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Numerical study on hybrid heat pump systems in existing buildings

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ABSTRACT

Air–water heat pumps suffer from reduced thermal output and poor efficiency in cold conditions. As a consequence, they are usually vastly overdimensioned for most of the heating season. These inherent disadvantages are largely mitigated in hybrid systems, in which a second heat generator provides heating support when required. In this work, a hybrid heat pump system for existing buildings consisting of a retrofitted air–water heat pump and a gas boiler is modeled and examined in full-year dynamic numerical simulations. It is benchmarked with comparable monovalent systems for a 1970s' single family home as well as a renovated variant of the same building. The nominal thermal output of the AWHP as well as the volume of the buffer storage tank are varied in order to study their impact on system performance.

With the renovated building model, significantly higher efficiencies (SPF 3.88 vs. 3.34) and load factors (0.57 vs. 0.36) are achieved. Medium-sized heat pumps attain the highest SPF values, the reason for which is rooted in the alternative-parallel bivalent operation scheme and the dependency of the bivalence point on the heat pump characteristic. The volume of the buffer storage tank has very limited impact on system performance.

1. Introduction

1.1. Motivation

Heat pumps are a promising approach to reduce the production of greenhouse gases in the building sector by utilizing freely available ambient heat. Electrically driven air–water compression heat pumps (AWHP) in particular are suitable for retrofits thanks to their relatively low investment cost, easy installation and little required space. However, AWHP possess an unfavorable performance characteristic: in the coldest days of the year, when the heat load is at its peak, the achievable thermal outputs and efficiencies are reduced due to the low source medium temperatures and great required temperature lifts. In consequence, monovalent AWHP systems are usually designed to meet the heat load at design conditions, which renders them decisively overdimensioned for most of the year.

In contrast, hybrid heat pump systems (also called 'bivalent heat pump systems') feature a second heat generator, which can be operated whenever heat pump operation is not economically or ecologically reasonable. Moreover, it can be used to support the heat pump when its capacity is insufficient to heat the building. Therefore, a smaller and more affordable AWHP for operation in favorable conditions may be chosen.

The concept of bivalent heat pump systems can be applied to any building. This study, however, focuses on the use of hybrid heat pump systems in existing residential buildings due to the following reasons:

(i) *Relevance*: In Germany, the annual number of new constructions is as low as 0.5% of the building stock [1]. In view of rising energy prices, existing buildings are often subject to technological upgrades. Advancements in heating concepts for existing buildings are hence crucial to efficiency improvements of the building sector.
(ii) *Second heat generator*: Existing buildings already have a sufficiently powerful conventional heat generator which can be adopted in a hybrid heat pump system. The existing heat generator does not cause any additional investment or installation cost.
(iii) *Reduced sink temperatures*: Through thermal insulation upgrades, the heat load is reduced and the supply temperature can be lowered accordingly. Even with a conventional radiator heating system, sink temperatures may become low enough to operate a heat pump economically and ecologically.

Many different hybrid heat pump system configurations have been investigated, most notably solar-assisted heat pumps, an overview of which is given by Chwieduk [2]. Scarpa et al.

Abbreviations: AFUE, annual fuel utilization efficiency (boiler); AWHP, air–water heat pump; COP, coefficient of performance; DPF, daily performance factor; org, original; PE, primary energy; PF, performance factor; ren, renovated; SPF, seasonal performance factor.

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Nomenclature

Symbols

$\dot{Q}$	heat flow rate
σ	standard deviation
f_{PE}	primary energy factor
i	operating cycles
n	radiator index
P	electrical power
Q	heat
T	temperature
W	work
x	load factor

Subscripts

biv	bivalence
boi	boiler
C	Carnot
cutoff	cut-off
el	electrical
log	logarithmic
nom	nominal
re	return
sup	supply
use	useful

investigate the suitability of a solar-assisted heat pump coupled to a gas burner in a single family home, but its application is restricted to hot water generation [3]. Li et al. analyze operation strategies for community-scale systems employing multiple sewage-source heat pump and boilers [4]. Qi et al. provide an overview of the status and development of different types hybrid heat pump systems [5].

Despite the identified factors favoring the use of systems featuring a heat pump and boiler in existing residential buildings, only a limited amount of work has been dedicated to this subject. A number studies on hybrid ground-source heat pump systems for large nonresidential buildings have been presented (e.g. [6–8]). Gustafsson proposes a method to calculate the most economical size for a heat pump in a bivalent system for a residential building in Sweden. His approach, however, is based on static calculations and a constant COP, thereby disregarding dynamic effects and the heat pump characteristic [9]. A simulation study on hybrid heat pump systems for residential buildings has been presented by Huchtemann and Müller in 2010 [10]. They conclude that the dimensioning of the components should be investigated further. This aspect is addressed by the study presented in this paper. It is largely based on a 2012 Master thesis by Konstantin Klein.

Much research has been done on the control of heat pump systems. Afjei suggests a return temperature control concept for heat pump systems in residential buildings [11]. Gabathuler successfully applies this concept to a two-point controlled heat pump in an existing building with a radiator heating system and no buffer tank [12]. Both authors conclude that a return temperature controller can only work if a constant mass flow rate through the heat distribution system is ensured.

1.2. Objectives

This work aims at investigating the feasibility of retrofitted hybrid heat pump systems for existing buildings by means of dynamic numerical simulation. The studied systems consist of an electrically driven air-to-water compression heat pump and a condensing gas boiler. In particular, the influence of three parameters on system performance is studied:

(i) *Building insulation*: Two variants of a single family building model are considered: one with typical 1970s' insulation in original condition and one featuring common energetic renovation measures.
(ii) *Nominal heat pump capacity*: Thanks to the second heat generator, the nominal thermal output of the heat pump can be chosen arbitrarily. Simulations with different nominal heat pump capacities are conducted and the influence of this parameter on essential performance indicators is examined.
(iii) *Buffer tank size*: Likewise, the dependency of system performance on the size of the buffer storage tank is studied.

While heat pumps can be used for both heating and cooling, this study only considers wintertime heating, since the radiators typically found in existing buildings are unsuitable for cooling applications. Domestic hot water, user behavior and internal gains are not part of this study. Because the cost-effectiveness of a heating system depends heavily on the local energy prices and government subsidies, the focus of this work is on energy efficiency rather than economical aspects.

2. Background

2.1. Fundamentals of air–water heat pumps

Electrically driven compression heat pumps are the most common heat pump design applied in residential buildings. The efficiency of this type of heat pump is often expressed in terms of the coefficient of performance COP. European standard EN 14511-1 defines the COP as the quotient of the usable thermal output $\dot{Q}_{use}$ and the effective power consumption of the device P [13].

$$\mathrm{COP} = \frac{\dot{Q}_{use}}{P} \tag{1}$$

The COP is a function of the source and sink temperatures, because a heat pump cycle is thermodynamically a counterclockwise Carnot cycle, whose efficiency can never exceed the Carnot efficiency $\mathrm{COP_C}$

$$\mathrm{COP_C} = \frac{T_{sink}}{T_{sink} - T_{source}}. \tag{2}$$

The actual COP values achieved by modern AWHPs are usually lower than the $\mathrm{COP_C}$ by a factor of 0.3–0.5 due to nonisentropic compression, hydraulic friction and heat losses [14]. While the COP states the instantaneous efficiency, the energetic efficiency over a time period is expressed by the performance factor PF. It is the quotient of the useful heat Q_{use} provided and the electrical energy W_{el} consumed within a certain time. The performance factor referring to one year is the seasonal performance factor SPF.

Air-source heat pumps grow an ice layer from air moisture on their air-side heat exchanger as soon as the evaporator operates under 0 °C. This ice layer acts as a thermal insulator and reduces the heat exchanger performance and overall heat pump efficiency. Hence, it is melted regularly in a so-called "defrost cycle".

In bivalent systems, the heat pump is supplemented by another heat generator. A frequently used performance figure of such systems is the load factor x_{AWHP}, which designates the fraction of the total produced heat which is delivered by the air–water heat pump. In order to determine which of the heat generators is more ecological to run at a given time, their primary energy consumption can be compared by considering the primary energy factor f_{PE}, which quantifies the amount of primary energy required to produce one unit of a certain form of end energy. In this work, the primary energy factors $f_{PE,el} = 2.4$ for electricity and $f_{PE,gas} = 1.1$ for gas are used in accordance with the DIN SPEC 4701-10/A1:2012-07 technical guideline [15]. The value for electricity refers to the