Increasing the Photovoltaic Self-Consumption by Integration of an Ice Storage into a Mono-Split-Air Conditioning Unit

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Abstract

Photovoltaic-driven air conditioning systems offer a lot of advantages over solar-thermal driven cooling systems. An open issue is the missing linkage between PV and AC system regarding the different temporal peaks of electricity generation and cooling demand. The paper presents investigation results of an ice storage coupled with a mono-split air-conditioning unit. Resulting average energy efficiency ratios of charging process are between 2.8 and 3.4. Maximum ice fraction was limited due to evaporator – storage geometry to 55 %. Between an ice fraction of 55 down to 5 % a cooling rate of 2 kW was achieved for discharge process.

Keywords: PV-cooling, ice storage

1. Introduction

The number of installed air-conditioning (AC) systems is rapidly increasing worldwide. About 130 million units a year are sold (Holley, 2014). The majority (about 120 million) are lower capacity units. A number of unfavorable effects are associated with the desired gain in comfort: (1) increasing electricity demand and thereby an increasing emission on greenhouse gases (indirect emissions), (2) direct greenhouse gas emissions due to usage of refrigerants with high global warming potential (GWP), (3) distinct peak loads in the grid.

To reduce the impact of solar-driven cooling technologies have been developed and applied in the last ten to fifteen years. In the past the focus was set to solar-thermal systems, due to the use of natural refrigerants (mainly water/lithium bromide) and the cost benefits of thermal collectors. The number of solar-thermal driven cooling systems increased but on low level. Only about 1000 systems are installed worldwide (Mugnier, 2015). A higher dissemination is impeded by high investment costs and complexity of those systems.

On the opposite distinct cost reductions have been achieved in the photovoltaic (PV) sector. Present electricity generation costs of PV-systems turn PV-driven cooling systems into an economic scenario. Investigations within the EvaSolK project revealed lower carbon dioxide abatement costs for PV-driven compression refrigeration systems compared to solar-thermal driven single stage refrigeration systems (Wiemken et al., 2012).

An issue of the majority of existing PV-driven cooling systems is the missing linkage of PV and AC system. Generally the PV-system is operated grid-connected, feeding in electricity during the period of high solar radiation around midday. In residential area AC-systems start operation in the late afternoon when people come home (see Figure 1, left figure). Hence, in countries with a high dissemination of rooftop PV-systems (e.g. Australia (Council, 2016)) the demand peak of AC systems is not noticeable reduced, but during midday an oversupply of electricity is fed in into the grid.

To balance the temporal divergence between electricity generation and cooling demand an integrated energy storage is required. Thermal cold storages offer a number of advantages compared to batteries: Materials are inexpensive and free of risk to the environment. Thermal losses can be regarded as far less relevant if storage is located in the air conditioned room. Using ice storages the required volume can be decreased to suitable sizes. Depending on the concept, maximum cooling capacity provided to the room can be significantly increased in case of parallel operation of storage discharge and outdoor unit.

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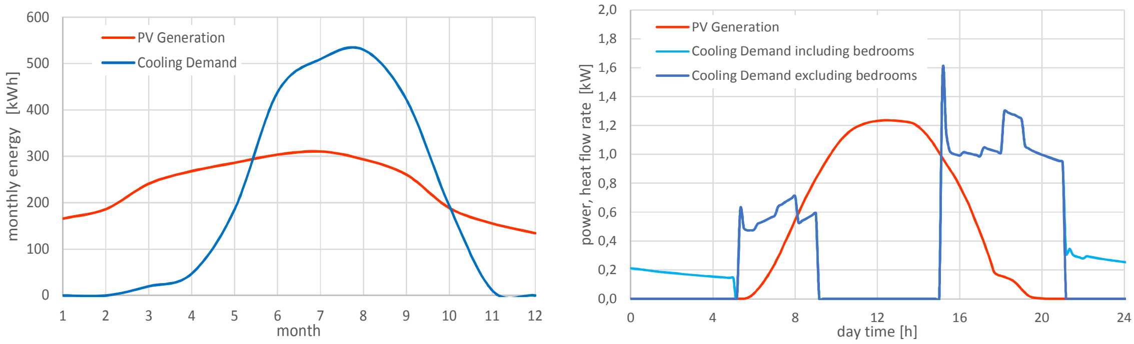


Figure 1: Seasonal (left figure) and daily (right figure) PV electricity generation and cooling demand in a residental building. source: ILK Simulation results for a residential building in Lisbon / Portugal using Modelica - BuildingsLibrary

2. System Concepts and Storage Dimensioning

System Concepts

A standard mono-split AC system consists respectively of an outdoor and an indoor installed unit, linked by a low pressure liquid and low pressure suction gas tube. From refrigeration side the outdoor unit contains compressor, condenser and electric expansion valve and the indoor unit the air-cooling evaporator.

Integration options of an ice storage into mono-split-AC-system can be characterized by

- storage position (outdoor, indoor or inside indoor unit)
- charging by direct evaporation process or via secondary cycle (brine, refrigerant)
- discharging using direct air contact (integration into indoor unit), external melting process (water cycle using the water of the ice storage) or an integrated heat exchanger (using the refrigeration or brine cycle)
- realization of direct cooling mode by usage or by bypassing the storage

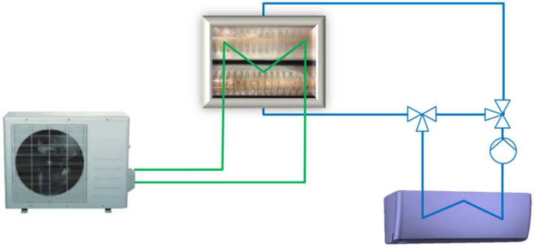
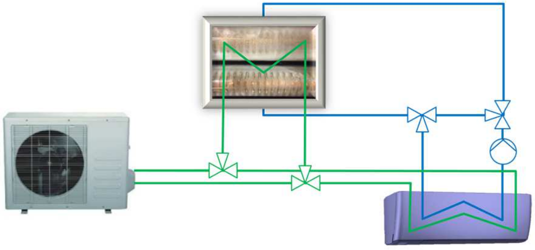
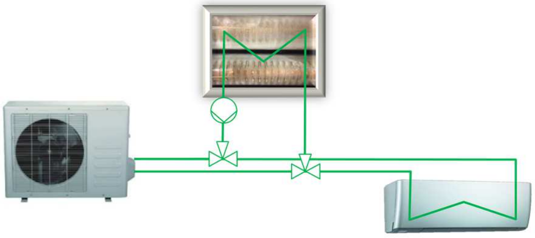
Varying the mentioned characteristics lead to a number of cycle options which even increases if valves, bypasses or pumps are taken into account to achieve a more flexible operation.

A number of boundary conditions resulting from market situation and trends, legal regulations and technical standards influences the selection process. Some main aspects are discussed below:

- Required technical solutions are not yet available on the market or in a reasonable cost ranges: Discharge process using the ice storage water by external melting process can be combined with standard air cooler units. But using water in the air cooler is not common in Mono-Split systems so far. Discharge process using the refrigeration cycle requires very low capacity refrigerant pumps with a high pressure rating. There are no standard refrigeration products including such pumps on the market. Pumps from other applications have to be adapted.
- Efficiency requirements arising from legislation and quality labels: The European product regulation requires seasonal cooling efficiency ratios (SEER) calculated according to DIN EN 14825 of > 7 and > 8.5 from 01.01.2019 for air conditioning units with a cooling capacity of less than 12 kW. The German quality label *Blauer Engel* requires an EER Cooling > 4.6. The direct cooling operation will be the minor operation mode of a mono-split-unit with integrated ice storage. Avoiding barriers in the product marketing requires an appropriate cycle design to fulfill these criteria.
- Requirements to refrigerant usage: European F-Gas Regulation requires the usage of refrigerants with a global warming potential < 750 from 01.01.2025 in small scale air-conditioning units. *Blauer Engel* requires the usage of non-halogen refrigerants. Within a progressive intensification of regulations the usage of natural refrigerants gain in importance. Almost all refrigerant with a GWP < 750 that can be applied in split systems are flammable. Therefore the refrigerant charge needs to be limited.

Based on an assessment matrix using the upper characteristics further theoretical and experimental analysis were focused on a small number of preferred options. Table 1 contains three promising options, including their advantages and drawbacks.

Table 1: Preferred integration options - system description and remarks

system description	remarks
option 1:  - direct charging using an evaporator in the ice storage - discharge using the water of the storage in an hydraulic cycle, indoor unit is replaced to a water based air cooler unit	advantages: - standard products can be applied, no refrigerant pumps required, no development of a specific indoor unit is required - cost efficient solution - simple control - ice melting direction inverse to freezing direction - air cooler surface temperature can be controlled by return flow addition in the water cycle for controlled dehumidification drawbacks: - poor cooling efficiency in direct cooling mode - thermally inertial system, especially not recommendable for heating mode
option 2:  - option 1 is extended by an parallel refrigerant cycle to the indoor unit.	advantages: - direct cooling and heating mode as efficient as in common mono-split systems - extended operation flexibility (e.g. parallel operation of direct cooling and storage discharge is possible) drawbacks: - non-standard indoor unit required - more complex control algorithms required
option 3:  - option 2 is extended by an additional refrigerant pump for discharge process, indoor unit is changed to standard split indoor unit, water cycle is removed	advantages: - standard indoor unit - no water cycle - direct cooling and heating mode as efficient as in common mono-split systems drawbacks: - refrigerant pump availability - discharge process probably less efficient - difficult dehumidification control

Storage Dimensioning

The mono-split unit including an ice storage is connected to a photovoltaic system as well as to the grid, increasing photovoltaic self-consumption and decreasing grid peak loads. The storage should allow equalizing the daily shift between solar irradiation and cooling demand.

A simple algorithm can be applied for storage size estimation

- creation of a building model and definition of surface area and orientation for photovoltaic installation
- definition of a lower radiation limit $E_{PVSurf,low}$, which will account for any cooling generation using electricity from the grid
- daily integration of cooling demand for the condition $E_{PVSurf} < E_{PVSurf,low}$

$$Q_{CD,grid,day,i} = \int_0^{24\text{h}} \dot{Q}_{CD} \quad \text{if } E_{PVSurf} < E_{PVSurf,low} \qquad \text{(eq. 1)}$$

- analysis of the class frequency distribution of $Q_{CD,grid,day,i}$ and selection of a proper storage size

For theoretical investigations a typical single family house according to the German building standard EnEV2016 was selected and modelled (Richter, 2016). The low radiation limit on the southern roof surface area was defined by $E_{PVSurf,low} = 200\ \mathrm{W/m^2}$. Simulation was done for the German site Mannheim.

In different scenarios building heat capacity was used as thermal storage. In case of sufficient solar radiation the building was cooled during absence of inhabitants to 20.0, 22.5 and 25.0 °C, respectively. Figure 2 represent the distribution of daily integrated cooling demand requiring energy from the grid for different scenarios: (1) building is only cooled in case of cooling demand (people are at home), (2 – 4) building is cooled to 25, 22.5 or 20 °C during the day in case of sufficient photovoltaic electricity generation.

Results from Figure 2 are: Cooling demand with electricity consumption from the grid occurs for 131 days a year (case 1). If building is used as thermal storage the number of days is reduced to 126, 125 and 114 (case 2 – 4). Considering only larger cooling demands the number of days decreases. Counting only days with cooling demands $Q_{CD,grid,day} > 5\ \mathrm{kWh}$ (all days below vertical blue lines), the number is reduced to 38, 24, 12 and 3 (case 1 – 4). That means integrating an ice storage with a thermal capacity of 5 kWh in case 1, the number of days with electricity consumption from the grid for cooling generation can be reduced from 131 to 38 days. For the remaining 38 days the cooling demand with electricity consumption from the grid is largely reduced. Using the building as additional thermal storage, the consumption from the grid or the cold storage capacity can be reduced further. But using the building envelope as thermal storage correlates with an increasing total cooling demand, due to additional thermal losses to ambience.

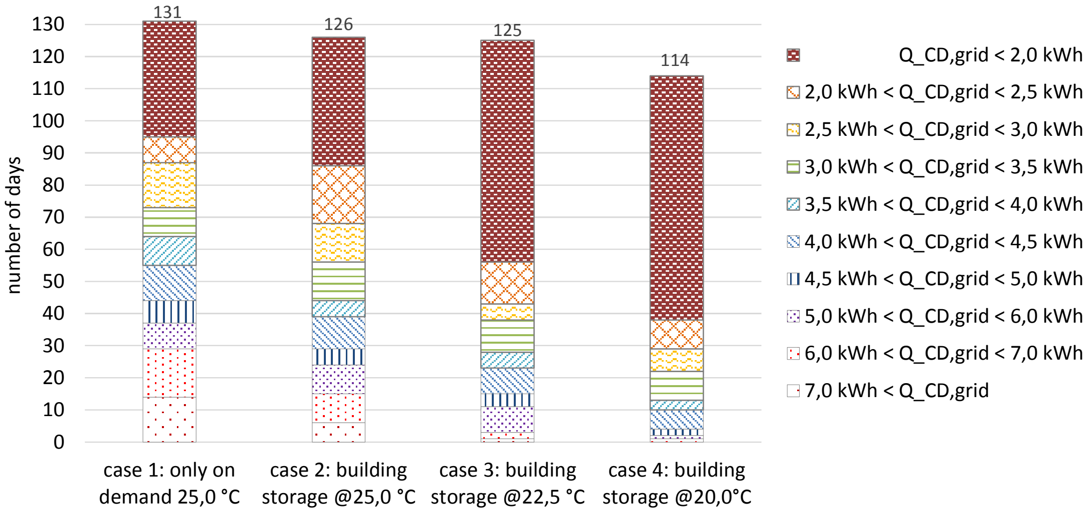


Figure 2: Distribution of daily cooling demand with energy demand from grid

3. Experimental Investigations – Integration Option 1

Motivation and experimental set up

Characteristic data for mono-split-AC-units are limited to air conditioning conditions and are only available as function of room and ambient conditions. Ice growth on evaporator during charging mode and melting during discharging mode represent non-uniform, three dimensional and dynamic processes. Furthermore, mono-split-AC-units include a number of implemented operation and safety algorithms, designed for building cooling (and heating) and dehumidification only. Hence, an evaluation of the operation of a mono-split-AC-unit with integrated ice storage requires experimental analysis.

Experimental investigations focused on

- evaluation of operation control and safety algorithm issues connected with the operation with distinctly lower evaporation pressure and non-corresponding response signals from indoor unit
- operational limits of the outdoor unit in case of distinctly lower evaporation pressures
- cooling capacity and cooling efficiency during charging process for different evaporators, different part

load factors and an increasing state of charge

- evaluation of operation in direct cooling mode (building cooling without changing the ice content within the storage)
- evaluation of influence on cooling characteristics and operational stability in case of partly charge and discharge storage cycles

For the experimental investigations, a test rig was built. The design includes options for extension to investigate a number of further integration options. A simplified piping and installation scheme to investigate option 1 is shown in Figure 3. It includes the outdoor unit (1), ice storage vessel (2), ice storage evaporator (3), hydraulic cycle for discharge mode (4), electrical water heater simulating cooling demand (5), additional manually and electronically controlled expansions valves (6) and an additional unit to directly control the compressor speed in the outdoor unit.

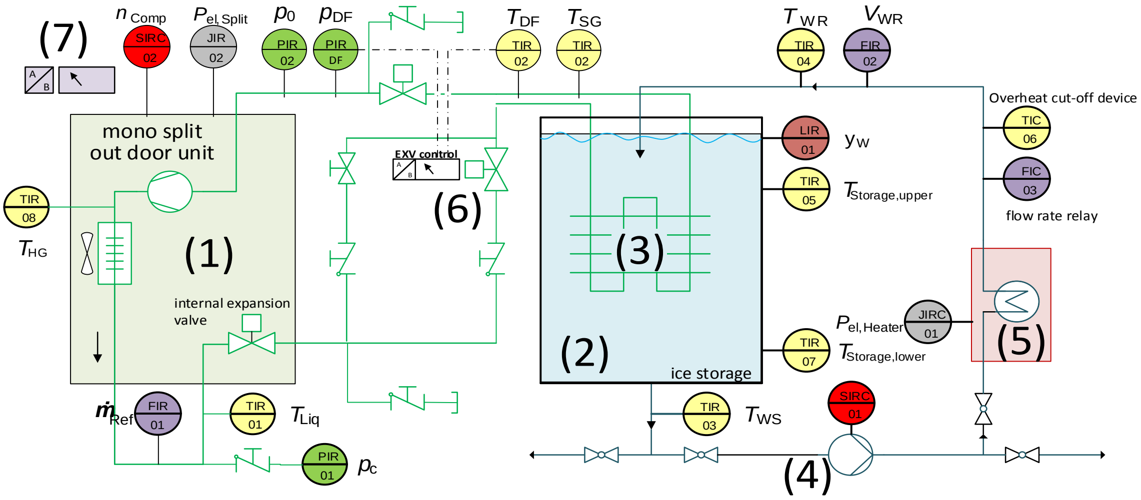


Figure 3: Piping and installation scheme of test rig to investigate the integration option 1 - direct charge process and discharge process applying external melting

Component dimensioning was carried out according to the results of a residential building simulation. A maximum cooling capacity of 2.5 kW is required. An oversized mono-split-outdoor-unit with a rated cooling capacity of 4.0 kW (Fujitsu AOYG 14LMCA) was selected to compensate the required lower evaporation temperature. The installed test rig is shown in Figure 4. Two different evaporator types have been investigated. The selection criteria focused on market availability and price. Table 2 gives relevant geometry parameters..

Table 2: Relevant geometry parameters of evaporators investigated

	tube and fin	**finned tube**
tube length	2 x 6.2 m, in series	4 x 4.95 m, in parallel
tube outside surface	0.39 m²	0.51 m²
fin water side area	2.32 m²	0.91 m²
total water side area	2.71 m²	1.42 m²
mean fin length	9.8 mm	11.1 mm
refrigerant volume	5.8 l	5.0 l

Refrigerant cycle operation is measured by high pressure liquid medium temperature in front of expansion valve inlet T_{Liq}, suction gas temperature at evaporator outlet T_{SG}, hot gas temperature as tube surface temperature at compressor outlet T_{HG}, condensing pressure p_C in front of expansion valve inlet, evaporation pressure p_0 between evaporator outlet and compressor inlet and refrigerant mass flow rate $\dot{m}_{Ref}$ in front of expansion valve inlet. Furthermore, split-unit power input $P_{el,split}$, which includes power demand for compressor / inverter, electronic control unit and fan. Compressor speed n_{Comp} and expansion valve opening is taken from split unit service tool, connected to electronic control unit.

Storage and water cycle is measured by upper and lower storage water temperature $T_{Storage,up}$ and $T_{Storage,low}$, return water temperature in front of storage inlet T_{WR}, supply water temperature behind storage outlet T_{WS} , water volume flow rate $\dot{V}_{WR}$ in front of storage inlet and storage liquid level height by an optical system y_W. Additional the power input of electrical heater $P_{el,heater}$ is measured.

If not mentioned differently, all temperatures are measured using PT100 sensor types, directly in the fluid.

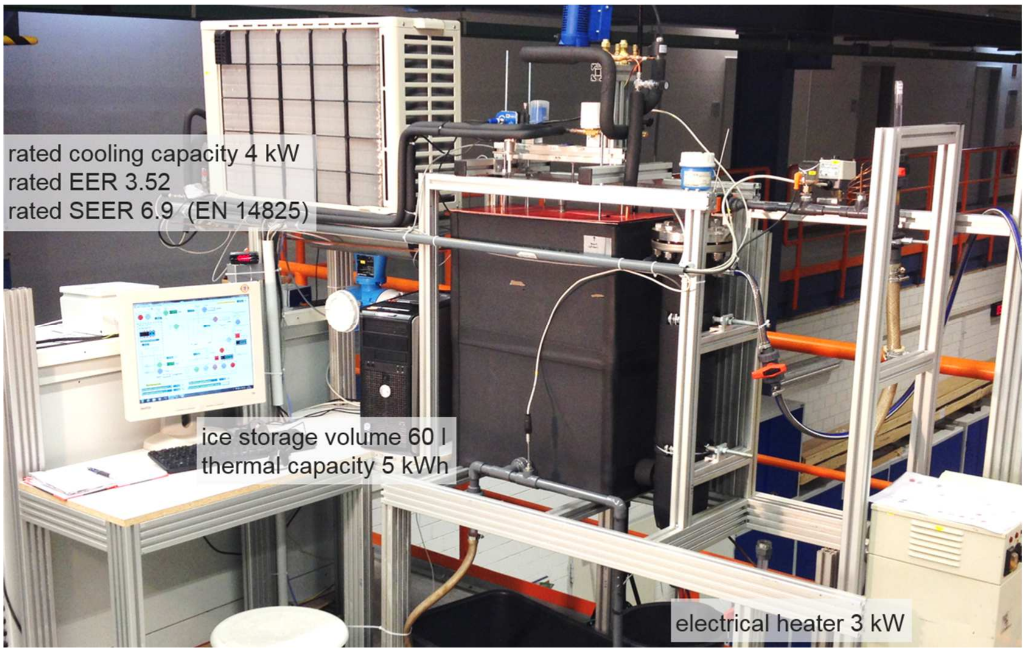


Figure 4: Photo of the test rig

Data post processing

Cooling capacity $\dot{Q}_{\mathrm{Ref,charge}}$ during charging process is calculated under the consumption of subcooled condenser outlet and superheated evaporator refrigerant state. These conditions have been proved for the whole measurement period, except a not fully liquid refrigerant state at condenser outlet for a short period after compressor start:

$$\dot{Q}_{\mathrm{Ref,charge}} = \dot{m}_{\mathrm{Ref}} \cdot \left(h_{\mathrm{gas}}(p_0,\ T_{\mathrm{SG}}) - \ h_{liq}\left(p_{\mathrm{C}}, T_{\mathrm{Liq}}\right)\right) \qquad \text{(eq. 2)}$$

Energy efficiency ratio of charging process EER_{charge} is calculated using cooling capacity and total power consumption of split unit. If convective heat transfer is enforced by pumping the water in the cycle during the sensible cooling phase, the electrical power demand of the pump has to be included.

$$EER_{\mathrm{charge}} = \dot{Q}_{\mathrm{Ref,charge}} \ / \ \left(P_{\mathrm{el,split}} + P_{\mathrm{el,pump}}\right) \qquad \text{(eq. 3)}$$

Ice fraction x_{Ice} of the storage is calculated based on the density difference between liquid and solid phase of water. A reference temperature T_{R} is defined for reference conditions of storage level height $y_{\mathrm{liq,TR}}$ and liquid water density $\varrho_{\mathrm{W,TR}}$.

$$x_{Ice} = \ \left(y/y_{\mathrm{liq,TR}} - 1\right)/\left(1 - \varrho_{\mathrm{W,TR}}/\varrho_{\mathrm{Ice}}\right) \qquad \text{(eq. 4)}$$

Discharge capacity $\dot{Q}_{\mathrm{discharge}}$ is calculated by the enthalpy difference resulting from the temperature difference between storage inlet and outlet. Required mass flow rate is calculated based on the measured volume flow rate in front of the storage inlet $\dot{V}_{WR}$ and the corresponding temperature T_{WR}.

$$\dot{Q}_{\mathrm{discharge}} = \mathrm{V}_{\mathrm{WR}} \cdot \varrho_{\mathrm{W}}(T_{WR}) \cdot \left(h_{\mathrm{W}}(T_{\mathrm{WR}}) - \ h_W(T_{\mathrm{WS}})\right) \qquad \text{(eq. 5)}$$

Overall discharge heat transfer value $G_{\text{discharge}}$ is calculated under the consumption of an ice surface temperature T_{IceSurf} of 0 °C.

$$G_{\text{discharge}} = \dot{Q}_{\text{discharge}} \cdot \ln((T_{\text{WR}} - T_{\text{IceSurf}})/(T_{\text{WS}} - T_{\text{IceSurf}})) \,/(T_{\text{WR}} - T_{\text{WS}}) \qquad \text{(eq. 6)}$$

All media properties for water and the refrigerant R410A are calculated using *CoolProp* (Bell et al., 2014).

Results – Charging Process

The charging process is investigated for both evaporator types varying the outdoor unit part load factor. Initial storage temperature is kept constant at 18 °C. Test rig is located in the main test hall of the institute. Ambient temperature depend on test hall temperature and varied in the measuring period between 20 and 25 °C. The charging process is terminated in case of ice fraction of 80 % or in case a further ice growth could lead to storage damages.

Figure 5 shows the cooling capacity versus ice fraction for both evaporator types and for varying outdoor unit part load factor (plf). Maximum achieved ice fractions are 75 % for the finned tube evaporator and 55 % for the tube and fin evaporator. The cooling capacity decreases with increasing ice fraction and with decreasing outdoor unit part load factor. The decreasing cooling capacity as function of ice fraction is more distinct for the tube and fin evaporator. The cooling capacity decreases from 0 to 50 % ice fraction to about 60 to 65 %. For the finned tube evaporator the cooling capacity decrease for the same ice fraction range to about 80 to 85 %.

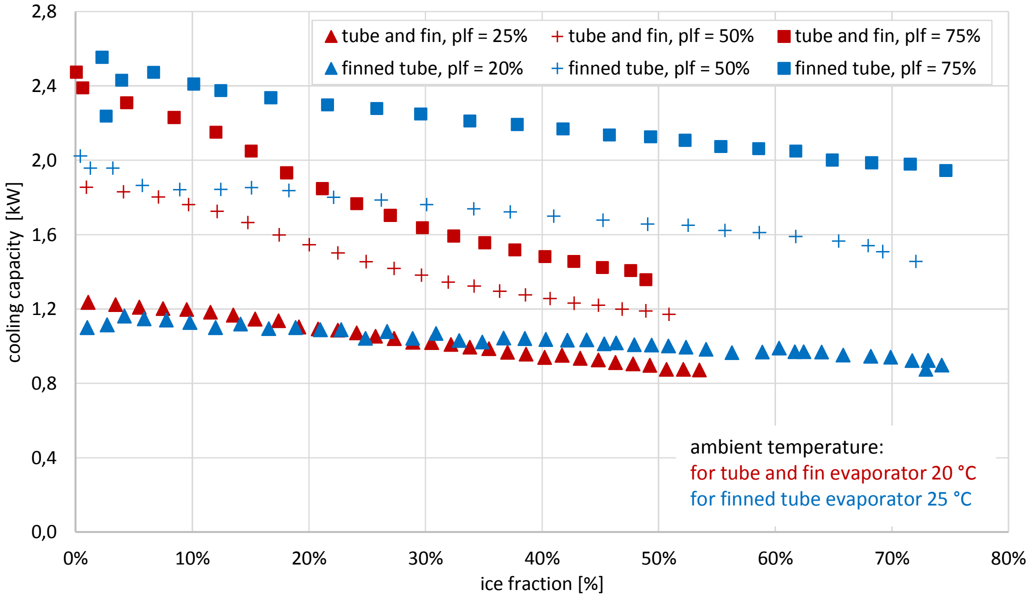


Figure 5: Ice storage charging process - cooling capacity versus ice fraction with variation of outdoor unit part load factor

Figure 6 shows the energy efficiency ratio (EER) of the charging process versus ice fraction for both evaporator types and for varying outdoor unit part load factor. The EER varies between 2 and 4.4. It decreases with increasing part load factor and increasing ice fraction. The EER for the split-unit at a part load factor of 75 %, an ambient temperature of 25 °C and an indoor temperature 25 °C can be estimated using the catalog data (Swegon, 2016) and the info sheet for SEER calculation according to eco design regulation (Fujitsu, 2015) to 6.0.

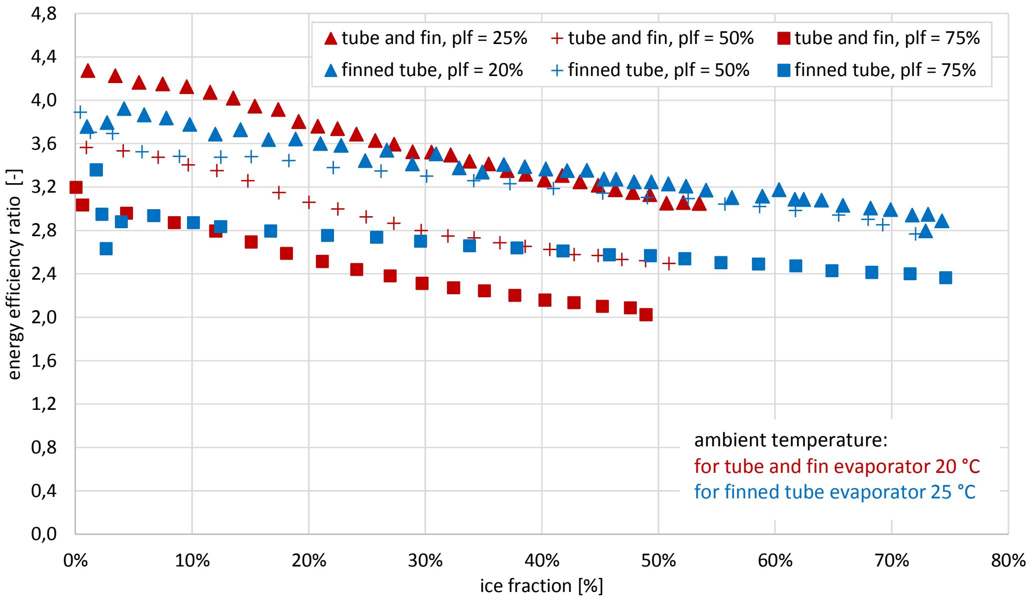


Figure 6: Ice storage charging process - energy efficiency ratio versus ice fraction with variation of outdoor unit part load factor

In Figure 7 charging time and average energy efficiency ratio between a storage temperature of 15 °C and an ice fraction of 50 % are shown as function of outdoor unit part load factor. Charging times for the finned tube evaporator are 40 to 45 minutes lower compared to the fin and tube evaporator for the same part load factors. For part load factors lower than 60 % a strong dependency between charging time and part load factor can be observed. A further increase of the part load factor result in only minor reductions of the charging time.

Average energy efficiency ratios for the defined charging range and ambient temperature of 20 and 25 °C vary between 2.4 and 3.9. Outdoor unit part load factor and average energy efficiency ratio show approximately a linear dependency.

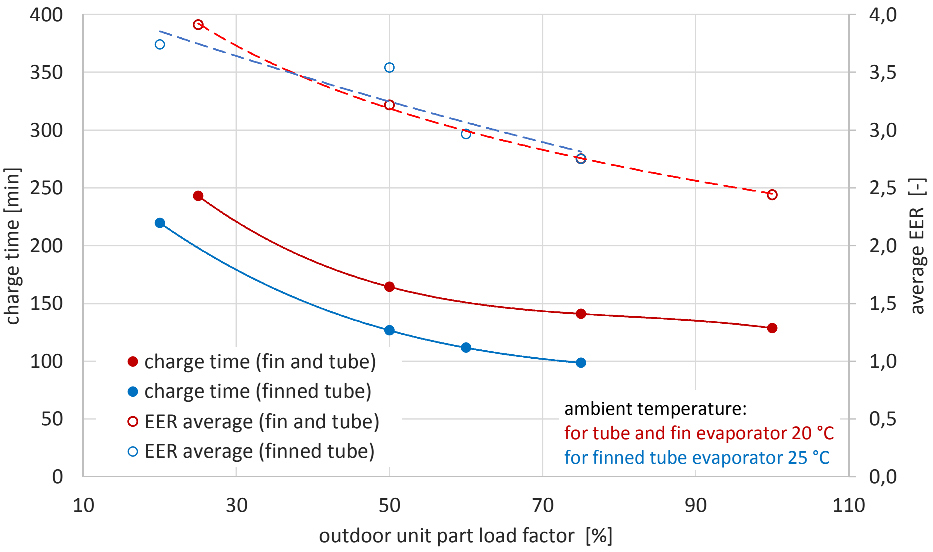


Figure 7: Charge time from 15 °C to 50 % ice fraction and average energy efficiency ratio versus outdoor unit part load factor

Results – Direct Cooling Mode

In direct cooling mode the cooling capacity supplied by the outdoor-unit is directly transferred to the water cycle. Ideally no change of storage state of charge occurs. Cooling capacity is limited by the heat transfer conditions in the storage. Heat transfer is characterized by forced convection due to the storage water flow rate. Evaporation temperature has to be limited to avoid ice growth on the surface. In this case the cooling capacity supplied by the outdoor-unit exceeds the cooling capacity transferred to the water cycle.

Figure 8 shows the maximum cooling capacity and the corresponding energy efficiency ratio depending on the storage volume flow rate for the finned tube evaporator. Maximum cooling capacity increases with increasing water flow rate, due to the improving heat transfer conditions. Energy efficiency ratio decreases with increasing cooling capacity due to the higher part load factor in the outdoor unit.

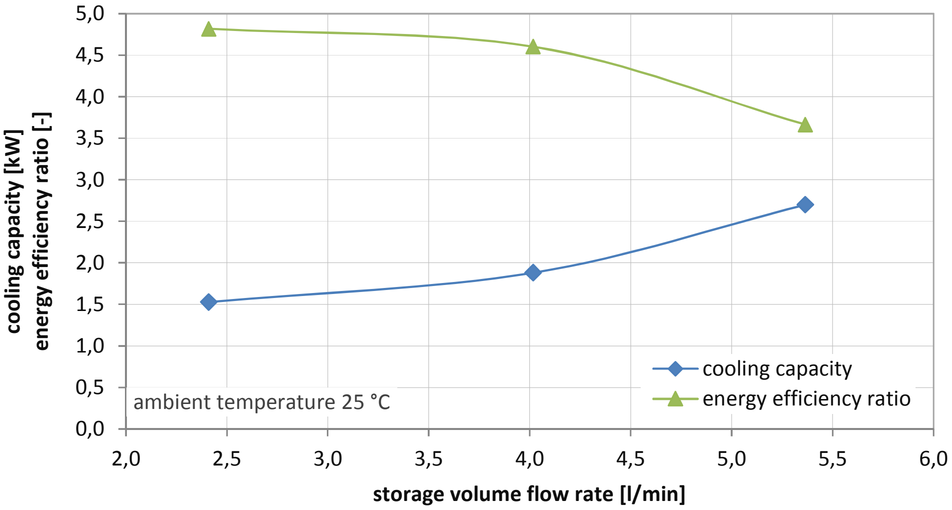


Figure 8: Maximum cooling capacity and energy efficiency ratio versus water volume flow rate for finned tube evaporator

4. Summary and Discussion

Based on daily characteristic of cooling demand and photovoltaic electricity generation in residential buildings the integration of a cold storage into the AC-system can significantly increase photovoltaic self-consumption. Integrating the ice storage into a mono-split-AC-system is a potential option. The system benefits from the high energy efficiency and low investment cost of mono-split-systems. Using an assessment matrix approach the large number of conceivable integration options is reduced to a few technically promising and economically feasible options. Three basic options were presented and discussed. Option 1, charging the storage with an evaporator, discharging the storage with a water cycle using external melting process, was experimentally investigated.

No additional modifications of the outdoor-unit were required. Only a mass flow sensor was implemented between condenser and expansion valve. A successful interaction, an efficient and stable operation of the outdoor unit with the connected storage was achieved after installation of additional refrigeration and electronic components. The required refrigerant charge had increased by about 100 g of R410A. As mono-split-units are designed to operate at evaporation temperatures above 0 °C, some protection functions had to be outwitted.

Charging process at part load factors between 20 and 75 %, ambient temperatures between 20 and 25 °C result in energy efficiency ratios between 2.0 and 4.4. In direct cooling mode in case of maximum achievable cooling capacity at given water flow rate and an ambient temperature of 25 °C energy efficiency ratios between 3.5 and 4.8 were achieved.

The efficiency during charging process is acceptable as in many cases there are not a lot of other applications for self-consumption during the day. For direct cooling mode the required efficiency ratio of 4.6 according to the German quality label *Blauer Engel* (EER = 4.6 at 27 °C room temperature and 35 °C ambient temperature) will be achieved only in low part load ranges.

Based on the obtained results, integration option 1 is a convenient integration option if cooling by storage discharge mode is the predominant operation. If direct cooling becomes more important, integration option 2 becomes more relevant.

5. Outlook

The test rig has been extended to experimentally investigate integration option 2 and 3. Other evaporation types will be included in the investigation. For an economic operation a suitable controller is required including forecast algorithms taking building behavior, weather and photovoltaic electricity generation into account.

For controller design and optimization a simulation model library have been developed in Modelica. Based on Modelica BuildingSystems models (Nytsch-Geusen et al., 2017) for buildings, weather, radiation processing and photovoltaic generators were created. Based on ThermoFluidILK and using results from experimental investigations a wide range of pure split-unit and split-units with integrated ice storages model have been implemented.

6. Acknowledgment

The investigations were carried out in the SolarSplit project (funding code 0325900A). It is managed by the project management organization Jülich (PTJ) and financially supported by German Federal Minister of Economics and Technology (BMWI) within the 6th Energy Research Program of the German Federal Government.

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