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Smart grid and PV driven ground heat pump as thermal battery in small buildings for optimized electricity consumption

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ABSTRACT

The purpose of this paper is to show the possible increase of self-consumption of photovoltaic (PV) electricity production for a building by intelligent use of thermal masses in the building. TRNSYS simulations were carried out for an electrically driven ground heat pump in combination with PV, thermally activated building systems and water storage (TES) in small single-family buildings. Several different control strategies adapting set-temperatures in combination with different building types and heat capacities were investigated. For a single-family house with 8900 kWh space heating and domestic hot water demand per year and a 20 m^2 PV system, the solar fraction (SF) increased from 11% for a standard configuration up to 61% with maximized use of overheating of the TES (2000 L tank) and the building mass. The running cost for the heat pump due to grid electricity consumption (0.18 EUR per kWh) decreased from 420 EUR per year – in the reference case without PV – to 373 EUR (SF = 11%) with PV, but in the standard configuration without PV self-consumption optimization, and to 69 EUR per year (SF = 61%) with PV self-consumption optimization, if the remaining PV electricity was completely sold at 0.05 EUR per kWh.

1. Introduction

Electrically driven heat pumps in combination with thermally activated building systems (TABS) and conventional hot water storages (TES) can be used as a thermal battery for electricity produced from renewable energy sources. This electricity can be produced locally by photovoltaic systems on the building, with the goal to realize a maximum of self-consumption. Based on a set of theoretical simulations, in this study it was investigated how a heat pump system in combination with a building containing differently designed TABS can act as a thermal battery when the heat pump system supplies space heating and domestic hot water to the building with different control strategies.

Several activities in research and development can be noticed, which try to increase the efficiency of buildings by load-shifting or to increase PV self-consumption using model predictive control (MPC) strategies. In his PhD thesis, De Connick (2015) presents a potential of 20–30% primary energy saving for space heating, using his own developed MPC controller. Also Pichler (2011, 2014, 2016b) made detailed theoretical and laboratory investigations using MPC controllers for several applications. In Pichler (2016a) he shows that, for a single-family house with a PV/heat-pump combination for space heating and domestic hot water preparation, the use of MPC has the potential to increase the PV self-consumption from 10% up to about 51%. However, such MPC concepts cause a relatively high effort in developing and parameterizing simplified models to be used in a controller.

Using concrete core activation as thermal storage was intensively studied in theory and practice on a demonstration single-family house by Handler (2014) in his PhD thesis. His work focused on the use of the building mass as heat storage in combination with solar thermal systems. A solar combisystem in a single-family house, with 18 m^2 collector area and 500 L water storage, achieved a solar fraction of around 45% in the simulation study. When including the concrete core activation for storing heat by overheating the building up to 24 °C (21 °C base room temperature), the solar fraction could be increased to around 51%. With a doubled collector area of 36 m^2, the solar fraction was reported to increase from 48% without concrete core activation up to 61% with concrete core activation.

Based on the results of Handler (2014), the goal of the present study is to show that similarly significant increases of PV self-consumption as those reported for very complex MPC systems with high efforts for parameterization can be achieved with advanced, but simple standard control concepts using only readily available information (like measured room, ambient and TES temperatures as well as actual PV power). Similar research on such simple control concepts is presented by Haller (2017), whose simulation studies and laboratory tests also show a potential increase in PV self-consumption by about 50%, with just using

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Nomenclature

B0W35	heat pump brine source inlet temperature 0 °C, water outlet temperature 35 °C
BUI	the building mass with the TABS is heated until a maximum room temperature of 26 °C is reached (in winter season)
CF	control functions
COP	coefficient of performance
DHW	domestic hot water
DHW + SHref	reference consumption for domestic hot water and space heating
HiL	hardware in the loop
HP	heat pump
MPC	model predictive control
OFF45	office building with 45 kWh/m^{2}a space heating consumption
PV	photovoltaic
PV20	PV area of 20 m^2
PV40	PV area of 40 m^2
REF	reference system using only electricity from the grid
RES15	single-family residential house with 15 kWh/m^{2}a space heating consumption
RES45	single-family residential house with 45 kWh/m^{2}a space heating consumption
SELF	operating exactly like the "REF" system and using PV electricity only if just by coincidence the heat pump is also in operation
SF	solar fraction
SPF	seasonal performance factor
SPF_el_grid	SPF based on grid electricity used by the compressor to cover DHW + SHref consumption
SPF_el_HP	SPF based on compressor electricity used to generate heat by the heat pump
SPF_el_use	SPF based on compressor electricity used to cover DHW + SHref consumption
T. amb	ambient temperature
T. evap in	brine source inlet temperature to heat pump
TABS	thermally activated building systems
TES COUPLING	heat pump is always heating the tank when PV electricity is available and the compressor power is controlled matching the PV power
TES	thermal energy storage
TES1000	TES volume of 1000 L
TES2000	TES volume of 2000 L
TES500	TES volume of 500 L

the TES for overheating. On the other hand, Baeten (2017) concludes in his PhD thesis, that large water storage tanks have a poor overall effect on system efficiency of heat pump systems due to increasing heat losses. Therefore, in this study, building mass activation with TABS as low-temperature heat storage is included into the system concept in addition to the TES overheating strategy. This study shall demonstrate the high potential of simple and cheap control concepts using already existing components (water storage, building mass) and therefore at almost no additional cost.

2. Setup of the simulations

Within the complete research project for the simulations, a TRNSYS model is set up with several building types, a general hydraulic concept and several control strategies.

2.1. Buildings

Simulations are done for two single-family houses (based on the IEA SHC Task44 reference building; Dott et al. (2013)) designed according to the passive-house standard (RES15) or low-energy standard (RES45) and for a small office building (OFF45) at Innsbruck climate, with different thermal active mass variations of floor or ceiling heating with different heat capacities.

The reference floor area is 140 m^2 for all buildings. The domestic hot water (DHW) consumption is 2175 kWh per year for the residential buildings and no domestic hot water consumption for the office building. As shown in Fig. 1, the RES45 is equipped with floor heating as TABS in both floors, the RES15 only has TABS in the floor between first and second floor (the heat load is much smaller than for RES45 and the potential of cost reduction shall be investigated) and OFF45 is equipped with ceiling heating/cooling as TABS in both floors (cooling from ceiling results in higher comfort than floor cooling and the floor is free to be used for infrastructure installations like IT-, electricity cabling, etc.).

2.2. Hydraulics and control concept

The heat pump is equipped with a desuperheater with variable volume flow. As shown in Fig. 2, the ground source brine heat pump (HP) is connected to a water storage (TES) directly via the desuperheater. The condenser of the HP can charge the TES or bypass the TES for direct heating of the building. Domestic hot water preparation is done with an external plate heat exchanger with controlled primary

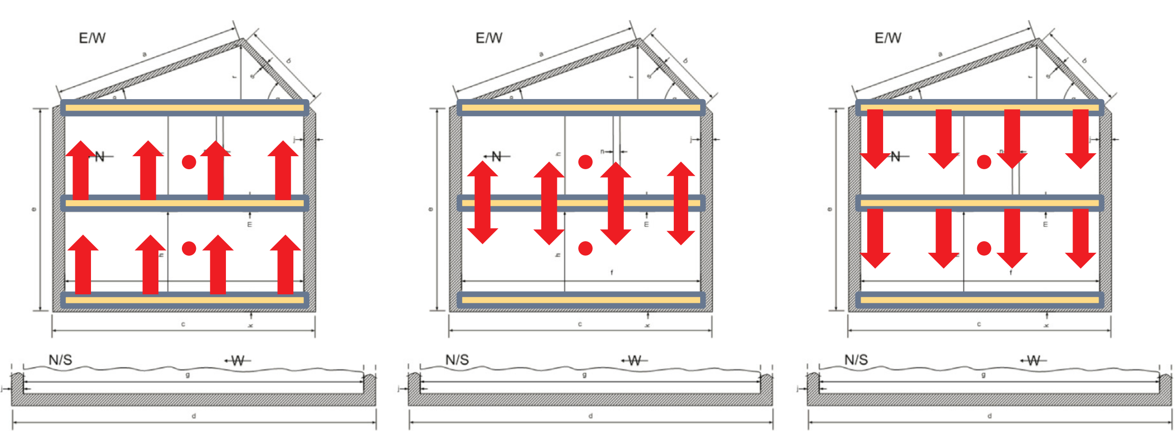

Fig. 1. TABS placed in the buildings, left: RES45, middle: RES15 and right: OFF45.

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