Energy 118 (2017) 853–864

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Model-based flexibility assessment of a residential heat pump pool

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ARTICLE INFO

Article history:
Received 10 April 2016
Received in revised form
8 October 2016
Accepted 26 October 2016
Available online 3 November 2016

Keywords:
Flexibility
Heat pumps
Thermal storage
Pooling
Demand side management
Smart grid

ABSTRACT

This paper presents and demonstrates a methodology to explore the flexibility of a heat pump pool. Three points are in the focus of this work: First the procedure to model a pool of residential heat pump systems. Second the study of the response of a large number of heat pumps when the Smart-Grid-Ready interface is used for direct load control. Third a general assessment of flexibility of a pool of heat pump systems.

The presented pool model accounts for the diversity in space heating and domestic hot water demands, the types of heat source and heat distribution systems used and system sizing procedures. The model is validated using field test data. Flexibility is identified by sending trigger signals to a pool of 284 SG-Ready heat pumps and evaluating the response. Flexibility is characterized by maximum power, shiftable energy and regeneration time. Results show that flexibility is highly dependent on the ambient temperature and the use of an electric back-up heater. It is found that using SG-Ready-like signals offers significantly higher flexibility than just switching off heat pumps, as it is mostly done today.

1. Introduction

In the central and northern European countries, about 800,000 heat pumps were sold every year from 2010 to 2015. The number of heat pumps in the field is adding up to approximately 7.5 million [1]. In Germany, 68,400 heat pump units have been sold in 2014. In the same year the share of renewable electricity generation has increased to above 25%[1] at national level. Including a high share of renewable electricity in the power system is one of the key challenges in the energy sector today. It has been shown that heat pumps connected to thermal storages can be operated and controlled with respect to renewable electricity in the power system [2–4], variable electricity prices [5–8] or to local needs in the electric distribution grid [9–11]. Thus heat pumps can be used to provide flexibility to the power system, easing the transition towards a 100% renewable electricity and heat supply [12]. For this purpose heat pumps need to receive information about the current or expected state of the system to adapt their operation, or they could be directly controlled by an external body for the benefit of the power system. To remotely access and control heat pumps for the purposes of the power system the Smart-Grid-Ready (SG-Ready) communication interface [13] has been developed, rolled out and is now available in the majority of new heat pumps in Germany [14].

SG-Ready offers a standardised interface to the heat pump and can be used to trigger 4 different operation states. Those are “Off”,“Normal Operation”,“Recommended On”, “Forced On”. This enables an external body to access the heat pump and use the flexibility. The response of the system towards each signal is roughly specified in the SG-Ready specification and detailed implementation is left to the manufacturers. The SG-Ready specification and the described signals build the foundation for flexibility assessment in the presented work.

For system planners and operators a key question is how much flexibility is available for a given pool of heat pump units? Furthermore the reaction of a heat pump pool to a given signal at a given time of the day and year needs to be known or at least approximated to design control strategies and demand response schemes for heat pump pools and operate those in practice.

For this purpose a methodology to study and characterise the response of residential heat pump pools towards SG-Ready trigger signals is presented in this paper. Further flexibility of such a heat pump pool is evaluated and flexibility parameters are identified and motivated. The focus of the study is on residential air and ground source heat pump systems, used for the preparation of

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[1] http://strom-report.de/strom-vergleich/#stromerzeugung.

http://dx.doi.org/10.1016/j.energy.2016.10.111
0360-5442/

domestic hot water (DHW) and heat for space heating, which are connected to thermal storage tanks.

1.1. A word on flexibility

In order to guarantee safe and stable power system operation, electricity generation and demand have to match all the time. A flexible operation of the demand side in the context of demand side management (DSM) is seen as a key component for flexibility in the power system [15,16]. But what exactly is flexibility?

The Oxford Dictionary defines flexibility as "*Easily changed to suit new conditions*".[2] In a power system context flexibility is seen as the ability to modify energy generation or consumption of a system in response to external signals [17,18]. The most common parameters found in academic literature characterizing the flexibility of a system are the amount of power change, duration of the change, rate of change, response time, shifted load and maximal hours of load advance [5,16,17,19–22]. Based on a study of the response of a pool shown in Section 3 it is suggested in this work that recovery time should also be included to the list of flexibility parameters, to know when a pool is ready to be used again by the operator after being used once.

1.2. Previous work

Heat pumps (HP) connected to thermal storage offer the possibility to decouple heat production and its associated electricity demand from the heat demand of a building over a certain time period. This offers the possibility to adjust operation to external needs to some extent. In recent years, a substantial amount of work on the operation of heat pump systems in a smart grid context has been presented, highlighting the possibilities to use individual heat pumps or heat pump pools for different applications and on different levels of system boundaries.

On a national aggregation level [19], shows the influence of heat pump flexibility on demand-side management for Germany in three use cases: reduction of variable costs, CO_2 savings, positive and negative balancing power. Also on national level, in Ref. [21] air source heat pumps covering 10% of the national heat load of Germany are used to smooth different load signals (PV, wind and residual load). An optimum operation schedule was calculated by solving a convex quadratic optimization problem. Both studies show how the power system can potentially benefit from flexible heat pump operation and highlight the seasonal characteristics of load shifting availability of heat pumps. The studies focus on a specific use case and assume optimal or near optimal heat pump operation.

On less aggregated level, studies on heat pump pools focus on controls, prediction and system identification methods for a pool of heat pumps [23–25]. In Ref. [26] a virtual power plant (VPP) consisting of 150 residential heat pumps is operated towards peak-shaving and system balancing. For the given use case average flexible power per month in kW and the share of heat pumps responding to the system balancing signals are used to describe flexibility [27]. evaluated flexibility of a heat pump pool by simulating the power and voltage at the distribution transformer [5]. analysed the load-shifting of heat pump systems coupled to a thermal storage. A pool of 160 heat pumps in a Dutch neighbourhood in the year 2020 is used for the study. An external signal, switching off the heat pumps, is used to influence heat pump operation. Flexibility is defined as the load shift in kWh per day.

[2] http://www.oxforddictionaries.com/definition/english/flexibility, accessed on 12th February 2016.

On individual household level, studies put the focus on system design, efficiency and control questions. Predictive and none predictive control strategies have been used to align heat pump operation with on-site generated PV [28–32], variable electricity prices [8,33,34] or a demand side management (DSM) signal from the power system [2].

1.3. Presented work

The previous studies provide valuable proof that heat pumps can be used for load shifting, highlighting the importance of the topic. Interesting control approaches, mostly based on optimisation, are demonstrated on the level of individual heat pumps and only few on the level of a heat pump portfolio.

However there are points that have not yet been sufficiently addressed in the discussion, which are treated in this paper:

- Most papers focus either on the control of individual heat pumps or on the general potential of heat pumps on a national level. Exploring the characteristics of heat pump pools has not been done sufficiently and is part of this work.
- For heat pump pools used in simulation the variety in system characteristics, efficiency and sizing is often neglected. This paper presents a model, which combines stochastic bottom-up energy demand models with generic heating system models and a randomisation approach for system sizing, efficiency and control set-points.
- Flexibility is mostly analysed for a specific use case. This is generally a good idea but information about the full potential of a technology could be lost by doing so. This is why in this paper a technical analyses, that explores the flexibility of heat pump pools in a generalised way is presented. This method can be applied for a specific use case by using the corresponding trigger signals.
- Most studies use optimisation or sophisticated algorithms for the controls of heat pumps and pools. By doing so often the basic characteristics of a pool and its general response are hard to identify or generally neglected. Further the possibilities and limitations to pool operation based on simple signals like SG-Ready are not sufficiently explored. This is why in this work the focus is on simple trigger signals and the study of the response.
- Although the SG-Ready signal is simple, provides more options than only an "Off" signal, and is currently market available it has not been studied for a pool of heat pumps. This study highlights the possibilities that are offered by this type of signal compared to "Off" signals that are mostly used in practical applications today.

This paper provides a methodology to model a pool of residential heat pumps, used for space heating and domestic hot water (DHW), and evaluate its flexibility. A pool is modelled as an ensemble of single building unit models, which are sized and operated individually. The approach to determine the flexibility of a given heat pump pool is shown in Fig. 1.

In Section 2.1 a generic model for single buildings units is presented. The single building models are extended in Section 2.3 to model a heat pump pool. This is done by randomizing building thermal loads, hydronic system characteristics, system sizing and heat pump characteristics. In Section 3.2 an exemplary heat pump pool is defined and used to identify the flexibility of heat pump pools. SG-Ready-like trigger signals as presented in Section 3.1 are applied to the pool and flexibility is evaluated. The findings presented and discussed in Section 3.4 highlight effects such as temperature dependency of flexibility and characteristic response.