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Feasibility study about using a stand-alone wind power driven heat pump for space heating

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HIGHLIGHTS

- This study studies a heat pump system directly coupled with a wind turbine for a detached house.
- The intermittency of wind energy results in significant thermal discomfort.
- Increasing the capacity of wind turbines does not necessarily lead to an improved thermal comfort.
- The battery system can effectively lower the loss of load probability.
- The time interval used in the dynamic simulation has significant influence on the results.

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ABSTRACT

Reducing energy consumption and increasing the use of renewable energy in the building sector are crucial to the mitigation of climate change. Wind power driven heat pumps have been considered as a sustainable measure to supply heat to the detached houses, especially those that even do not have access to the electricity grid. This work is to investigate the dynamic performance of a heat pump system driven by wind turbine through dynamic simulations. In order to understand the influence on the thermal comfort, which is the primary purpose of space heating, the variation of indoor temperature has been simulated in details. Results show that the wind turbine is not able to provide the electricity required by the heat pump during the heating season due to the intermittent characteristic of wind power. To improve the system performance, the influences of the capacity of wind turbine, the size of battery and the setpoint of indoor temperature were assessed. It is found that increasing the capacity of wind turbines is not necessary to reduce the loss of load probability; while on the contrary, increasing the size of battery can always reduce the loss of load probability. The setpoint temperature clearly affects the loss of load probability. A higher setpoint temperature results in a higher loss of thermal comfort probability. In addition, it is also found that the time interval used in the dynamic simulation has significant influence on the result. In order to have more accurate results, it is of great importance to choose a high resolution time step to capture the dynamic behaviour of the heat supply and its effect on the indoor temperature.

1. Introduction

Currently, the building sector has consumed more energy than the industry sector, the transport sector, the agriculture and non-energy use sector, accounting for more than one third of the world's energy consumption [1]; and more than 50% is used for space heating and cooling [2]. In Sweden, the energy consumption for space heating and domestic hot water (DHW) production reached 100 TWh in 2014 [3]. Sweden has already set a target to reduce it by 20% by 2020 and 50% by 2050 comparing to the level in 1995 [4]. To achieve a sustainable development, reducing energy consumption in the building sector is playing an important role.

In Sweden, there are different ways to supply heat, such as district heating (DH), heat pumps (HPs), electrical radiator, and biomass/oil/gas boilers. Even though, DH is the most common way to supply heat, accounting for more than 50% of the total heat demand, there are still

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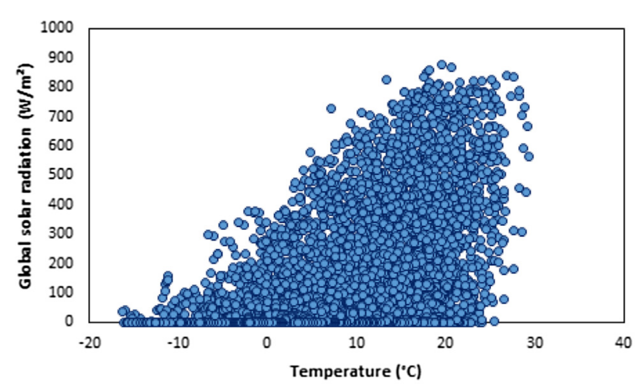
many single family houses that are not connected the DH network. HPs represent an energy efficiency technology for heat production; however, the share of HPs in the Swedish heat market is not very high, only covering a little more than 20% of the heat demand. Meanwhile, although there is a tiny share of power from fossil fuel in Sweden, nuclear power accounts for a big proportion, more than 40% [5]. Nevertheless, nuclear power is planned to be phased out in Sweden, therefore, more power should be explored from other renewable resources, such as wind power. Wind power has experienced a fast growth in the past 10 years. The installed capacity in 2016 was more than 10 times of that in 2004, reaching 6.5 GW and the produced power was 15.4 TWh [5]. Since wind potential is usually high during winter, in which the heat demand is high, using wind power to drive HPs is a proper technical solution and will be of significance to achieve the Swedish energy target in 2020 and 2050.

Some works have been done to evaluate the potential of using wind power to drive HPs. Waite and Modi evaluated the effects of coupling large-scale wind power installations in New York State with increased use of electric heat pumps to meet a portion of space heating and DHW demands in New York City [6]. Results showed significant increases in wind-generated electricity utilization with increased use of HPs, allowing for a higher installed capacity of wind power. Hedegaard et al. analyzed how the heat pumps can influence the integration of wind power by applying an energy system model that optimized both the investment and operation, and covered various heat storage options [7]. It was found that the HPs can contribute significantly to facilitating larger wind power investments in net zero energy settlements and reducing system costs, fuel consumption, and CO_2 emissions. Meibom et al. technologically and economically analyzed the integration of HPs with wind power [8], showing that the introduction of HPs was beneficial as the curtailment of wind power production was reduced, the price of regulating power was reduced and the hours with very low power prices were reduced. Warmer et al. investigated the performance of a heat pump integrated with wind power based on performed field test. Results showed that by making use of large buffering capacity in a number of installations large parts of the wind power fluctuations can be eliminated [9]. Fischer and Madani investigated HP systems in smart grid [10]. The results suggested that the integration of wind power on building level can be supported by HPs and the required electricity from the grid can be reduced by up to 95%. Poulet and Outbib concluded that heat pumps, operated in an optimal way, can be used to increase the absorption of wind power while at the same time reducing the need for peak capacity and thus costs [11].

Moreover, for detached houses that even do not have access to the electricity grid, HPs that are directly coupled with wind turbines (WT-HP) are more attractive [12]. There are some studies about developing WT-HPs. Jwo et al. have experimentally investigated the performance of a WT-HP system, proposing a method to improve the energy efficiency [13]. Other works [14–16] have also been conducted to investigate the dynamic performance of WT-HP, most of which focus on the system itself, such as the coefficient of performance (COP) and heat production, even though the detailed heat demand was not integrated. However, due to the intermittent characteristic of wind power, even though an energy storage is considered, there is no guarantee of a satisfying indoor thermal comfort when a standalone system is used. Therefore, to study the feasibility of WT-HP, it is essential to evaluate the system based on the real dynamic demand. Papaefthymiou et al. presented a methodology for the quantification of the flexibility offered by the thermal storage of building stock equipped with HPs, to power systems with significant penetration of wind power [12]. Li et al. proposed an hour-ahead heating strategy scheduling mode to accommodate curtailed wind power with a typical wind power output profile [17]. Østergaard analyzed and compared compression HPs and geothermal absorption HPs integrated with wind power in EnergyPLAN [18]. Many studies have been carried out regarding hybrid systems, which do not only consist of wind power. Poulet and Outbib studied energy conversion for dwellings by using hybrid systems based on HP variable input power [11]. Both wind power and PV were included. Sichilalu et al. studied a PV-wind-fuel cell-HP hybrid system that can produce both electricity and heat [19]. An optimal energy management strategy was proposed to minimize energy cost and maximize fuel cell output. The same authors also develops an optimal control model of a HP water heater (HPWH) supplied by a wind generator-photovoltaic-grid system [20]. Whereas, it was assumed that the demand can be fully satisfied by the hybrid system. Few studies have been done only for WT-HP. Chemekov and Kharchenko designed a WT-HP system to supply heat for an individual dwelling house with a total area of 295 m^2 situated in the city of Tuapse, Russia [21]. Both thermal energy storage and electricity storage were involved. Due to the fluctuation of wind power output, the mismatch between heat demand and heat supply was identified. Nevertheless, no results about indoor temperature were given.

Recent studies have focused the interest on the coupling of HPs and solar PV systems for space heating thanks to the drastic reduction of PV module prices [22,23]. Nevertheless, the major challenge for PV systems when used for space heating applications is the mismatch between heating load and PV production. In this perspective, despite the higher investment costs, small WTs can play an important role in space heating. This can be clearly understood when comparing the mutual relationships between ambient temperature vs global horizontal radiation and wind speed (at 10 m height), as shown in Fig. 1a and b. However, according to the literature review, there has been little information about the thermal comfort when a standalone WT-HP is used to supply heat to a detached house. Since the primary purpose of space heating is to provide a good thermal comfort, only assessing how much heat demand can be covered by a WT-HP is not sufficient to justify the feasibility. There is also a lack of knowledge about how to improve the thermal comfort when WT-HP is adopted. In addition, it is common to assume that the indoor temperature is constant when estimating the



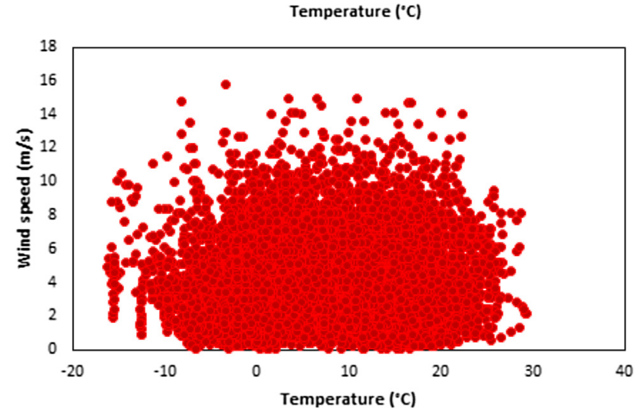


Fig. 1. (a) ambient temperature vs global solar radiation (up), and (b) ambient temperature vs wind speed (at 10 m height) (down) (the weather data refer to Stockholm (59.33 N, 18.06 E) and were retrieved from Meteonorm database [24]).