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Smart Energy Usage for Vehicle Charging and House Heating

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Abstract: In northern Europe the electricity price is set by hourly rates one day in advance. The price fluctuates due to supply and demand, and these fluctuations are expected to increase when solar and wind power are increased in the energy system. The potential in cost reduction for heating a house and charging of an electrified vehicle by using a smart energy management system in a household is investigated. Dynamic programming is used and a simulation study of a household in Sweden comparing this optimal control scheme with a heuristic controller is carried out. The time frame in the study is one year and a novel way of handling the fact that the vehicle is disconnected from the grid at some times is developed. A plug-in hybrid electric vehicle is considered, but the methodology is the same also for pure electric vehicles. It is found that the potential in energy cost reduction for house heating and vehicle charging is significant and that using a smart energy management system is a promising path of cost reduction, especially with the introduction of electrified vehicles.

Keywords: Electricity price optimization, Electric vehicle, Plug-in electric vehicle, Household, Smart energy management

1. INTRODUCTION

Today, Swedish households can buy electricity with varying hourly rates, and these rates are determined for the coming day at lunchtime and are based on electricity producers' capacity to supply electricity and consumers' predicted demand. Since the electricity prices vary throughout the day and are known in advance, it is possible to reduce the cost of household electricity by moving a portion of the energy consumption to times when it is cheaper. Domestic heating and electric vehicles are examples of large electric loads where the energy consumption could be shifted in time. This paper studies how much electricity costs and energy consumption could be reduced for a household by introducing smart energy management based on, among other things, varying electricity prices and weather. How much the electricity price varies over the days differ, but in general the electricity price is cheaper during the nights and most expensive in the mornings and evenings, see Figure 1 where the average electricity price for each hour of the day during 2013 is presented.

Advanced energy management provides besides lowering the cost of electricity also other advantages. Electricity price and total power demand is strongly correlated as can be seen by comparing the electricity price in Figure 1 with the power consumption per hour in Figure 2. When electricity prices are high and demand for energy is high, back-up generators such as gas turbines and coal plants are used to a greater extent. A reduction of the energy output during these times makes the electricity production more environmentally friendly and less dependent on fossil fuels. In addition to lowering the cost of electricity the knowledge that electricity is produced in a more environmentally friendly way could be an important incentive for consumers to invest in smart energy management. Furthermore, if many households start to use smart energy management it would have a peak shaving effect and the capacity of back-up power plants can be reduced.

A simulation study has been conducted to estimate the reduction in electricity costs for a household with an electric or plug-in hybrid electric vehicle. A large part of the energy consumption for a Swedish household is used for heating and the indoor temperature depends on several factors. Here we consider heating, household electricity, weather such as solar radiation and outside temperature, and the building's thermal inertia. In order to obtain a representative value that takes into account the effects of different seasons, the household has been simulated for one year with conventional heating and direct charging and compared it with the cost of electricity when smart energy management is used. Several approaches have been

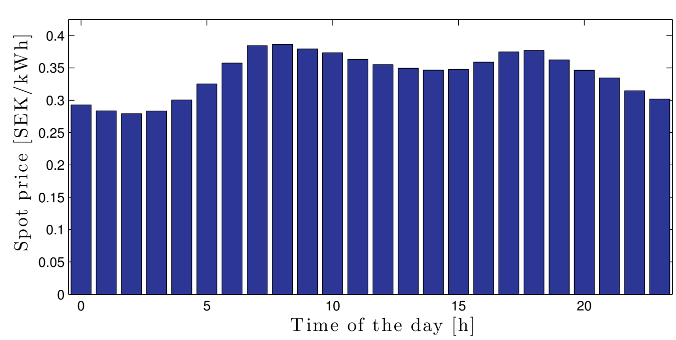

Fig. 1. Average spot price per hour of the day in the Swedish price area SE3 during 2013.

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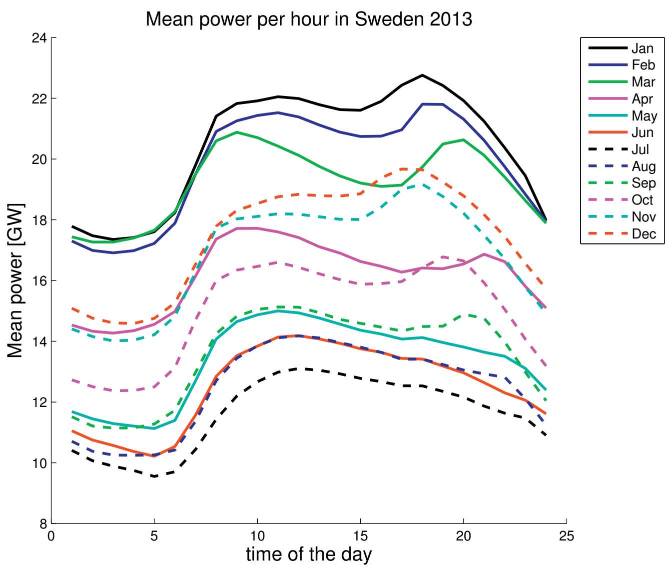

Fig. 2. Mean power consumption per hour in Sweden 2013 for different months.

used previously; In Logenthiran et al. (2012) heuristic optimization is used to control the domestic electricity demand, in Mohsenian-Rad et al. (2010) game theory is used to control the household loads, and in Sarabi and Kefsi (2014) dynamic programming is used to charge electric vehicles in order to reduce the overall peak power in the system. In this study dynamic programming is used to minimize the electricity cost, and to illustrate the optimization a typical Swedish house has been considered. Few houses in Sweden are equipped with air cooling systems and therefore cooling has not yet been considered.

The outline of the paper is as follows. First, Section 2 provides an overview of the household including an electric vehicle and a formalization of the energy management optimization problem to be solved. Section 3 describes a thermodynamic model of a house and an electric vehicle model designed with dynamic programming in mind. Section 4 describes and discusses how smart energy management is included in the dynamic programming framework such as vehicle charging, heating, and the choice of state and time discretization. The optimization assumes future electricity prices, weather, and household energy consumption to be known which gives an upper limit of the gain introducing smart energy management. Section 5 shows the results of simulations of a typical household with and without smart energy management. The optimal solution is shown and characteristics of it discussed. Finally some conclusions are drawn in Section 6.

2. PROBLEM FORMULATION

The purpose of the paper is to investigate possible electricity cost savings by introducing smart energy management to a household with an electric vehicle. This section provides a more detailed description of the studied optimization problem.

Figure 3 shows a control oriented view of a household including an electric vehicle. The control variables considered here are heating power P_{heat} used for controlling indoor

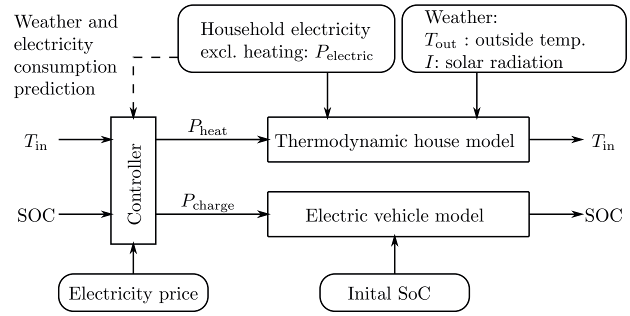

Fig. 3. Control oriented view of a household with an electric vehicle.

temperature T_{in} and vehicle charging power P_{charge} used for state of charge (SoC) control. The control objective is to minimize electricity cost while keeping the indoor temperature T_{in} above a specified minimum temperature and to reach a fully charged state of the electric vehicle before a user specified time. The total power consumption of the household is assumed to be bounded to a specified value $P_{\max}$, i.e.,

$$P_{\max} \geq P_{\text{heat}} + P_{\text{charge}} + P_{\text{electric}}$$

where P_{electric} denotes the total power of household electricity including all electric loads except for heating and vehicle charging.

Household electricity is from a control perspective considered as an uncontrollable disturbance both because it influences the power available for heating and charging, but also because it generates heat in the house. The weather condition is another disturbance influencing indoor temperature. Here two weather related signals are considered, the outside temperature T_{out} and the solar radiation intensity I.

The inputs to the controller are measured indoor temperature T_{in}, estimated state of charge SOC, future electricity price, measured household electricity power P_{electric} and outside temperature T_{out}. The energy management system could also benefit from using weather forecasts and predicted user behavior, such as predicted household electricity and vehicle charging behavior including when the vehicle is connected to the household and at what initial SoC and at what time the vehicle is expected to be fully charged.

In this paper the performance of an ideal control scheme is studied to investigate the potential savings for such a smart energy management system in terms of electricity cost. Therefore, dynamic programming is used to find the cost optimal solution given that weather, household electricity, and vehicle charging behavior is known by the controller in advance.

3. MODELS

This section describes the thermodynamic house model and the electric vehicle model that will be used for the electricity cost optimization of the household.

3.1 Thermodynamic house model

The thermodynamic house model is used to simulate the temperature variations with different heating control