Aalborg Universitet

CLIMA 2016 - proceedings of the 12th REHVA World Congress

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Heiselberg, P. K. (Ed.) (2016). CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 4. Aalborg: Aalborg University, Department of Civil Engineering.

Preliminary Report: Controller Prototyping and Validation for Photo-Voltaic Comfort Cooling

Mads Kronborg Agesen[#1], Arne Skou[#2], Keld Lotzfeldt Pedersen[*3]

[#]*Computer Science, Aalborg University*
Selma Lagerlöfs Vej 300, 9220 Aalborg Ø, Denmark
[1]kronborg@cs.aau.dk
[2]ask@cs.aau.dk
[*]*Energi Nord A/S*
Over Bækken 6, 9100 Aalborg, Denmark
[3]kp@energinord.dk

Abstract
Large office buildings - typically with glass fronts - often suffer from a high cooling demand during summertime. Typically, this requires a large amount of additional electricity for the cooling system. One straightforward alternative is to store cooling energy using electricity generated by solar cells, and this paper investigates, demonstrates and validates the feasibility of providing energy efficient comfort cooling with a low environmental impact, while offering flexibility to the electrical grid. Also, the possibility of reusing unmodified existing CTS systems is investigated. Finally, the possibility of providing improved comfort through intelligent supervisory control is studied. The system is comprised of a grid coupled photo-voltaic system, a heat pump, an ice bank and a cooling coil to interface the existing ventilation system in the office building.

Keywords - Photo-voltaic cooling, Energy storage, Supervisory control, Demonstrator

1. Introduction

During summer time, the amount of electrical power spent on the supply of comfort cooling is a major contribution to the peak load of most distribution grids [5]. An obvious way to reduce this contribution, is to introduce photo-voltaic supply as a supplementary energy source for the cooling equipment. In particular, this alternative is relevant when the indoor temperature of the target buildings is highly dependent on the amount of direct sun - like e.g. in office buildings with a large façade of glass.

The power supply from PV cells strongly depends of the availability of direct sun, and also the heat exchange between indoor rooms and the outside is rather slow. Therefore, there is a need to keep comfort cooling operational beyond the periods of direct sun. Hence, some kind of energy storage of excess PV power is needed.

Furthermore, the quality of existing comfort cooling systems is rather diverse. The primary reason for this is the large variety of building characteristics that makes it hard to provide an operational strategy that covers them all. So, there is a need to make experiments with alternative strategies, and an obvious idea to enable such experiments is to replace the built-in control with a control algorithm that monitors room temperatures and controls the setpoints of the comfort cooling system.

In order to pursue the above ideas, a consortium consisting of one university, a building owner and four supplier companies (grid, energy storage, solar cells, sensors) has carried out the PVCC project (Photo Voltaic Comfort Cooling) resulting in a prototype demonstrator system to be described in this paper.

The demonstration building of the project is a typical banking branch office situated in a minor Danish city. Being part of the marine west climate zone, and hence having long periods without sufficient solar energy to drive a heat pump this means that energy storage in terms of batteries will be a very expensive solution. In this demonstration project, the choice has been to store excess PV energy in an ice bank through a PV-powered heat pump. Other options exist, but in the present consortium the choice has been guided by the partner expertise.

The major problem of the existing ventilation system is the variance of the actual temperature compared to the desired setpoint. Our approach has been to develop high level Simulink® models of the different system components and then add more detailed models of the control algorithms.

The main results of the present paper are first of all a demonstration of the feasibility of the above ideas and furthermore a somewhat surprising observation that comfort cooling in the Danish climate zone may be exclusively powered by PV in combination with an energy storage. Thereby a way to substantial reduction of CO_2 footprint can be pursued through product finalization and replication.

The rest of this paper is organized as follows: Section 2 presents related work, and Section 3 describes the demonstrator setup in detail. Section 4 goes through the results in detail – including the controller algorithms, and Section 5 contains the conclusion and further work.

2. Related work

A large number of studies have been made on thermal storage of PV energy through heat pumps [1,6], and in terms of COP performance our system clearly performs well by having COP values around 3 as opposed to around 2.5 for similar cooling systems. This is also the case when comparing to those systems that are specifically aimed at supporting cooling systems [3].To the best of our knowledge, our study is the first presentation which includes an ice bank in a combination with an existing cooling system. However, commercial systems like CALMAC exist, but no details of the technology has been provided (see www.calmac.com). Also, those systems are also dimensioned to provide additional general purpose electricity. Mathematical modelleing of an ice bank as presented in [1] is possible, however not used in our study. Instead, we demonstrate a functional system using simple empirical models.

3. Demonstrator setup

The demonstrator setup is, besides control and monitoring equipment, composed by four major components that are all installed on-site for demonstration purposes: a grid coupled PV electrical power inverter, a heat pump, an ice bank and a heat exchanger for interfacing the existing building ventilation system. An overall block diagram is shown in Figure 1 below.

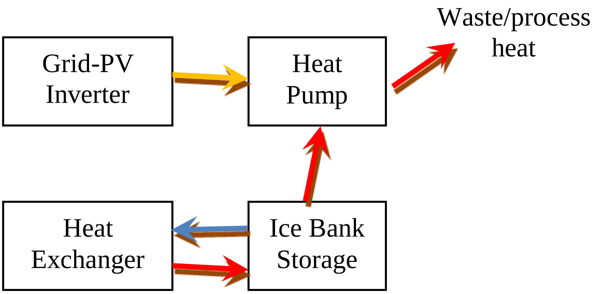


Figure 1: Overall PVCC diagram including major components and conceptual energy flow by color; electricity **orange**, heat flow **red** and cooling **blue**

As depicted in Figure 1, the cooling capacity is provided directly by the ice bank. Heat/Energy is transferred by the heat pump as waste heat to the outside. In this way, ice bank and heat exchanger provides a well-defined interface for existing building ventilation systems.

In order to validate the controller before deployment, models have been made of the major components: The inverter follows a static mapping from radiance to available power; The heat pump follows a static, non-linear mapping from compressor speed to power consumption and cooling energy; The heat exchange is part of a standard, first-order building model; in order to verify the overall system behavior, the ice-bank model is a first-order transfer function from cooling energy to ice-bank capacity – assuming temperature saturation around zero degrees during ice formation.

Two overall use cases are to be investigated using this demonstrator setup; operation as off-grid cooling system and normal grid-coupled operation. For the purpose of off-grid operation a number of concerns are brought up during development of the demonstrator. Especially sudden cloud coverage and large variations in produced electrical power is expected to stress the heat pump if not shutdown properly. Thus a great concern is to have a fast reacting control loop enforcing shutdown based on PV power production. Typical commercial available PV-inverters provide either none or only a highly averaged monitor output either as MODBUS, a REST web service or other proprietary interfaces. Using an external irradiance measurement provides a reliable input to facilitate the off-grid control scenario.

The following table provides an overview of essential sensors and actuators.

Energy Balance	**PV subsystem**	**Ice Bank**	**Heat Pump**
Electrical power from grid, P_{grid} [kW]	Phase Voltage, U_{phase} x3 [V]	Ice levels switches 1-4 [-]	Compressor load set point [%]
Consumed electrical power, P_{plant} [kW]	Phase Power, P_{phase} x3 [kW]	Ice Bank Temperature, $T_{ice\ bank}$ [°C]	
Building Cooling, $Q_{cooling}$ [kW]	Total PV Power, P_{pv} [kW]		
Heat flow through condenser, $Q_{condenser}$ [kW]	Solar Irradiance, E_e [W/m^2]		
Heat flow through evaporator, $Q_{evaporator}$ [kW]			

A. Demonstrator Architectur

Data collection for most of the sensor equipment is performed by a sensor gateway (GW) supplied by one of the consortium partners, for which an adapter for the HomePort platform was developed in [3]. HomePort is originally designed to provide a generic abstraction of various protocols in the area of home automation and thus provides the ability to interconnect devices as well as software models using adapters [2].

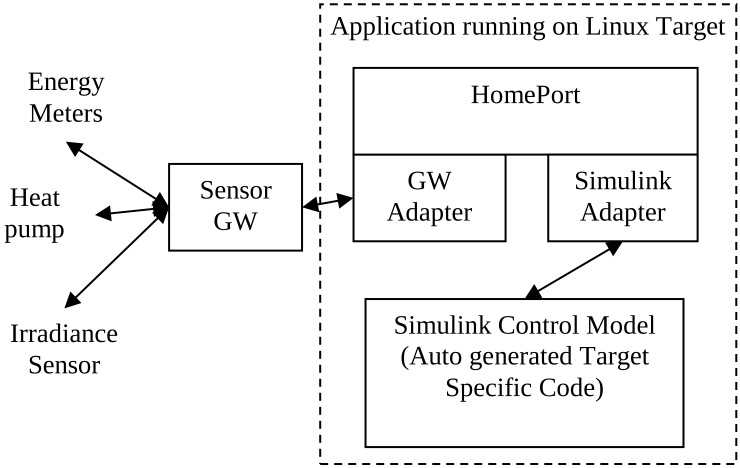


Figure 2: The HomePort architecture as reference architecture for Rappid Controller Prototyping using Simulink Coder

Utilizing existing device adapters and a Simulink Linux Target Adapter as depicted in Figure 2, we have a Linux-based architecture for model based rapid controller prototyping.

B. Model Based Controller Prototyping

For the purpose of this feasibility study a controller for the system has been developed using a model based approach using Simulink models at two levels. The initial model at an overall system level is developed in order to verify control strategies and serves the purpose of communication among project partners while modelling each major system component. The control strategies were simulated using historical irradiance data captured at the Port of Aalborg at 1 sec. intervals.

Modelling was conducted using Simulink® and implemented using Simulink Coder, which enables automatic code generation for a specific target. The code generation process from a Simulink model is depicted in Figure 3 below.

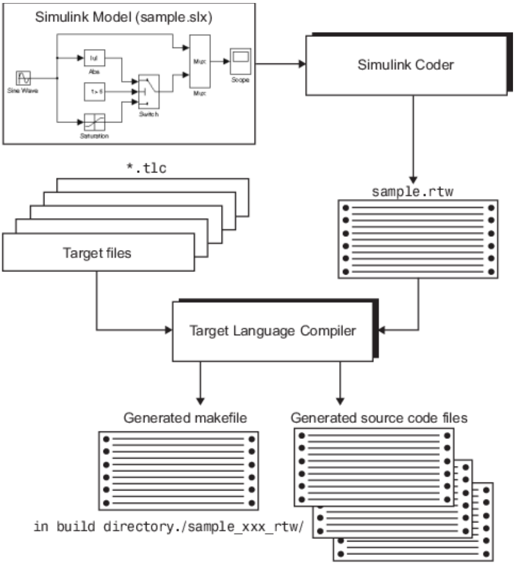


Figure 3: Simulink Code Generation Process. Simulink Coder and the Target Language compiler processes the model and target files respectively and outputs an autogenerated makefile and model implementation in target specific source code, e.g. C og C++.

For our demonstration purpose, we generate code for a slightly modified standard ERT Linux target running on a Raspberry PI, adopted to facilitate communication with the sensor GW and logging to a central database for data analysis.

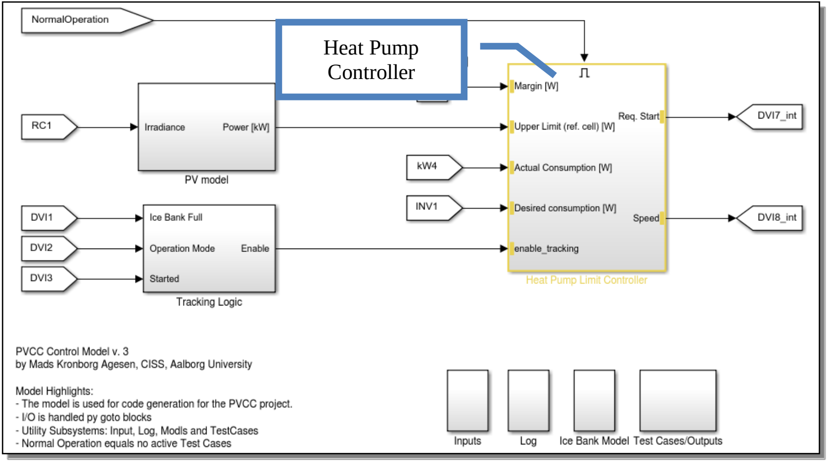
4. Results

This feasibility showed that it is possible to utilize solar energy to provide energy efficient and environmental friendly cooling of medium size office building. A demonstrator setup was deployed using a conventional PV system, a heat pump and an ice bank for cooling storage. The existing ventilation system was fitted with a conventional heat exchanger to cool the intake air. For this feasibility study, the monitoring and control system for the cooling plant was developed using an agile approach which involved model based development and code generation using Simulink®. The controller algorithm was deployed on a DIN rail mounted Linux powered Raspberry PI.

A. Control Models

The derived control model consists of utility blocks for I/O, logging etc. and the derived control algorithm implemented in Simulink®. The

Simulink® model is depicted in Figure 4, showing the model root. The control model includes a PV model to estimate PV production based on the solar irradiance sensor. This estimate is used as input for the Heat Pump Controller subsystem white-boxed in Figure 5.



PVCC Control Model v. 3
by Mads Kronborg Agesen, CISS, Aalborg University

Model Highlights:
- The model is used for code generation for the PVCC project.
- I/O is handled py goto blocks
- Utility Subsystems: Input, Log, Modls and TestCases
- Normal Operation equals no active Test Cases

Figure 4: Simulink Control Model. The model includes I/O Handling, Component Models (e.g. PV model and Ice Bank Model) and Heat Pump Controller.

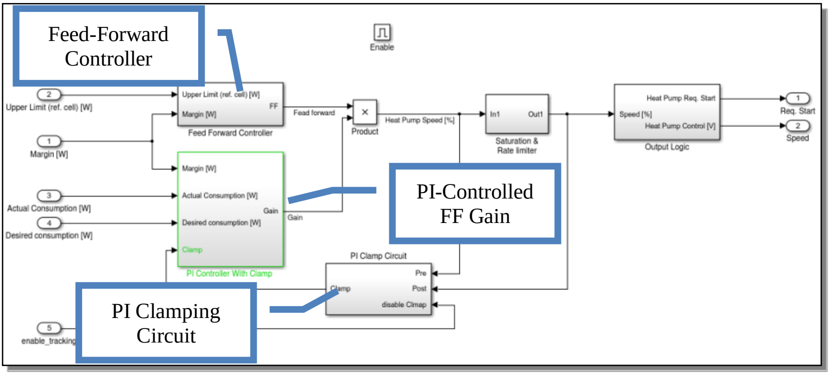


Figure 5: White Boxed Heat Pump Controller Subsystem.

The current heat pump controller is implemented for off-grid demonstration and implements a Feed-Forward control schema for fast response from irradiance measurement to controlling the heat pump. The Feed-Forward gain is controlled by a traditional PI-controller with a clamping circuit due to the discontinuous nature of rate limitation and output saturation interfering with the integral part of the PI-controller.

B. *Cooling Efficiency and Comfort*

Using high level simulation models, we showed that is feasible to balance the power produced by the PV plant and the cooling demand of the building, by stretching out the cooling capacity using an ice bank. Results of this simulation are showed in Figure 6.

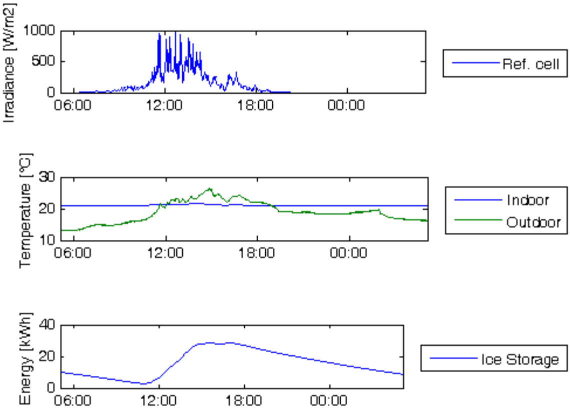


Figure 6: Simulation results using real irradiance temperature data. Top most graph shows irradiece measurement from a reference cell, middle graph shows estimated indoor and measured outdoor temperature while ice bank capacity estimate is shown in the lower graph.

From the simulation of initial controller and the developed high level models we observe that it is feasible to power a comfort cooling system entirely through PV cells.

Initial test of the plant has shown a cooling COP value of approx. 3 in load scenarios from minimum to 60 % of full load. At full load, the COP is reduced to 2.5. Specified minimum and maximum loads corresponds to the operating range of the heat pump, i.e. delivering 12-24 kw cooling to the ice bank. The results of the initial test are depicted in Figure 7.

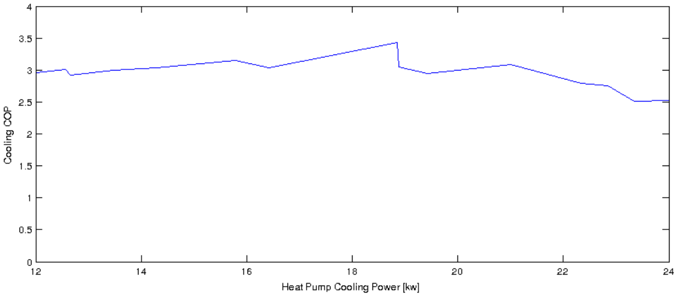


Figure 7: Results of initial COP test. Cooling COP of approx. 3 with loads in [0-60%] of normal operating range. COP decreases to 2.5 at full load.

Finally, we have demonstrated a fully operational system during component integration and test on a warm summer day. The plant was unmonitored at the time of operation but showed promising results with respect to keeping the indoor temperature fluctuations to a minimum.

5. Conclusion and future work

In this paper we have described and demonstrated a solution to the problem of reducing the amount of electrical Grid-supplied power spent on comfort cooling. The solution consists of a combination of PV cells, heat pump, ice bank, an existing cooling system and a new algorithm for controlling their interplay. The solution has been demonstrated at a branch-typical banking branch office building in Denmark. The demonstration has shown that it *is* possible to power an existing comfort cooling system entirely through PV cells through a combination of model based control and energy storage. Also, the COP value of 3 indicates a good performance of the system – albeit the ice bank seems to be over dimensioned. The results are based on a partial summer season (2015) and as part of our future work they will be further analysed throughout the full 2016 season. Also, needed capacity of the ice bank will be further analysed. Finally, the control algorithm will be extended to take weather forecasts into account. Thereby, the system is expected to be able to exchange flexibility offers with future energy markets. This may imply the need for further improvements of the control strategies developed so far.

Acknowledgment

This work has been supported in part by the Danish EUDP research programme through grant 64013-0134.

References

[1] H. Henning, "Solar assisted air conditioning of buildings – an overview," *Applied Thermal Engineering,* no. 27, pp. 1734-1749, 2007.

[2] T. Le Guilly, P. Olsen, A. P. Ravn, J. Rosenkilde and A. Skou, "HomePort: Middleware for heterogeneous home automation networks," in *IEEE, PERCOM,* San Diego, 2013.

[3] M. Albano and et.al., "The ENCOURAGE ICT architecture for heterogeneous smart grids," in *IEEE Eurocon,* Zagreb, 2013.

[4] P. Byrne, L. Fournaison, A. Delahaye, Y. Ouméziane and et.al., "A review on the coupling of cooling, desalination and solar photovoltaic systems," *Renewable and Sustainable Energy Reviews, Elsevier,* pp. 703-717, 2015.

[5] B. Paridaa, S. Iniyanb and R. Goicc, "A review of solar photovoltaic technologies," *Renewable and Sustainable Energy Reviews 15 (2011) 1625–1636,* no. 15, pp. 1625-1636, 2011.

[6] R. Kamel, A. Fung and P. Dash, "Solar systems and their integration with heat pumps: A review," *Energy and Buildings, Elsevier,* no. 87, pp. 395-412, 2015.