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Demand response potential of electrical space heating in Swedish single-family dwellings

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ABSTRACT

This paper investigates the potential and economics of electrical space heating in Swedish single-family dwellings (SFDs) to provide Demand Response (DR) for the electricity load in Sweden.

A dynamic and detailed building-stock model, is used to calculate the net energy demand by end-use of a set of sample buildings taken as representative of all Swedish SFDs with electrical heating. A new sub-model optimizes the dispatch of heating systems on an hourly basis, for each representative building, minimizing the cost of electricity purchased from the hourly spot market.

The analysis of the Swedish SFD buildings indicates a technical DR capacity potential of 7.3 GW, which is considerable and can be used for the management of intermittent electricity generation. This potential could also prove to be valuable in the operating reserve market. However, this requires that the DR, rather than being governed by a single hourly electricity price signal, would instead be subject to a more centralized control. The modeling shows that DR can be expected to result in up to 5.5 GW of decreased load and 4.4 GW of increased load, if applying current Swedish electricity prices. The modeling shows that DR shifts up to 1.46 TWh of electric heating, corresponding to 1% of total Swedish electricity demand. The potential savings from DR for individual SFDs is found to be low, 0.9–330 €/year, given current Swedish electricity prices.

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1. Introduction

One way to facilitate large-scale integration of intermittent electricity generation is to match electricity supply and demand by applying Demand Side Management (DSM) measures. One such DSM measure is Demand Response (DR), whereby electricity consumers, in response to some incentive, alter their consumption patterns to in a more optimal way match the generation of electricity [1]. With the implementation of electricity smart meters in Sweden it has become possible for residential customers to have real time pricing and thereby take part in DR [2]. With the residential sector in Sweden accounting for 23% of total electricity consumption, residential loads could potentially have a significant role in balancing variations in the electricity supply system. The potential for dishwasher, laundry and water heating loads has previously been studied by Puranik [3]. Electrical space heating of single-family dwellings (SFDs) represents about 50% of the residential electricity demand and has a higher power capacity compared to other electrical household devices, such as white appliances [4]. Thus, electrical space heating offers a substantial contribution to variation management. This demand can be used for DR purposes through the storage of the heat produced by electric heating systems, e.g., heat pumps and electric radiators, in the building mass and in the indoor air [5,6]. The present study aims at investigating the DR potential, in terms of time frame for load shifting as well as capacity and energy of the shifted load, for electric space heating in Swedish SFDs through using the thermal inertia of the building stock. From these results, we show the potential impact such DR could have on the load curve in the Swedish electricity system.

Three different options for heat storage in buildings were introduced by Arteconi et al. [7]: latent heat storage in the form of phase-changing materials; sensible heat storage through active storage, i.e., *via* the use of heat storage equipment; and sensible heat storage through passive storage that utilizes the thermal mass

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of the building by varying the indoor temperature. The present study focuses on the latter option, utilizing sensible heat storage. Several studies have investigated the possibility to utilize this type of storage to shift electricity consumption for heating or cooling loads temporally. The modeling approach in literature can be divided into two types of models, system level optimization models and simulation models, simulating an individual or a few individual buildings in order to analyze strategies for shifting load.

Studies that have investigated the use of thermal mass of buildings to move cooling loads [8–13], mainly target commercial buildings due to their high levels of electricity consumption for cooling. The analysis of the load shifting is usually based on the performance for days up to weeks. Yin et al. [11] identified the possibility to shift peak loads (on a single building level) to achieve a 10%–30% reduction in the maximum electricity load of the building. Furthermore, Morgan and Krarti [10] and Braun [12] have shown that the operating cost of cooling systems can be reduced by 10%–20% by shifting the load from peak demand hours. Published studies on the pre-heating of buildings mainly propose strategies to control the heating system to shift the load and optimize electricity consumption with respect to reduced peak demand [14–16]. Apart from reducing the peak load, Hughes [17] has concluded that load shifting facilitates the integration of more renewable energy sources into electricity systems, such as wind power. Reynders et al. [18] modeled the potential for thermal storage using space heating in a net zero-energy building in Belgium equipped with a PV system. They conclude that there is a mismatch between PV generation and space heating demand. Consequently, it is not obvious how to apply thermal storage in order to increase the use of PV electricity. Yet, DR through thermal storage was shown to reduce demand with up to 94% during peak demand hours [18].

Patteeuw et al. [19] investigated different optimization modeling approaches for DR of electric heating systems and their ability to describe the DR behavior. They conclude that in order to capture the characteristics of DR, models that include both supply and demand is preferable (which they denote integrated models).

A few studies have investigated the potential of DR residential heating loads on a system level with different geographic scope, i.e., Hedegaard and Balyk [20] and Hedegaard et al. [21] for the Danish heating system, Papaefthymiou et al. [22] for Germany, and Meibom et al. [23] for Northern Europe, all of which have focused on the integration of wind power into the electricity system. Papaefthymiou et al. [22] showed that for a case with renewable energy penetration of 47%, heat pumps reduce system costs to a greater degree than pumped hydro storage. This is because the losses incurred by the round-trip efficiency of the pumped hydro storage are higher than the losses that result from storing heat. Papaefthymiou et al. [22] concluded that taking into account the minimum load requirements and start-up costs for conventional power plants without allowing curtailment increases the system value of the DR measure. Hedegaard et al. [21] concluded that investments in heat pumps together with passive storage, i.e., using the thermal inertia of the buildings, could reduce fuel costs and CO_2 emissions to a break-even cost in the Danish energy system when there is 50% wind power (the possibility to export/import electricity is included). They also found that investments in heat storage in the form of accumulation tanks are not cost-effective. However, their study was limited to future investments in heat pumps and did not consider the currently existing heating technologies in the Danish building stock. As Hedegaard et al. [21] utilized a simplified modeling of the thermal behavior of the buildings, their results may overestimate shifting times. Papaefthymiou et al. [22] applied more in-depth modeling of the buildings, although the temperature dependency in the heat losses was not accounted for in their analysis. In the study of Hedegaard and Balyk [20], a modeling framework for the thermal behavior of the buildings was implemented, although it did not include solar radiation and lacked a detailed description of the building stock. They showed that the use of heat pumps for DR resulted in a reduced need for peak and reserve capacity investments.

Although the above works indicate that implementing DR may be favorable for the electricity system, none of the above papers assessed how building characteristics influence the use of electric heating for DR, in the form of passive storage, in the building stock. There is also a lack of studies on the effects of large-scale implementation of DR by electric heating in Sweden and its effects on the Swedish electricity system. Therefore, the present study investigates the potential of electrical space heating in Swedish SFDs to act as a DR and examines both how DR influences the electricity load curve and the magnitude of the economic benefit from the resulting reduction in the cost of electricity. More specifically, we address the following four research questions: (1) What is the DR potential available under the present price structure given an individual DR?; (2) What would the potential effect of such a shift be on the Swedish electricity load curve and on the final electricity demand for space heating?; (3) Which building characteristics influence load shifting the most?; and (4) What are the possible monetary savings for consumers who shift their electrical space heating load, assuming the current market structure?

2. Electricity demand in Swedish SFDs

The total amount of electricity consumed in Sweden during Year 2012[2] was 143 TWh: 42% by industry, 25% by the residential sector, 25% by the tertiary sector, and 8% attributed to distribution losses. In the residential sector, permanent SFDs use 25.6 TWh of electricity (56% for space heating and production of hot water, and 44% for household electricity), while multi-family dwellings (MFDs) use 6.4 TWh (23% for space heating and production of hot water, and 77% for household electricity) [24]. The low level of electric heating use in MFDs is due to the fact that 92% of the MFDs are connected to the district heating grid [4]. In all, space heating in SFDs accounts for 12% of the total electricity consumption in Sweden. These values are comparable with the most recent data for the year 2013 [25], although the overall electricity demand was slightly (3%) lower during 2013.

There are approximately two million SFDs in Sweden,[3] out of which 1.3 million have some form of electrical heating system [24,26]. Fig. 1 shows the distribution of heating sources in Swedish SFDs. In the electricity category, electric radiators, electric boilers, and air-source heat pumps are included. It is clear that electric heating by itself or in combination with other heating systems constitutes a major proportion of the installed heating systems. The other electricity-consuming category is ground-source heat pumps, which includes heat pumps that draw energy from the ground or a body of water. Comparing the 2012 to data for 2013 the changes in distribution of heating sources and number of households are minor [27].

Swedish SFDs that are heated directly with electricity consume on average 15,000 kWh/year of electricity for space heating [24]. In contrast, households that are indirectly heated by electricity (both partially and using heat pumps) consume about 6000 kWh/year of electricity for space heating [28].

In summary, there is substantial potential for DR of space heating electricity in Swedish SFDs. The purpose of this paper is to investigate to what extent and under which conditions this

[2] One of the years modeled in this work.

[3] Year 2012.

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