

MULTI-FUNCTIONAL FAÇADE WITH PV FOR SOLAR AUTONOMOUS COOLING APPLICATIONS

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Abstract

The objective of the Austrian research project COOLSKIN is the development, assessment and functionality approval of a façade-integrated energy system for cooling. Façade integrated photovoltaic modules directly convert the solar irradiation onto the vertical surface into electricity, which operates the compressor unit of a heat pump cycle for controlling the indoor temperature of the adjacent room. The COOLSKIN system concept addresses a) decentralization of the energy supply and b) energy autarky by the usage of solar electricity, i.e. no external energy sources are required. Methods to fulfil the project requirements are i) elaborated system simulations, ii) experimental tests with a functional model of the system and iii) field tests under real operating conditions. With this paper, the authors present the a) specification of the COOLSKIN system design and b) first results and findings of both conducted system simulation and laboratory test measurements of electric components.

Keywords: Multi-functional façade, solar autonomous cooling, façade integrated Photovoltaics

1. Introduction

In 2015 the Austrian research project COOLSKIN was launched, in which a multidisciplinary team aims to develop, assess and test different façade concepts with the technical integration of both photovoltaics (PV) and air-conditioning or cooling system into the façade construction. There is a good coincidence between the daily and/or seasonal profiles of the cooling demand in buildings and the solar irradiation hitting the surface area of the façade. Furthermore, there has been a significant cost reduction of photovoltaic modules in the last decade (Fraunhofer ISE). The COOLSKIN energy design concept focusses on technical solutions for achieving high level of energy autarky in the operational phase, i.e. there is no connection to the public grid. The COOLSKIN concept addresses as well a high level of pre-fabrication of the technical façade solution.

The COOLSKIN team formulated additional framework conditions for the development:

- Office buildings offers a greater potential for decentralized cooling system solutions compared to residential buildings. Therefore, primarily office buildings are investigated. The technical configurations of the façade do respect the boundary conditions and specifications of an office façade.
- Europe is the primary target market – Increasing demand for cooling and air-conditioning in the building sector and the climate change will lead to additional markets. All European cities are considered for being a potential application field.
- COOLSKIN concept addresses primarily technical solution for covering the cooling demand in buildings. Nevertheless, there is an emphasis on technical solutions for all-year operation, and other energy demands like heating and electricity for other appliances are going to be investigated as well.

For achieving the COOLSKIN target the research project is sub-divided into three development steps: i) evaluation of promising system configurations, ii) construction and dimensioning of a functional model and iii) implementation and energy monitoring with the help of a field test façade. This paper reports on first results and findings of the two first development steps i) and ii).

2. System design by simulation

Definition of boundary condition

As a first working step, boundary conditions were defined with regard to climatic, geometrical and utilization-related aspects. The definitions serve as the basis for the calculation of cooling and heating loads to be covered, the system considerations and simulations. An office was defined as a reference room, which was analyzed under different conditions with regard to climate and orientation. Three climatic data sets were selected as climatic boundary conditions, in order to represent a cold, medium and warm European climate. A comparison of all European capitals has shown that the cities of Helsinki (cold), Ljubljana (moderate) and Madrid (warm) are well suited to show the range of climatic conditions to be expected in Europe. For these cities a 10-year average climate was therefore created with the software Meteororm (Meteotest, 2009).

Definition of the reference room

An office with an occupancy of three persons was defined and implemented as a thermal building model in the simulation environment (TRNSYS, 2011). The room has a net floor space of 25 m² and was simulated as four separate thermal zones facing into the main compass directions. An additional space or a thermal zone was positioned in the center as shown in Figure 1 (left). The used wall constructions and U-values are summarized in Figure 1 (right). It is assumed that the rooms are positioned in an intermediate store, thus there is no heat exchange through the floor and ceiling. The same applies to the partition walls, as it is assumed that a similarly conditioned room is adjacent. A façade configuration has been defined concerning the layout and the dimensions of the glazing surfaces, as depicted in Figure 2.

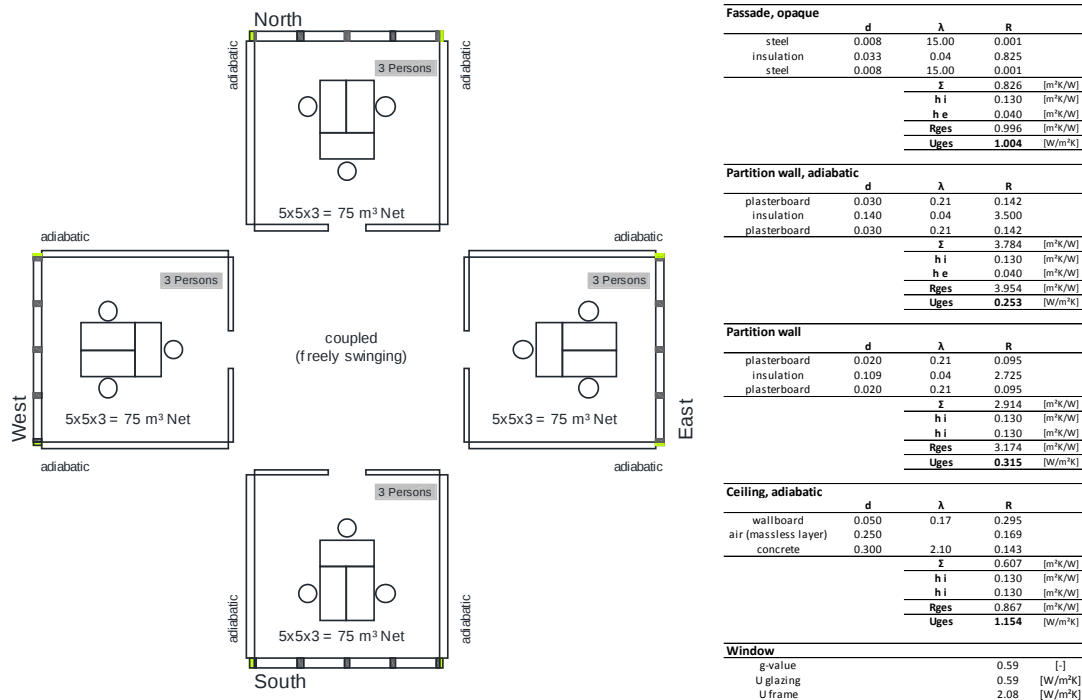


Figure 1: Reference office room geometries (left), wall construction details (right)

Determination of energy demand and generation profiles

In the simulation the thermal conditioning (heating and cooling) of the reference office room is ideally regulated. This means that the room is supplied with precisely the thermal power, which is necessary in order to maintain a room temperature above 21 °C (heating) and below 26 °C (cooling). An additional thermal zone was positioned in the center of the four virtual rooms, which is in heat exchange with the four rooms and assumed to be "free swinging", i.e. which is not thermally conditioned (Figure 1). External shading was assumed for the transparent surfaces, which is activated with a shading factor of 0.75, when the room temperature rises above 24 °C and deactivated, when it drops below 22 °C. A fresh air supply of 108 m³/h is assumed during the presence time

(working time varying between 8:00 and 18:00), with a controlled ventilation and exhaust air heat recovery (recovery rate 60 %). In the cooling case the heat recovery is deactivated, when the outside temperature is lower than the room temperature.

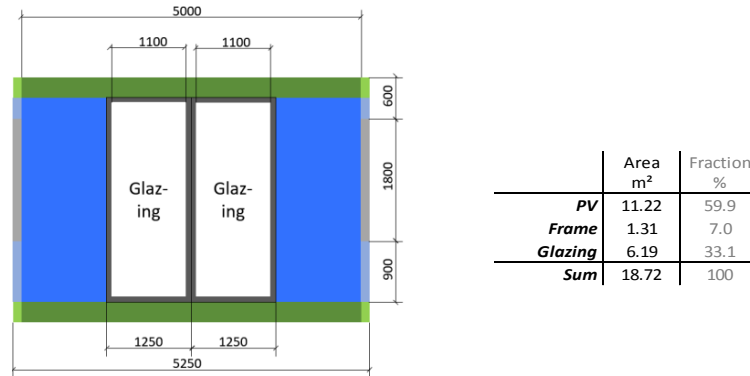


Figure 2: Façade configuration

Photovoltaics

For the simulation of the photovoltaics, the model Type 94a included in the TRNSYS library, which is based on a 4-parameter approach (TRNSYS, 2012), is used. The parameterization was carried out according to the manufacturer data of a polycrystalline PV module available on the market. It is assumed that the PV is integrated vertically into the façade with the maximum possible area for the particular façade configuration, as specified in Figure 2.

Heat demand and PV-yield

Simulations with a time step of one hour were carried out for the described configurations concerning the orientation of the room and different climates. As an example, the results on a monthly base are shown in Figure 3 for the location Ljubljana. According to these results the cooling demand coincides well with the PV yield and it can be assumed that sufficient PV electricity is available to cover the cooling demand for all four orientations, assuming a *Coefficient of Performance* (COP) of a hypothetical cooling unit of 2 to 3. With the assumed dimensioning of the PV it should also be possible to cover the heating demand of the room.

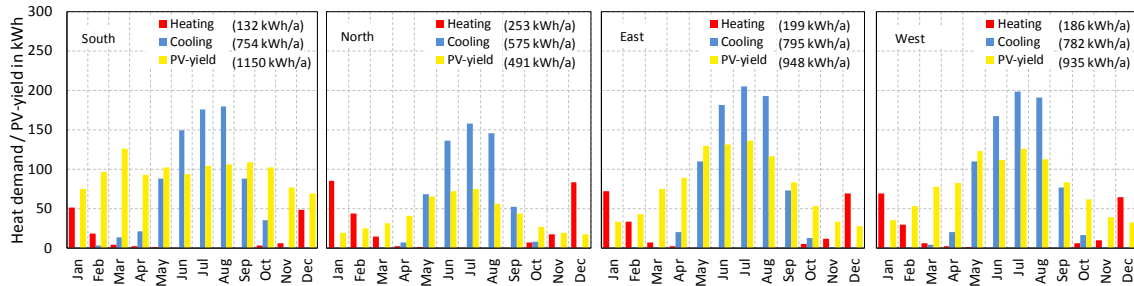


Figure 3: Simulation results: Monthly sums of heating demand, cooling demand and PV-yield for Ljubljana, yearly sums in brackets

However, for a real system it is essential, how well the demand and the PV electricity generation coincide on a smaller time scale and how much energy has to be stored, in order to be able to compensate times with an excess supply or an undersupply of electricity. For an exemplary week in July, hourly values of the cooling demand and the PV-yield are shown in Figure 4. Depending on the orientation, the peaks for both values occur at different times and with different size.

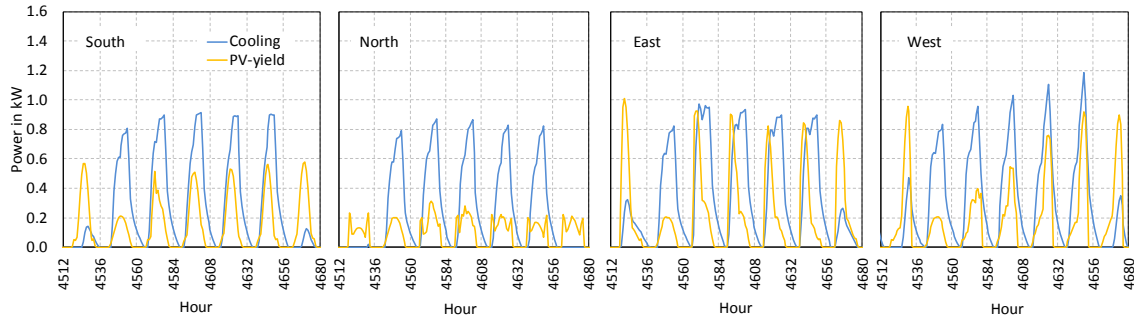


Figure 4: Simulation results: Hourly values of the cooling demand and the PV-yield for an exemplary week in July in Ljubljana

Analysis of the time shift between supply and demand and the need for energy storage

Based on the simulation results described above, an analysis of the temporal shift between supply and demand as well as a rough estimation of the necessary capacity of an energy storage was carried out. A very simple model of a compression chiller is used for the supply of the cooling demand, the cooling capacity and the electrical power consumption being assumed as a function of the room temperature and the outside temperature. In order to compare the occurrence of the power consumption and supply of cooling capacity of the chiller with the cooling load of the building and the PV-power the approach described in the following is used.

It is assumed that the chiller is capacity-controlled and that it is only running, when a cooling load occurs. Due to the temporal offset of the PV yield and the power consumption of the compressor, electrical energy has to be stored. This is shown qualitatively in Figure 5. As cooling capacity is provided at times of an occurring cooling load, the previously generated PV electricity has to be stored in an electrical storage in order to use it at later times. This is indicated by the gray surfaces in the diagram. The green surface represents the share of energy, which can be covered simultaneously and without storage.

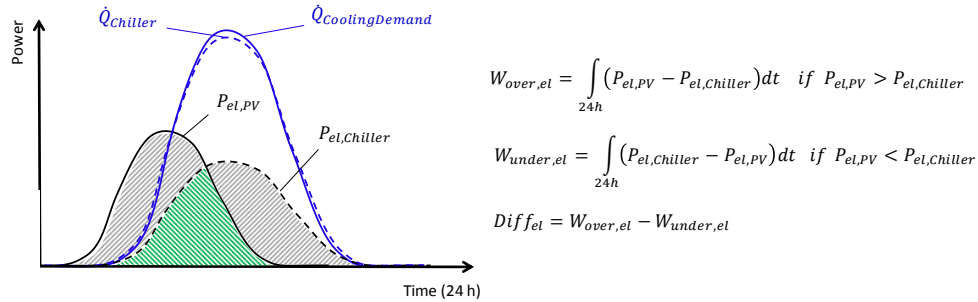


Figure 5: Qualitative daily sequences for the comparison of the electricity consumption of the chiller ($P_{el,Chiller}$) and the electricity generation of the PV ($P_{el,PV}$)

For each day of the year the electrical over- and under-supply as well as the difference between the over- and under-supply is calculated (equations in Figure 5). Figure 6 shows the results for the Ljubljana climate and the south-orientation in the form of ordered duration curves for two different sizes of the PV (5.6 m² on the left and 8.4 m² on the right). In this example, a chiller with a cooling capacity of 0.85 kW is used. For each case the right diagram shows, on how many cooling days a certain amount of over- and under-supply is exceeded.

According to these results, an under-supply of maximum 2 kWh has to be covered out of an electrical storage. Of course for this a corresponding over-supply is needed beforehand, in order to charge the storage. From the diagram on the left it can be seen that this is not the case on every day for both dimensioning's (negative $Diff_{el}$), of course with better results for the larger PV area. But it has to be mentioned, that these results are of course quite theoretical, as every single day is treated individually, i.e. it is assumed that the storage is empty at the beginning of each day. However, for the desired purpose (rough dimensioning of the storage capacity), the method is considered to be appropriate and a storage of 2 kWh should be appropriate for the considered application. For the other orientations, the results are slightly different, but the required storage capacity of 2 kWh stays the same.

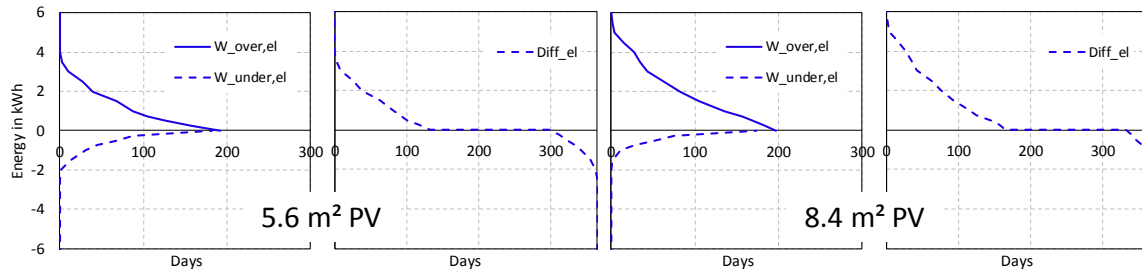


Figure 6: Duration curve of electrical over- and under-supply and daily difference between over- and undersupply for Ljubljana, south orientation for two different PV sizes (cooling capacity chiller 0.85 kW)

3. Experimental components and system tests

This chapter reports on the laboratory tests of the operational behavior of each single electric component and the compatibility test of the overall system. Main components of the setup are shown in Figure 7. Photovoltaic modules (1) generate electricity used as energy source for the cooling process. The maximum power point (MPP) tracker (2) ensures that the photovoltaic system operates in its most efficient operating point and it controls the battery charging process. A Lithium iron phosphate (LiFePO_4) battery (3) functions as an energy storage, when the current PV electricity generation for the compressor motor of the cooling system is not sufficient. The battery voltage of 25.6 V is transformed to 230 V, 50 Hz AC-Voltage by the inverter (4) in order to run the AC-Compressor motor. Due to the energetic conversation losses of MPP-Tracker (η_{MPP}), Battery (η_{Bat}) and Inverter (η_{Inv}), not more than 85 % of energy harvested by the photovoltaic modules can be used to operate the compressor motor of the cooling machine. In part load operation or extreme environmental conditions, the efficiency might be even worse. These energy losses are transformed into 100% heat, which requires an internal active cooling of these electric components. MPP-Tracker and Inverter stop working in case of temperatures higher than 60 °C.

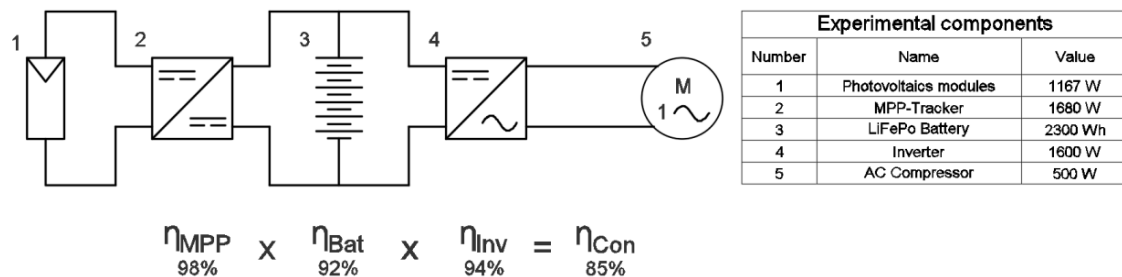


Figure 7: Block diagram of the electric circuitry with conversation efficiency.

After the successful completion of the laboratory tests, all components were assembled to enable a simple installation at the mounting site. Figure 8 shows the two test boxes at the campus of Graz University of Technology with the installed PV modules. The box on the right with the installed “black line” photovoltaic modules is used as test box where the cooling system will be installed for a long run test under real climate conditions. The box on the left side where the “digital print” photovoltaic modules are installed is the reference box.



Figure 8: Test boxes with installed aluminum frame and the photovoltaic modules, the right box is the test facility with the installed cooling system while the left box is used as reference box (Source: TU Graz)

4.1 Test photovoltaic modules

Two different glass-glass photovoltaic module types, both with mono crystalline cells, were tested: i) “black line”, with blackened bus bars and ii) “digital print”, with screen printed front glass. Four modules of each type were produced. The size of the “digital print” modules are the same as the “black line” modules. Pictures of the used modules are shown in Figure 9. Mounted at the test boxes either the “black line”- or the “digital print”- modules will be used to run the cooling machine. The COOLSKIN project aims to demonstrate that the designed façade integrated energy system operates even when architecturally appealing photovoltaic modules with relatively low efficiency are applied.

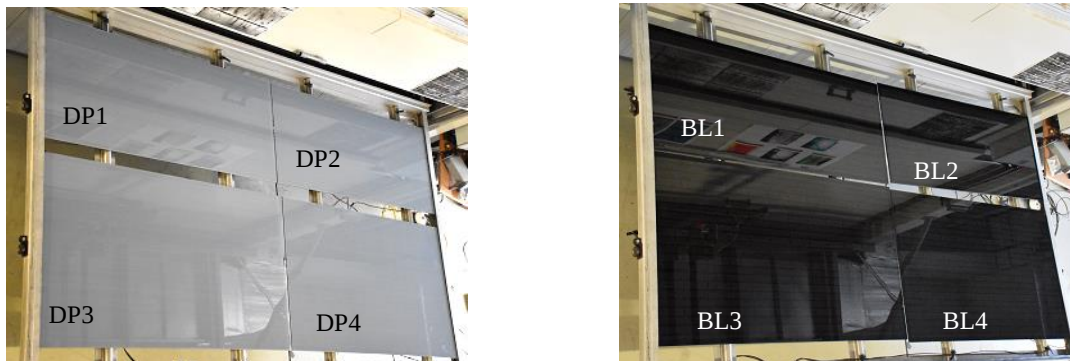


Figure 9: Photovoltaic module type “digital print” DP (left) and type “black line” BL (right) (Source: AIT)

Measurement results show that the module type “digital print” has approximately 2.6 percentage points lower efficiency than the “black line” modules. The cumulated power of the four “digital print” modules is 952 W, which is roughly 18 % lower than the cumulated power of the four “black line” modules with 1167 W. Additionally all glass-glass photovoltaic modules were checked in advance before its test box installation regarding cell cracks. Figure 10 displays an electroluminescence picture of one of the eight tested glass-glass photovoltaic modules.



Figure 10: Electroluminescence picture of glass-glass photovoltaic modules without any cell cracks.

4.2 Test batteries

Two Lithium iron phosphate (LiFePO_4) batteries are used as buffer storage between the photovoltaic system and the cooling machine. LiFePO_4 batteries are a type of lithium-ion battery, with the advantage of a higher energy density, higher power density, longer lifetime and, because of its thermal and chemical stability, improved battery safety. Cell voltage of a LiFePO_4 stays close to 3.2 V during discharge until the cell is exhausted. Due to that, the cell can deliver nearly full power until it is discharged. In one battery, four cells are connected in series for a nominal battery voltage of 12.8 V. At cell voltages beyond 3.6 V or under 2.5 V, severe damage will occur in most instances. Therefore a so-called battery management is needed, which balances the cell voltages, stops charging in case of over voltage and stops discharging in case of under voltage.

The two LiFePO_4 batteries are connected in series to a nominal Voltage of 25.6 V and a capacity of 2304 Wh when discharged with less than 90 A.

As the used charging system has no temperature compensation, the temperature behavior of a battery cell was tested in a climate chamber. A fully charged LiFePO_4 cell was cooled down to -25°C and heated up to 55°C while the cell voltage was measured.

Measurement results are shown in Figure 11. The cell voltage is nearly stable from -25°C to 45°C . In this temperature range, no temperature compensation is needed for the charging process. At temperatures beyond 45°C , cell voltage decreases and a battery management with temperature compensation would be recommended. The COOLSKIN system design contains an active cooling system in the façade mock-up to keep temperatures below 45°C .

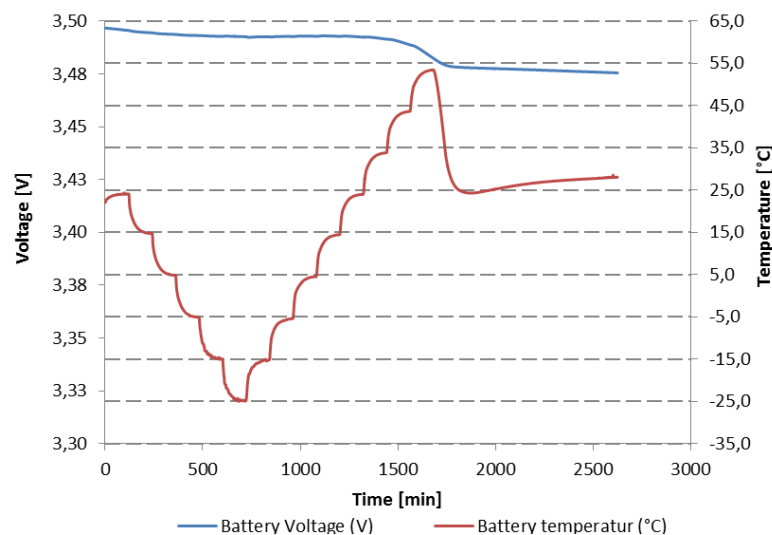


Figure 11: Voltage curve of a LiFePO_4 cell in a temperature range from -25°C to 55°C .

4.3 System test

Charge process is started in case that the battery voltage is lower than the charge cut-off voltage of 28.4 V and the available photovoltaic power is higher than the load plus conversion losses. The MPP-Tracker (i.e. charge controller) controls the charging progress according to the charge level, which is indicated by the voltage level of the battery. The controller is configured for a three-phase charging process:

1. Bulk: The controller delivers as much charge current as possible to rapidly recharge the batteries.
2. Absorption: When the battery voltage reaches the absorption voltage setting, the controller switches to constant voltage mode. When only shallow discharges occur, the absorption time is kept short in order to prevent overcharging of the battery. After a deep discharge the absorption time is automatically increased to make sure that the battery is completely recharged. Additionally, the absorption period is also ended when the charge current decreases to less than 2A.
3. Float: During this stage, float voltage is applied to the battery to maintain it in a fully charged state. When

the battery voltage drops below float voltage during at least 1 minute a new charge cycle will be triggered. An example for the three-phase charging process is shown in Figure 12.

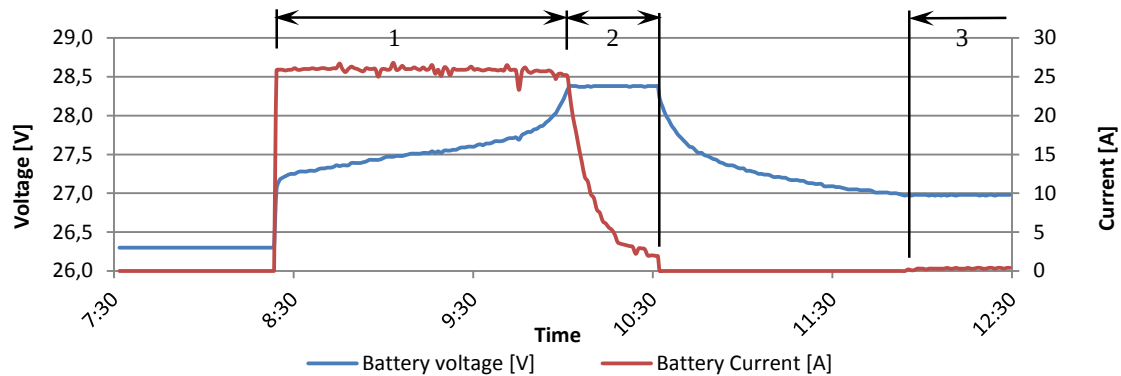


Figure 12: Example of three-phase charging process.

Discharging process starts when the load is higher than the photovoltaic yield. In this application, the main load would be the compressor of the cooling machine with 500 W. Nevertheless also, the monitoring system, the inverter and the MPP-Tracker have standby energy consumptions. In total this standby losses are in a range of 10 W to 20 W. However, a discharge protection is needed to disconnect any load before deep discharging the battery. In this application, the inverter stops before the battery voltage decreases below 23 V. In addition to that a battery protect relay cut off the battery from all loads, including standby consumers, if its voltage decrease below 22 V.

Figure 13 shows a measured battery discharge processes. The average battery voltage of 25.8 V and the average battery current of about -25 A result in an average battery power output of 640 W. The compressor motor consumes 500 W electric power, 140 W can be assigned to conversion losses and standby energy consumptions. This results in an overall efficiency of 78 %. According to the datasheet the total capacity of the battery pack is 2,304 Wh. Concerning a power output of 640 W, this would result in an operation time of 3.6 hours, which correlates to our measurement results.

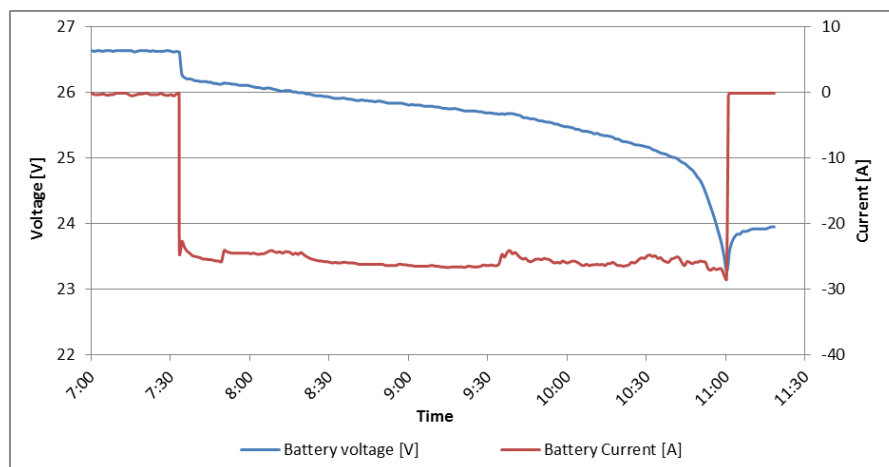


Figure 13: Battery discharge process with a 500 W compressor as load.

Once the inverter stopped because of deep battery voltage, it will not restart until the battery it is recharged to 25 V. In case that battery voltage is low and the energy consumption of the load is higher than the photovoltaic yield, the inverter will start and stop periodically. An example of this undesirable behaviour is shown in Figure 14. The energy need of the load is higher than the photovoltaic yield, which leads to a discharge of the battery and hand in hand with that to a negative battery current. Due to the discharge process, the battery voltage decreases until the inverter stops. As the major part of the load is disconnected when the inverter stops and photovoltaic yield is still available, the battery is charged. The inverter restarts if the battery voltage is higher than 25 V.

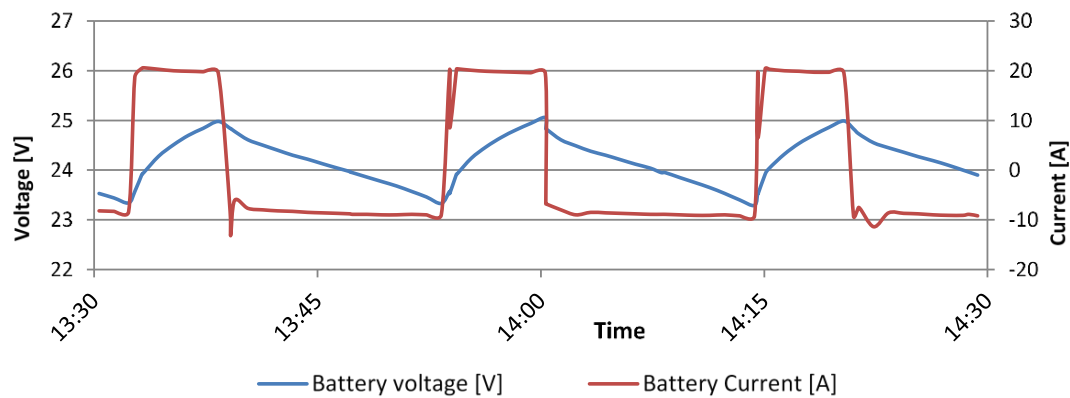


Figure 14: Start-stop behaviour of the inverter at low battery charging state and higher energy consumption than production.

A disadvantage of the used compressor type is shown in Figure 15. The relatively high starting power that may be four to eight times the nominal power could rapidly decrease the battery voltage which would strengthen the above mentioned start-stop behaviour. To avoid this effect a speed controlled compressor will be used in the field tests.

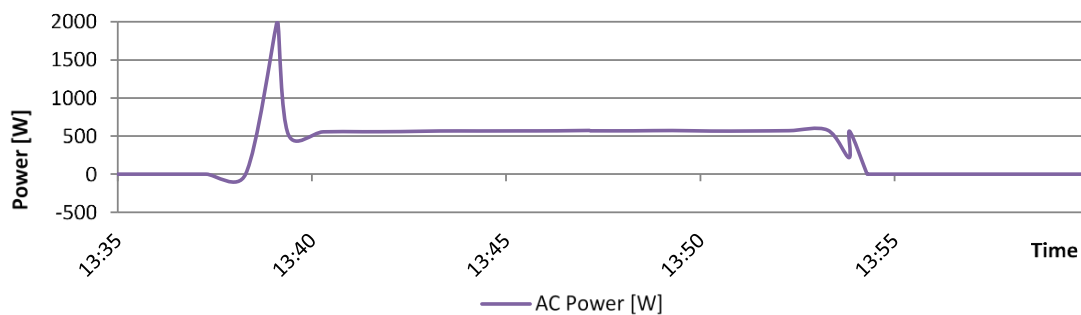


Figure 15: Start-stop behavior of the compressor.

4. Findings

Following key findings were made on the results from the simulations and laboratory tests

(a) Simulation

Based on results of the energy demand simulation some facts could be revealed which are important for the operation of a decentralized cooling system like the one of COOLKSIN. First, it was shown that under the configuration of the free-swinging coupling of the rooms the monthly cooling demand (see Figure 3) of north and south oriented rooms is only slightly different while the energy production from the PV-system is differing significantly. The corresponding analysis of the east orientation towards the west orientation shows that for them the monthly demand and production are more equal. From this, it can be concluded that a completely decentralized supply is mainly possible for south, east and west, where south might produce more than needed. If a north façade should be used for cooling excess energy from the other facades has to be provided via battery storage.

Analyzing the highly resolved data from Figure 4 one finds that for daily cycles the main result stays the same as for Figure 3. The south and north façade consume about the same amount of cooling demand, but the production at north is poor. For the east and west façade one finds that during the week under analysis the cooling demand of east and west façade differs significantly first for its daily evolution and then also for its evolution during the week. This behavior is strongly dependent on the daily and weekly distribution of sun hours. Even for a series of clear sky days the east and west would differ, as during the day the environmental temperature also raises.

An analysis with a simple worksheet approach showed that an electrical storage with a capacity of about 2 kWh should be sufficient to compensate the offset in time between the PV-yield and electricity consumption of the chiller.

(b) Experimental test in laboratory

From the experiments as shown in Figures 11-15 the main advantages and disadvantages of the system set-up can be extracted. First, the direct coupling of the battery and the load in series does not allow to bypass the battery. This might be useful in a real setting, when the battery is empty and should be loaded, there is enough solar energy to run the load, but it will take some time to recover the battery voltage above the security threshold (here this was between: switch off: 23 V, switch back on: 25 V. If load priority is a set target; the bypass is essential, in a setting similar to Figure 14.

Further it was important to test all critical settings of the systems: the lower voltage of the battery and switch off, meaning that there is not enough solar electricity but the load was powered (see again Figure 13, as it is). Very important for the real running of the system out-doors was also the operation point where the load is powered, the battery is full, but the solar production is slightly decreasing, leading to a discharging of the battery. This behavior can show if the PV-system size it at all big enough (including the losses due to the inclination for the modules in the façade).

In a worst case scenario there will be day with cooling demand but not sun irradiation to run the system. From this scenario the needed storage size could be extracted for running the cooling system only via the battery: then the storage system capacity SC is given by the time interval t where the demand is provided, the electric load demand ELD and the DoD of the battery system by: $SC = t \cdot ELD / DoD$ (Compare, 2016). For running for n days this can be expanded by $n \cdot t$.

The last important test is the test showing the “flickering” of the whole system in Figure 14. It shows that for a certain irradiation budget the system layout from battery capacity and PV-array size is too weak. From such a behavior it would follow that the PV-size or the battery size and the PV-size should be increased. In a setting where the system components can be programmed one should try to avoid this behavior, e.g. by increasing the level, where the battery is reconnected to the load (e.g. from 25 V to 26 V or even above).

(c) Experimental test set up in the façade

Technical description

The setup was built in a way that the most flexible alterations can be done between battery, PV-system and cooling equipment. The system contains of 4 subsystems of PV-arrays. The black-line is high efficient while the colored edition is reduced in its efficiency. It was taken care in the irradiation simulation of the laboratory experiments to include this behavior also. Then the lower panels and the upper panels differ in electric output power also, see table 1. The corresponding sub-arrays of upper digi-print, lower digi-print, upper black-line, lower black-line then give then a maximum electric power of 220 W, 551 W, 481 W and 685W, respectively. This power output has then to be considered also with approx. 0.65 for the daily energy yield compared to an optimal oriented PV-facility due to the façade integration. By standard setting all digital-print or all black-line modules are connected in series to MPP tracker and the battery system. The setting can be switched. Also, only the small systems or only the lower systems can be connected separately in order to simulated bad system layouts with too small PV-capacity.

Field tests planned

For the field tests several runs are planned. The most important experiments are those of continuous running with parallel data evaluation in order to identify times of system behavior reflecting cases from Figure 11 to Figure 15. These are:

- Continuous loading while load is connected
- Continuous de-charging while load is connected
- Voltage all day between 23 V and 28 V
- Flickering

After doing that, single cases can be investigated to higher extent, like altering the system configuration by the PV-panels connected to the battery. Also, the comparison of the influence of the power loss from digi-print will be done systematically

5. Outlook

Next activities in the COOLSKIN project are dedicated to a) the assembling of the outdoor test facility including cooling system and b) the examination of the long-term observation of the energy performance by a scientific monitoring till august 2018. Figure 16 shows a three-dimensional CAD model of the aluminum frame with the integrated cooling system. According to this CAD model, this system will be attached to the test box for long-term tests. The cooling system consists of five main assembly units. The first unit is the electric cycle that receives electricity from the photovoltaic modules, charges the batteries and serves as electrical source for the other units inside the cooling system. The next unit is the heat pump cycle, where energy for cooling as well as for heating is generated. The heat pump cycle is connected with an air channel by an integrated heat exchanger, which serves as condenser in cooling mode and as evaporator in heating mode. The heat pump cycle can either charge into a water cycle via a plate heat exchanger or into the room air. The water cycle is connected to the cooling and heating system of the test box (activated ceiling and/or floor). On the other hand the room air of the test box can be directly conditioned through a conventional air conditioning system (fan coil), which is also integrated in the aluminum frame.

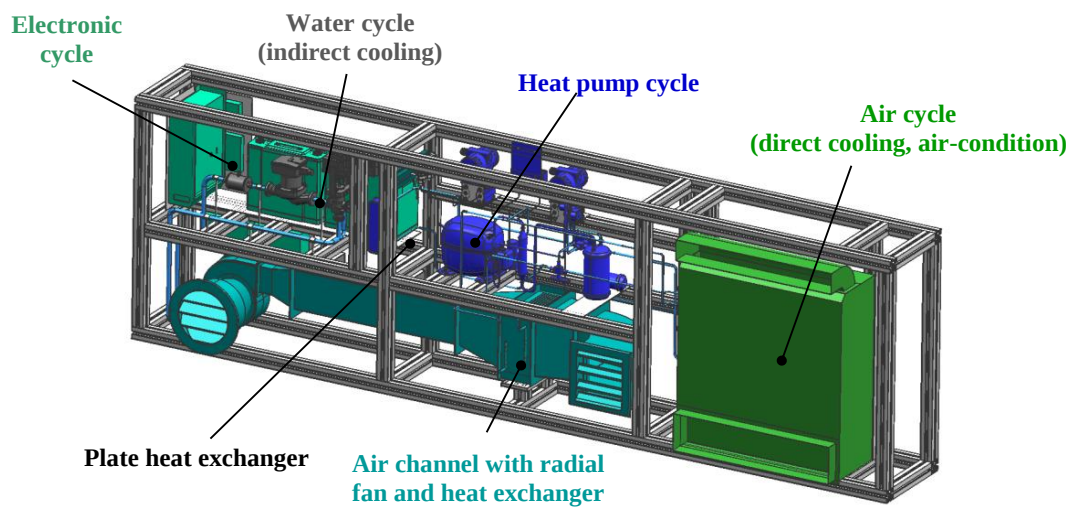


Figure 16: 3D CAD model of the aluminum frame with the integrated cooling system (Source TU Graz)

The whole system is going to be assembled and put into operation in the laboratory of the Institute of Thermal Engineering. After the system is working, it will be attached to the test box (see in Figure 8) for long-term tests under real climate conditions (covering all seasons). In this test, it will be figured out if the system is able to cover the cooling and heating demand for a comfortable indoor climate. Furthermore, the thermal behavior of the interior room can be compared with the indoor climate of the reference box (see in Figure 8). The reference box has only a floor heating system and allows no cooling. For the long run tests, the boxes' interior rooms will be simulated as an office. Among others in the test boxes are considering interior heat loads and hygienic air exchange from 8 am to 4 pm at working days.

6. Acknowledgement

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