. A parameter study was performed to evaluate the energetic efficiency for this system in a single family home. A short economic evaluation compares the concept to a system without storage and to a system with battery storage.

1. Introduction

In the past years the increasing amount of renewable energies, like photovoltaic or wind energy, has started to cause significant fluctuations in power generation. New storage technologies and concepts are needed to compensate the difference between generation and load. The topic of this work is to present and evaluate an innovative concept to increase the energy efficiency for providing refrigeration in residential as well as in commercial cooling and freezing applications. It is based on load management for photovoltaic energy (PV), by using the surplus electricity to load a low temperature thermal storage by a vapor compression chiller.

Refrigeration and freezing applications are responsible for about 17% of the electrical energy demand in the German residential sector [1]. Theoretically there are many different processes to achieve low temperatures, for example sorption based systems like absorption chillers or chemical heat pumps, Sterling gas chillers or vapor injection chillers. Nevertheless, in domestic application the electrically driven vapor compression chiller is by far the most widely used technology for supplying cooling. The cycle process, which is installed in almost every refrigerator and freezer, works with the aim to transfer heat from a lower to a higher temperature level and thus making heat transfer to the environment possible. The required service temperature in refrigerators is hereby around 5 °C, for the freezing case on the other hand the service temperature is about −18 °C [2]. Most attempts to improve the energy efficiency of household refrigerators and freezers focus on optimizing the thermal insulation, utilization of highly efficient compressors or enhanced heat transfer in the evaporator unit and the condenser unit [3]. Furthermore, the research concerning new refrigerants is focused on increasing the coefficient of performance of the thermodynamic cycle process and decreasing the global warming potential [4,5].

Thermal energy storages are widely used in domestic applications, mostly for storing and supplying hot water. Storages for low temperature heat, e.g. cold storages on the other hand may be integrated into Ventilation and Air Conditioning systems to increase the efficiency [6]. Latent heat storage applications in buildings are usually divided into active and passive systems [7,8]. Passive storage systems are designed to minimize the use of heating and cooling systems, for example by utilizing the thermal mass of the building [9]. In refrigerators phase change materials (PCM) are used to decrease the number of start-stop cycles for the compressor and to decrease the overall temperature level for heat release to the ambience [10,11]. The energy saving potential of different cold storage systems for refrigeration and freezing applications was discussed in a previous work [12].

2. Description of the system concept

The concept described in the present work, aims at decreasing the energy cost for the cooling and freezing applications in domestic households by using excess solar power. The idea is suited for buildings with an existing photovoltaic system or at least access to photovoltaic energy. The overall system concept schematically pictured in Fig. 1 shows the important energy flows (heat and elec-

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Nomenclature

P	Power
E	Energy
G	Solar radiation
Q	Heat energy
A	Area
t	Time
T	Temperature
r	Radius
L	Length
Δh	Specific enthalpy difference
R	Heat transfer resistance

Greek letters

η	Efficiency
λ	Thermal conductivity
α	Heat convection coefficient
ρ	Density

Subscripts and superscripts

F	Freezer
R	Refrigerator
SL	Solid liquid
S	Storage
PCM	Phase change material
th.	Thermal
total	All influences
evap.	Evaporator
in	Inner radius
acc	Accumulator
chiller	Cooling machine
PV	Photovoltaic
env.	Environment
iso	Insulation
cond.	Heat conduction
conv.	Heat convection

tricity) as well as the main system components like the required chillers, cold storages and the photovoltaic system.

Due to the fluctuating solar radiation the photovoltaic system generates a fluctuating power output. Refrigerators or freezers on the other hand require a demand-driven supply of cooling, which is mostly constant throughout the day. To cover the cold energy demand suitable energy storage is needed. Instead of storing the electric power directly, the excess solar energy is used to run a cooling machine. Depending on the varying load profile of the photovoltaic module the cycle process extracts heat energy from the cold storage. This implies that at times with high solar radiation, like during summer days, the storage is loaded by the vapor compression chiller. The required cold load is constantly provided by the cold storage. Therefore, during times of low solar radiation the storage is unloaded. If the storage is entirely discharged and no photovoltaic energy is available, it is necessary to buy extra electrical power from the grid to load the storage so the cooling demand can be satisfied. In this case a direct cooling of the refrigerator respectively the freezers by the chiller was not considered because additional compression chillers would be necessary. To achieve a constant temperature of the storage a phase change material is used as storage material. Depending on the required temperature level, different storage materials can be employed. As mentioned before there are basically two cooling applications in a European household, the refrigerator and the deep freezer. Therefore, the system investigated in this article uses two storages. A first one for the refrigerator with pure water as storage medium and a second one with a eutectic water-salt mixture for the freezer. This is required to achieve the lower temperatures for the freezer. Another reason why a latent heat storage is used in this concept is the increased volumetric storage density compared to sensible heat storages [13]. This is of particular importance, if it is intended to install the storage inside the refrigerator enclosure. Furthermore, it is important to consider the fact that in domestic buildings with a photovoltaic system the generated electrical power is used to meet the current electricity demand. The amount of excess solar power that can actually be stored in the cold storage system not only depends on the photovoltaic power production but also on the electric load profile of the respective household.

Table 1
Energy demand and radiation data for the reference system.

Reference system	Value	literature
Electric Energy Demand — 4-Person SFH/kWh a^{-1}	4057	[1]
Electric Energy Demand — Refrigerator/kWh a^{-1}	115.0	[14]
Cooling Demand — Refrigerator/kWh a^{-1}	373.1	–
Electric Energy Demand — Freezer/kWh a^{-1}	172.0	[14]
Cooling Demand — Freezer/kWh a^{-1}	343.7	–
Solar Radiation Data/years	2011–2015	[15]

Most parts of the in Fig. 1 depicted energy system were modelled in Matlab. The commercial software tool Aspen Plus® was used to model the thermodynamic cycle process of the vapor compression chiller. To evaluate the energetic efficiency the presented concept was compared with a reference single family home (SFH) containing standard A+++ refrigerator and freezer, which is summarized in Table 1.

To secure a constant energy supply for cooling and freezing, it is necessary to guarantee a sufficient cooling power of the storage. As it is visible in Fig. 1, this was done by the vapor compression chiller. Whenever there is no excess photovoltaic energy and no stored energy available, the electric energy for charging the storage has to be taken from external sources. The energy saving for the overall concept with refrigerator and freezer in one year is defined in formula 1.

$$\Delta E_{year} = \frac{E_{PV,R} + E_{PV,F}}{E_{chiller,R} + E_{chiller,F}} \tag{1}$$

The energy saving ΔE_{year} is calculated by dividing the part of electric energy from the photovoltaic system used for cooling ($E_{PV,R}$, $E_{PV,F}$) and the overall energy demand for cooling refrigerator and freezer ($E_{chiller,R}$, $E_{chiller,F}$). In this context the term energy saving assumes that the energy demand is reduced by the amount of photovoltaic energy stored in the storage system. Therefore the term energy saving is a measurement for the amount of cooling demand covered by photovoltaic energy.

3. Modelling

3.1. Modelling of the photovoltaic system

The model used in this work considers the influence of the fluctuating photovoltaic power by calculating the generated electrical power directly from the solar irradiation profiles of the particular year.

$$P_{PV}(t) = PR \times \eta_{PV-Module} \times G(t) \times A \tag{2}$$

Formula 2 describes the time-depending photovoltaic power output P_{PV} as function of the performance ratio PR, the efficiency of the solar module $\eta_{PV\text{-}Module}$, the area of the installed solar module A and the global solar irradiation G. As input data for the solar irradiation G, measurement data from the DWD for the region of Nuremberg in Germany were employed [15]. Around 90% of