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Contributions of heat pumps to demand response: A case study of a plus-energy dwelling

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HIGHLIGHTS

- Assessment of several dynamic pricing strategies in a plus-energy dwelling.
- Evaluation of consumption, cost, heat pump use in peak hours and thermal comfort.
- Using heat pumps and the storage capacity of buildings for DR proved highly beneficial.
- Optimal strategies were found choosing different temperature and price thresholds.
- Cost savings up to 25% may be achieved without significant thermal comfort losses.

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ABSTRACT

Demand Response programs are increasingly used in the electricity sector, since they allow consumers to play a significant role for balancing supply and demand by reducing or shifting their electricity consumption. For that purpose, incentives such as time-based rates have been proposed. The present study analyzes the potential benefits of operating the heat pump of a plus-energy dwelling which participates in a dynamic pricing market, benefitting from the thermal storage capacity of the building. The software TRNSYS 17 has been used to model the building and the supply system. A validation of the model was carried out by using available measurements of the dwelling.

Three setpoint temperature scenarios have been considered for sixteen different strategies which depend on temperature and electricity price thresholds, with the aim of determining which alternatives could lead to significant savings while maintaining an acceptable thermal comfort. Several factors such as cost savings, heat pump consumption, ratio of self-consumption of the dwelling and use of the heat pump during peak hours were also evaluated in every case.

The results show that dynamic price thresholds should be used instead of fixed price thresholds, which may cause low activations of the heat pump or overheat the building above the comfort limits. Cost savings up to 25% may be achieved by using optimal strategies, increasing the self-consumption ratio, having almost no influence on the thermal comfort and achieving significant peak reductions on the grid. The outcomes of this study show the importance of looking at the implications of such strategies on several criteria within a demand response framework.

1. Introduction the need for demand response

Unlike other energy resources, electricity has to be used when it is generated, since its storage on a large scale is still an intricate task. Utility companies increasingly have to deal with peak demands in constrained networks, so regulating the electricity use is critical. The grid frequency is the indicator of the balance between supply and demand, dropping when the consumption exceeds the supply and increasing when generation exceeds consumption. In addition, with the increasing penetration of intermittent renewable generation there is a growing need for ancillary services to absorb the related disruptions [1].

Blackouts happen if the supply is incapable of meeting the demand, which can be solved either by investing in new power plants and transmission lines, or by reducing the electricity demand. However, the first option might not be economically feasible, since critical periods

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only occur a few hours per year and increasing the price of electricity would not easily solve the problem. For this reason, in order to relieve the electricity grids it is of paramount importance to be able to reduce the peak demands or shift the loads during peak periods through Demand Side Management (DSM) and control systems. As a by-product there may exist significant economic gains if the adequate strategies are followed.

A practical example to illustrate this situation is shown for Ontario, Canada [2]. Here the highest 3% of peak load occurs for less than 15 h during a year, but costing more than 130 million US dollar per year to maintain the peak generation capacity. For this reason, a program called "peak saver" was created, which allows utilities to remotely control thermostat settings at volunteering homes, therefore reducing the air conditioning peak loads by setting the thermostats a few degrees higher on hot summer days in which the peaks occur.

Thanks to the technological advances in control and communication systems, Demand Response (DR) is emerging as an interesting strategy for peak demand reduction, allowing direct load control, time-of-use tariffs and interruptible programs. Many different approaches are being evaluated to participate in these markets, for example by determining the potential of electric vehicles to provide reserve power as a vehicle-to-grid concept [3]. Nonetheless, incentives, dispatch methods and compensation of DR remain challenges that restrain system planners and operators from adopting these strategies [4]. During the past years there has been a noticeable increase of interest in DR strategies, which is reflected in the rise of scientific publications from 219 in the year 2000 up to 1418 publications in 2016 (own survey in the ScienceDirect database).

As it is widely known, buildings are responsible for a large portion of the total electricity consumption in many countries, and they are critical in efforts towards attaining the much needed operational flexibility in the grid [5]. Among the different contributors, heating, ventilation and air conditioning (HVAC) systems are the most influential. To reduce HVAC energy consumption, a very simple and effective way would be to improve the control strategies, allowing the use of DR instead of replacing the existing equipment.

Currently, the concept of DR is mainly applied in relation to the electricity grid, but similar benefits can also be obtained from district heating systems [6], especially if heat pumps (HP) or co-generation engines are available to connect the electrical and thermal energy sectors (sector coupling). District heating systems are able to de-couple the fluctuations in the heating demands of buildings from the grid, therefore smoothing the peaks. When heat pumps are used for domestic hot water and heating systems supply, it is advantageous to use low temperature distribution networks as the heat source compared to ambient air. Low temperature heat can be provided by waste heat, low depth geothermal energy, Photovoltaic Thermal (PVT) collectors or comparable sources. In a cold district heating network (CDHN), the supply temperature is less than the one required for heating or Domestic Hot Water (DHW). Low network temperatures reduce heat losses in the distribution system, improve the efficiency of the HVAC equipment and allow the use of other renewable energies.

If the electricity market conditions are favorable, heat can be produced with the HVAC system to preheat, heat or even overheat the building, and thus storing energy in the building thermal mass or in storage tanks. This of course depends on the availability of pricing programs which allow time-of-use (TOU) tariffs. In these tariffs, the prices are set in advance and vary throughout the day, being higher in peak periods and lower in off-peak periods. Conversely, in Dynamic or Real-Time Pricing (RTP) customers are notified of the rates on a day-ahead or hour-ahead basis. A dynamic electricity market is already available in many countries for large consumers, and it is being extended to residential customers, which increasingly generate their own renewable energy and become prosumers. By using photovoltaics with or without battery storage, buildings may achieve high self-sufficiency levels and reduce network distribution losses and fossil fuel use in the electricity sector.

According to [7] the status of EU Member States regulation concerning DR can be divided into three groups: those who have yet to seriously engage with DR reforms (Portugal, Spain, Italy, Croatia, the Czech Republic, Bulgaria, Slovakia, Hungary, the Baltics, Cyprus and Malta), those in the process of enabling DR through the retailer only (Germany, the Nordic countries, the Netherlands and Austria) and those who enable both DR and independent aggregation (Belgium, France, Ireland and the UK). A very complete review of dynamic pricing programs in the U.S. and Europe has been done [8], stating that Europe has a strong focus on large-scale roll-outs of smart meter devices.

1.1. Thermal mass storage and setpoint strategies

Buildings have a thermal mass that provides inertia, taking some time to heat up or cool down. Like other technologies to store energy, this inherent property can be used to store energy at peak periods and preheat or precool the building, but is available at no additional investment cost. Given the right control system, an electric heater or electric Heat Pump could be used flexibly depending on the grid conditions, without significantly compromising the thermal comfort of the occupants and contributing to the reduction of peak loads. Using the thermal inertia enables electricity and thermal demand to be partially decoupled through flexible HVAC operation while maintaining thermal comfort. During hours of no occupancy this strategy has an even higher impact, since it allows to relax the comfort constraints.

One way to increase the potential of using the structural thermal mass of a building for DR purposes could be to use higher temperature setpoints during off-peak periods, preheating or even overheating the building and lowering the setpoints during peak periods. A promising technology to activate the thermal storage mass in buildings is the Thermally Activated Building Systems (TABS), which includes pipes or ducts embedded in the building surfaces to work as heat exchangers, providing heating or cooling and storing heat in the thermal mass [9]. TABS help to activate the thermal mass of the building, allowing load shifting strategies. By making use of dynamic pricing strategies there might be significant cost savings, but overheating the building above its normal setpoint temperature results in energy losses, therefore increasing the energy consumption. In addition, raising or lowering setpoint temperatures may have notable peak load reduction potentials, but the operation of the HVAC should also take into account its effect on indoor comfort, which describes the satisfaction of the occupants with the thermal environment and has great influence on their productivity.

In addition, thermal energy storage (TES), which requires an additional water loop to charge and discharge the water tanks, can also be used for DR. According to [10] DR using TES can be categorized into two groups: based on simple heuristic rules and optimal DR control. The major difference is whether these methods consider the trade-off between peak demand reduction and the possible energy increases by load shifting, crucial for achieving electricity cost savings. Oversizing the storage tanks used as thermal energy buffer may also increase the amount of energy which can be shifted, thus improving the flexibility of the system. However, due to higher thermal losses the costs would most likely increase, so the economics should be evaluated in every case.

Among the different technologies available to carry out DR strategies, heat pumps may play a vital role. According to [11], there are three main categories of applications using heat pumps in a smart grid context: stable and economic operation of grids, integration of Renewable Energy Systems (RES) and operation under variable electricity prices. Changing residential space heating from the use of gas boilers towards heat pumps is recognized as a method to reduce emissions and increase the energy efficiency [12]. Heat pumps might become effective in balancing the electricity supply and demand when combined with the thermal inertia of buildings, contributing as well to the integration of renewable energies. They might therefore be able to use dynamic pricing as a means to induce users to generate or absorb electricity depending on the grid imbalance.