Electric Power Systems Research 111 (2014) 103–114

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Estimating the impacts of demand response by simulating household behaviours under price and CO_2 signals

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ARTICLE INFO

Article history:
Received 29 July 2013
Received in revised form 5 December 2013
Accepted 16 February 2014
Available online 19 March 2014

Keywords:
Demand response
Emission factor
Ex ante evaluation

ABSTRACT

To facilitate the implementation of demand response (DR), it is necessary to establish proper methods to estimate and verify the load impacts of it. This paper develops a simulation model to investigate the joint influence of price and CO_2 signals in a DR program in the ex ante evaluation. It consists of a Markov-chain load model for forecasting the power demands of residential consumers and a scheduling program for providing optimal schedules for smart appliances. A case study of the Stockholm Royal Seaport project is analysed to demonstrate how to apply the simulation model to assess a DR program by simulating consumers' behaviour change in response to the DR signals. The results show that consumers' attitude to the signals and willingness to change (expressed by weight λ and time preference) largely affect the load shift, bill saving and emission reduction. Moreover, by observing the load shifts over different lengths of the testing period, the model could also provide suggestions on the required testing period to get sufficient load data to distinguish the load patterns between consumers in different testing groups.

1. Introduction

Along with the increasing demand for energy and more concerns about the environment, the existing power supply systems are facing challenges. Security of supply, sustainability and competitiveness are the requirements for European energy supply systems in the future [1]. The smart grid provides a future vision of European power networks to overcome the challenges and fulfil these requirements. As a cornerstone of smart grid, demand response (DR) aims at stimulating end-use consumers to change their electricity consumption patterns through a series of technical and economic approaches. A grid level optimization could be achieved through the modification of consuming time, instantaneous demand or total electricity consumption by consumers [2]. The modifications of consumption patterns are generally triggered in two ways: incentive payments (Incentive-Based Programs) or dynamic price rates (Price-Based Programs) [3]. Incentive-Based Programs try to use the demand as reserve to balance the power system and maintain a reliable operation [4]. Load shedding could be achieved in either automated (Direct Load Control) or voluntary ways (e.g. Interruptible/Curtailable Programs). The major purpose of Price-Based Programs is to promote the economic efficiency of the power systems [3]. There have been many applications of Price-Based Programs such as Time of Use (TOU), Real Time Price and Critical Peak Pricing in residential sectors [5–7]. These programs intend to flatten the load curves by offering higher prices in peak hours and lower prices in off-peak hours. Compared with Incentive-Based Programs, Price-Based Programs are more flexible regarding the influence on the change of consumption patterns. Since there is no mandatory limitation of how much load should be reduced during specific periods, the success of such programs depends on the awareness, attitude and behavioural adaption of consumers [8].

Smart meters and feedback through in-home display, website or handheld devices have been proven effective for increasing consumers' awareness about the energy use and providing them opportunities to make more informed decisions about how and when to consume electricity [9]. The feedbacks encompass a large amount of information concerning energy consumptions as well as corresponding cost and carbon footprint. However, some studies show that the "response fatigue" due to an overwhelming volume of information is a challenge faced by many DR programs [10]. For example, consumers may feel tired to make frequent active decisions responding to the dynamic price rates by keeping track of the price and usage information and reprogramming appliances. To solve these problems, smart appliances attract interest by enabling consumers' active reaction to the feedbacks. Based on

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http://dx.doi.org/10.1016/j.epsr.2014.02.016
0378-7796/

communication infrastructures, smart appliances can be controlled centrally within the home or from controllers remote from the home [11]. The home energy consumption could be better managed by the auto-controlled appliances through optimum algorithm. For example, a dishwasher could be rescheduled to run in off-peak hours to reduce the electricity cost.

Many studies have simulated and examined the potential changes in home electricity consumption under dynamic price rates by rescheduling appliances. Optimum load management strategies have been proposed to support consumers' active decision for a better control of energy demand and assisting the modification of life style during peak periods. Ref. [12] presented a load management strategy for residential consumers. The strategy establishes the optimal relationship between hourly electricity prices and the use of appliances and electric vehicles in a typical smart house by considering the energy demand, electricity price, renewable power production and the power purchase of energy of the consumer. Case studies show that the proposed model allows users to reduce the electricity bill between 8 and 22% for a typical summer day. Ref. [13] presented a simulation model to investigate the impact of smart appliances and dynamic price rates on electricity bills of a household. The model generates household load profiles under flat tariffs and simulates changes in the profiles when households are equipped with smart appliances and face a TOU price rates. Ref. [14] presented simulation results of a proposed residential energy management system. The system provides automated DR in response to price or system condition utility signals. It results in reduced average power and energy use during the DR service time by delaying the use of controllable appliances.

Studies have also investigated the willingness of consumers to reduce and move consumptions due to different motivations. Ref. [15] suggested a framework for controlling home energy consumption in which the energy efficiency and consumers' lifestyles are simultaneously considered. It quantifies consumers' preferences for using appliances during peak periods according to electricity cost, emergency, welfare and enjoyment of usage. Ref. [16] estimated the potential peak load reduction resulting from the voluntary DR by using a diversified demand modelling method along with energy audit data. Consumers' willingness to change behaviour in response to the information about the security of supply, emission profile and electricity cost is explored through mail-back surveys.

Until now, many studies focus on the impact of dynamic price rates and try to propose optimum energy solutions largely according to the price information. Even though environmental response factors e.g. the CO_2 emission factor are identified as a trigger for the voluntary load shedding [16], they have only been used as ancillary signals in some DR pilot projects (e.g. [17]). Surveys showed that consumers are more sensitive to the price and supply security than emission [16]. But along with more concerns about the environment by the public, it is also valuable to examine consumer' attitude to the emission factors and its potential impacts. This paper aims to investigate the joint influence of both price and CO_2 signals in DR programs in which both signals are provided and households are equipped with smart appliances. A simulation model consisting of a load forecasting model and a scheduling program for smart appliances is developed and applied. It can be used for the ex ante evaluation of DR programs to predict the potential load shift and bill savings of households. The simulation results can also be used to establish the required length of testing period depending on the number of households participating in the program.

The paper is organized as follows. Section 2 describes the test bed of the proposed simulation model. The prototype of a smart apartment is introduced. The correlation between the dynamic price rates and CO_2 emission factors are explained. Section 3 presents the simulation model in detail. Section 4 applies the model to perform an ex ante evaluation of the DR program in the Stockholm Royal Seaport project. The load shift, bill savings and emission reductions are estimated for the TOU program according to the simulation results. Finally, Section 5 gives conclusion of the paper.

2. The test bed of the proposed simulation model

The proposed simulation model is designed to evaluate the load impacts of a DR program by comparing the load curves of two groups of households: the households living in smart apartments and those living in ordinary apartments as reference. Fig. 1 illustrates the relationship between the inputs and outputs of such

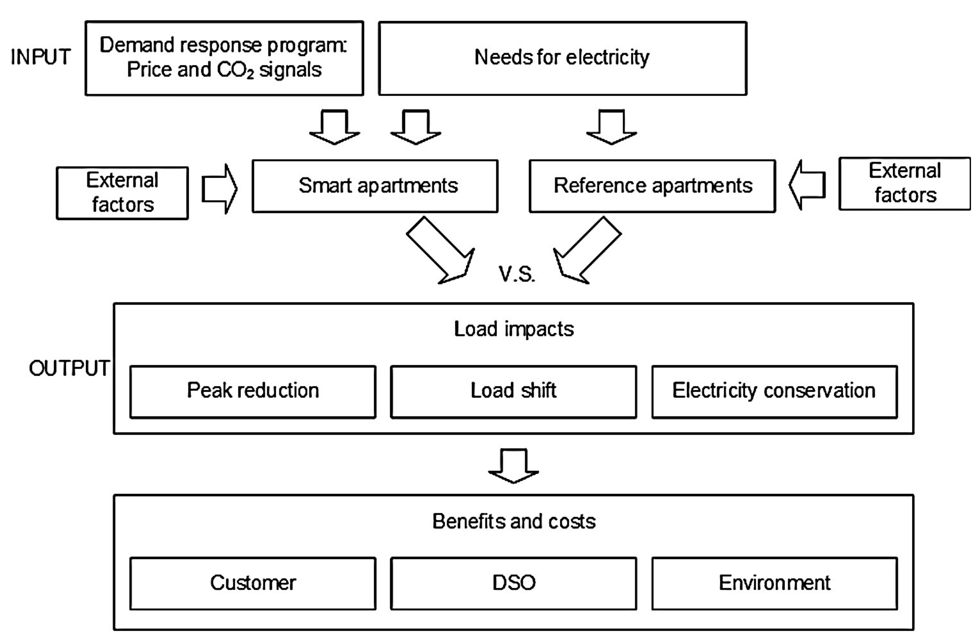

Fig. 1. The relationship between the inputs and outputs of a DR program.