The Role of Heat Pumps in Future Urban Energy Systems

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In one of our recently published scientific articles we provide a holistic view on the role of heat pumps in the context of smart grids. Three main categories of heat pump applications in a smart grid context have been identified: stable and economic operation of power grids, the integration of renewable energy sources, and operation under variable electricity prices. In all these categories, heat pumps - when controlled in smart way - can help easing the transition to a decentralized energy system accompanied by a higher share of renewable energy sources and more importantly, empowerment of the future "prosumers". In this short article, we provide a brief summary of the role of heat pumps in future urban energy systems, breaking it down to four different boundary levels. We also introduce the concept of Integrated Design, Dimensioning and Control as a part of a holistic approach towards the future energy systems.

Introduction

We are moving towards a new energy paradigm characterized by:

i. a growing penetration of intermittent and decentralised renewable energy sources,
ii. emergence of millions of households acting as local producers and consumers (prosumers) of the energy, and
iii. increased electrification in all energy sectors, from transport to building heating and cooling.

These changes challenge the traditional power system which is designed for a small number of large power plants, operated to supply the demand at all times. A growing penetration of renewable energy sources such as solar and wind with their nature of intermittency and high fluctuation makes stable and profitable operation of the electric power system a challenging task. To accomplish this task, the energy infrastructure needs to be upgraded to accommodate higher flexibility, on both the supply and the demand side. Short term energy storage in the form of batteries or thermal-electric systems connected to thermal storage can provide some of the needed flexibility.

This paper deals with the role of heat pumps in the future energy system and highlights how heat pumps can contribute to this process towards net primary

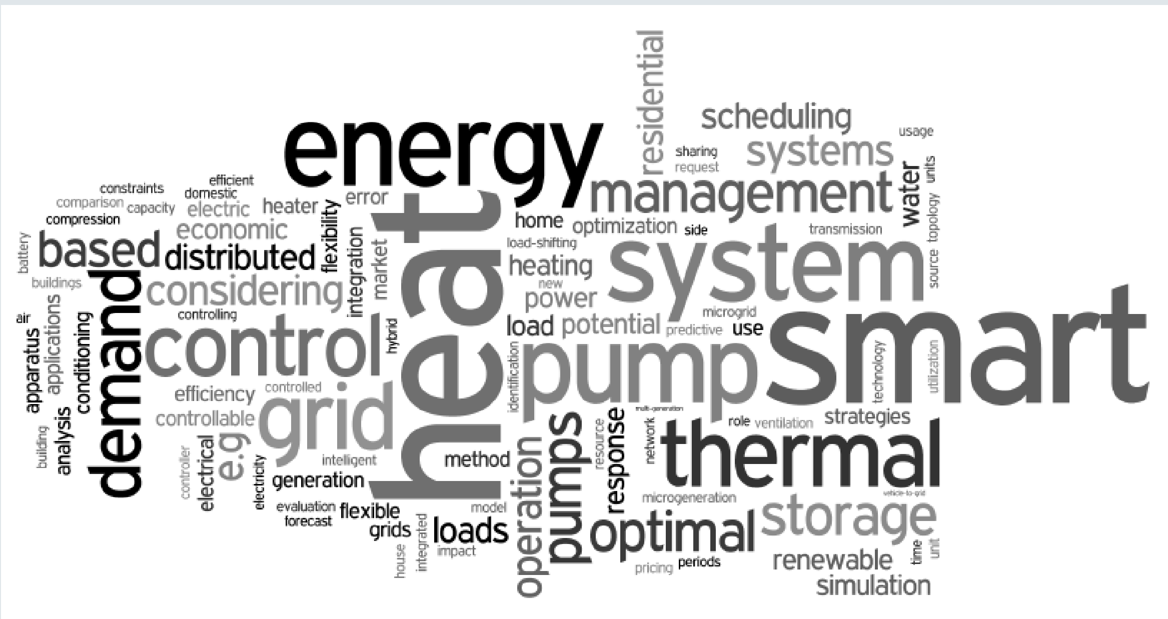

Figure 1. Wordcloud of the 100 most frequent words in paper titles when querying for "heat pump", "smart grid" at Reuters Web of Science.

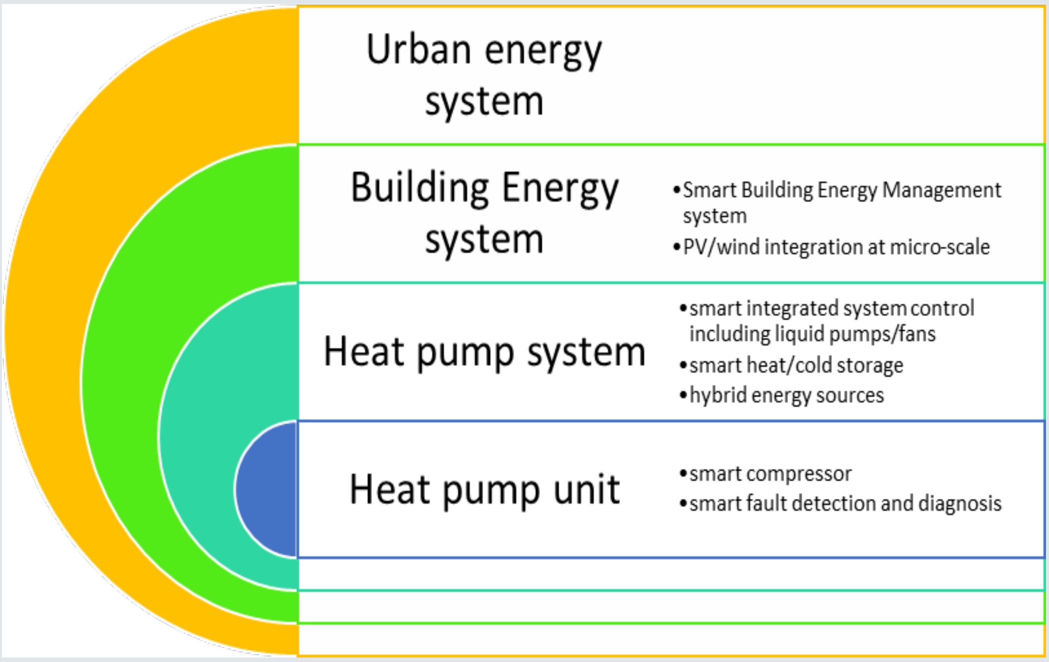

Figure 2. Smart heat pump system viewed from four different levels depending on where the system boundary is drawn.

energy savings and optimised operation of the demand side at the same time. Several important concepts are briefly mentioned in this short article and treated more comprehensively in [1].

Heat pumps' role in the future smart energy systems

Heat pumps link the thermal and the electric sector. In the future these systems will play a pivotal role in the energy infrastructure due to the ability to modify their electric demand for a certain time and thereby providing flexibility to the power system. This will facilitate the integration of distributed renewable power generation as managing electricity demand is a core requirement when dealing with fluctuating electricity generation sources. In order to discuss how to realize the role of heat pumps in a renewable and interconnected energy system we define four different system levels (see Figure 1). Each of them with a different system boundary reaching from the narrow perspective, which deals with the pump unit only, up to a wider system perspective taking the entire urban energy system into account (see Figure 2). We suggest that the different benefits and possibilities by using smart heat pumps are revealed by extending the boundary of the heat pump systems beyond the heat pumping cycle. The heat pump system not only provides a sustainable heating and cooling solution for the buildings but can also act as an enabling technology in future energy systems.

The heat pump unit level – level 1

The most narrow and common system is the heat pump unit itself. It comprises an evaporator, a condenser, an electrically driven compressor, an expansion valve and a working fluid which together, through the thermodynamic process, enable the "pumping" of heat from the low temperature renewable heat source to higher temperature useful for space heating and/or domestic hot water. A smart heat pump at the "heat pump unit level" can for example use a control system to detect and diagnose any fault at the unit level such as a faulty compressor or a frozen evaporator. This type of control is more or less becoming standard. The typical measure of performance is the Coefficient Of Performance (COP) rated at some typical temperature lift and operating conditions.

The heat pump system level – level 2

In order to make sense and bring more possibilities, the boundary level for heat pumps can be extended to include the heat source (outside air, exhaust air, shallow or deep geothermal energy, lake or sea water), the liquid pumps, fans, the heat distribution system, the auxiliary heater, or hot/cold storage. For example, a smart heat pump at the "heat pump system" level can do a lot more than at level 1. It can change the pump or fan speed for the source or sink side to meet the heat demand or minimize pressure drop. Thermal storage can be used to decouple heat generation, and thus electricity demand from the heat demand of the building. The complexity of controls increases significantly due to difference in dynamics (time scales) and information exchange with surrounding systems. This may open up many new possibilities such as using weather forecasts, price signals and so on. The full potential of these are difficult to harvest unless the characteristics of the building are taken into account.

The building system level – level 3

At the building level where the whole building is included within the system boundary, advanced control strategies can be used taking the inhabitants' behaviour, the thermal inertia of the building, or weather forecast into account. The system adjusts the control parameters continuously based on the static or dynamic behaviour of the building and the building inhabitants. A smart heat pump at the building level could monitor and predict the future space heating and domestic hot water demand based on measured data and weather forecast. This information can be used to plan heat pump operation in advance and use the given storage opportunities in the best possible way. It could also communicate with the building inhabitants via smart phones or tablet apps in order to provide the comfort condition in the most cost-effective way. If the building is equipped with solar PV, the heat pumps can help the building optimize the use of the solar PV-system.

The urban energy system level – level 4

An even more inclusive system boundary level, the "urban energy system" level, has a wider perspective on the heat pump and takes the primary energy supplied to the system into account. The smart heat pump at the "urban energy system" level is a part of a smart grid. EU directives, such as the Renewable Energy Sources (RES) directive, promote increasing the share of renewable energy sources in the electricity generation. This can lead to residual loads, caused by large amounts of highly volatile renewable electricity generation such as wind turbines or solar PV cells. Load management with heat pumps can be used to ease grid congestion during peak hours or to align electricity demand of the heat pump with the availability of renewable electricity. Furthermore, time variable electricity prices can be used to incentivise heat pump operation whenever the cost of electricity generation is low. In such a case, locally optimized controls can help reducing the operating cost of heat pump systems.

Heat pumps, if used in a smart way, can provide flexibility to urban energy systems and facilitate the transition towards a future fully operated by renewable energy sources. Electrification of building heating and cooling technologies and a decarbonized electricity sector using technologies such as photovoltaic or wind turbines can be regarded as the most natural path towards the more sustainable future within the 2 K or even the 1,5 K scenarios. Heat pumps can support the future prosumers to consume their on-site generated renewable electricity, store the energy in the form of hot and cold storage, and ultimately use the heating and cooling energy when needed.

The essence of integrated design, dimensioning, and control

To unlock the full potential of heat pumps in the future energy systems, we propose a new concept called Integrated Design, Dimensioning and Control (IDDC) for heat pump systems. Today, heat pump systems including the energy storage mechanisms are designed, sized, and controlled in separate processes. But several of our studies [2-5] show that the system configurations, component sizes and the control strategies are strongly inter-connected and a trivial change in one can considerably affect what should be chosen for the other ones. For example, a control strategy which is appropriate for one system layout can become inappropriate for another layout. Similarly, the system layout and control strategies can strongly influence the optimal size of the system components. Despite the strong inter-connection between design, dimensioning and control processes, there is no coordinated effort between the ones who design and dimension the system and the system operators who control the system.

Consequently, in order to exploit the potential of heat pump in future energy systems, better system management is required integrating the design, dimensioning, and control processes; thus, the system designer is well-informed about the control strategy applied in advance and can optimize design and dimensioning process based on the control strategy and vice versa.

Keep in mind: Heat pumps are not black boxes!

There have been several comprehensive studies on the role of heat pumps in load management and integration of decentralized renewable electricity [6-8]. In addition to these efforts, we should also consider the fact that the heat pump is not a black box whose electricity consumption can be easily ramped up or down based on the grid requirement. The heat pump system efficiency is strongly influenced by the variation of the electricity consumption, caused by variation of compressor speed or switching of the unit. Therefore, a control solution which is cost-effective from the power system perspective may add to the operating cost of the heat pumps, which is paid by the end-user. Conversely, the best control strategy or the customer which yields an optimum seasonal performance factor, SPF, for the end-user may lead to higher costs and higher CO_2 emissions in the electric power system. Consequently, a holistic planning and operation procedure is essential to allow for the most cost-effective control strategy considering the net benefit of the whole system, from both the power system and the end-user perspectives.

Final remarks

Heat pumps can have a unique role in the energy system of the future. The system integration capabilities of heat pumps, bridging the electric power and the heating and cooling sector for enhanced overall energy efficiency, can be used as an asset in the future energy system.

Besides lower carbon emissions compared to boilers fed by fossil fuels, the possibility to decouple heating demand from electricity consumption, and thereby offering flexibility to the power system, can be considered as the key benefit of heat pumps. To integrate heat pump systems into the future energy system in the best possible way, controls, sizing, and system layout need to be adjusted. To achieve the maximum benefit for the whole system, the concept of Integrated Design, Dimensioning, and Control (IDDC) is suggested by the authors and seen as a part of a holistic approach towards the future energy system.

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