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Residential emissions reductions through variable timing of electricity consumption

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HIGHLIGHTS

- Residential emissions reduced through shifted timing of appliance use.
- Locational marginal prices are used to predict changes in emissions from electricity generation.
- Reductions in emissions of SO_2, NO_x, CO_2e, Hg, and Pb from residential consumers of 12–26%.
- Significant emissions reductions are possible with a variety of fuel mixes.

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ABSTRACT

A real-time electricity emissions estimating tool, the Locational Marginal Price Emissions Estimation Method (LEEM), is assessed for its ability to reduce emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), global warming potential measured as carbon dioxide equivalent (CO_2e), mercury (Hg), and lead (Pb) on a residential scale. Through LEEM, residential electricity use can be shifted to low emissions times of day. In the study area of Michigan, USA emissions from five types of appliances (hot water heater, refrigerator defrost, dishwasher, clothes washer, and clothes dryer) were calculated to be theoretically reduced by 21–35% annually through a "best-case" application of LEEM. Annual emissions of the five pollutants, SO_2, NO_x, CO_2e, Hg, and Pb, can be reduced across the state by 429,000, 110,000, 87,240,000, 2.21, and 4.53 pounds, respectively – all without a reduction in the electricity used in the period of study. Despite different fuel mixes, similar emissions reductions were calculated for other regions of the country, as well.

1. Introduction

Power utilities continuously respond to changing electricity demand by dispatching or shedding generator output. In open markets, the price queue that is used to incentivize or discourage generation is the Locational Marginal Price (LMP). The LMP is the wholesale cost to serve the next incremental unit of load at a particular time and place. LMPs are published periodically in real-time (RT) as well as day-ahead (DA) projected prices.

Demand response is the ability of electricity consumers to reduce their loads in response to information signals such as information pertaining to peak load, high cost periods, or when system reliability is in jeopardy. According to a 2009 FERC Report, the residential class represents the "most untapped potential for demand response" [1]. With RT and predictive DA emissions estimates, residential customers can make informed decisions about the timing of the use of electricity-consuming devices.

In this work, probability distribution functions were used to tie RT and DA LMPs to four generator types: fuel oil, coal, natural gas, and a combined group of low cost, low emissions sources of electricity, which we have classified here as nuclear/renewable/hydro [2,3]. Each generator has a unique profile of air emissions based on the type of fuel consumed, efficiency of the equipment, and the type of pollution controls installed. This linked pricing and emissions information was developed into the LMP-Emissions Estimation Method (LEEM), which can be used to predict marginal emission rates [2,3]. By selecting the commercial pricing node located closest to a point of interest, LEEM provides the user with an estimate for the marginal generator and the marginal emissions. LEEM currently covers the same territory covered by the Midcontinent Independent System Operator (MISO) with four distinct fuel

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types (coal, natural gas, fuel oil, and a combined category of nuclear/renewables/hydro), which are linked to marginal electricity prices through a probability distribution function. Details on the LEEM Version 1.0 and 2.0s methodologies are provided by Carter et al. [2] and Rogers et al. [3], respectively.

The work presented here builds on earlier work that links LMPs with emissions. Wang et al. [4] used LEEM to drive an apportionment of electricity loads among several locations to minimize emissions. CO_2, SO_2, and NO_x were all reduced by a LEEM-based spatial shift in load more strongly than a strategy based on minimizing LMPs alone. LMPs were also used to determine the effect of electricity trading between Quebec with New York and New England on CO_2 emissions [5]. In this study, LMPs were linked to fuel type and then used to compare the relative emissions rate for Quebec over a three-year period.

A bidding strategy for electricity generating companies that optimizes both cost and emissions was modeled by Vahidinasab and Jadid [6]. They demonstrated that emissions and costs can be optimized simultaneously with benefits to both. Long-range marginal emission factors for CO_2 were modeled in the British electricity system based on expected changes to fuel mixes and power plants where an increase in low-carbon generator types is expected to drive changes marginal fuel types and marginal emission factors [7].

Valenzuela et al. [8] compared dynamic electricity pricing (excluding emissions) with user behavior with respect to time-flexible tasks. When high response rates were accounted for, additional issues were observed in the simulation including increased congestion and shifted load profiles.

In this paper we explore how LEEM 2.0 can be used to time electricity loads as a way to reduce overall air emissions from the residential sector. The main contributions of this paper are (i) quantitative single home and regional emissions reductions estimates based on emissions driven demand response (ii) a comparison of real-time and day-ahead LMPs and (iii) emissions reductions modeled and compared across three regions to explore the impacts of fuel mixes and regional emission factors on a demand response emissions reduction program.

2. Methodology

The study area is the state of Michigan. Emissions calculations come from the ReliabilityFirst Corporation – Michigan (RFCM) subregion of the U.S. Environmental Protection Agency's (EPA) Emissions and Generation Resource Integrated Database (eGRID) [9], which covers roughly the geographic area of Michigan's lower peninsula. The study year is 2009, which is the most recent year for which we have a nearly complete data set.

The selection of electricity consuming devices was limited to five appliances whose use was deemed ''shiftable'' in time. Many of these appliances could be placed on an automated controller set to run only when emissions would be minimized, however most appliances currently in residential use require user intervention to adjust the timing of when units run. For the purposes of this project, the appliances analyzed were the water heater, refrigerator defrost cycle, dishwasher, clothes washer, and clothes dryer. It was assumed that consumers would be unwilling to change the timing of the use of other electricity-consuming devices such as entertainment equipment, lighting, and other common appliances such as the stove. Notably, heating, ventilation, and air conditioning (HVAC) equipment was excluded from the study. Although HVAC equipment represents the largest portion of home energy use [10] and shows great potential for emissions reductions, a significantly more in-depth analysis including accounting for weather would be required to portray accurately the effect of the timing of HVAC on emissions.

A base case household was defined and the timing of the five household appliances was explored to estimate the emissions reduction potential from a single family home. A comparison of RT and DA-driven emissions reductions was performed as was an order-of-magnitude assessment on a regional scale. All emissions are estimated based on LEEM 2.0 [3]. Simulations were built in Microsoft Excel 2007.

2.1. Base case – single family home

The creation of an ''average household'' provided a basis for estimating the effect of timing the use of the five household appliances on emissions. For the purposes of this study, the base case household was assumed to be similar to the average residential customer of DTE Energy, a utility serving the study area of Southeast Michigan. At the time of the study (2011), the average DTE Energy residential customer's electricity bill was $85.00 per month corresponding to a consumption of 23 kW h/day [11]. This relates well to the average energy use of 23.8 kW h/day for all Michigan residents in 2009 [10]. The base case analysis assumes all appliances run on the preferred schedule shown in Table 1.

2.1.1. Electric water heater

Electric hot water heaters were identified as a convenient appliance to selectively time based on emissions. Although most hot water heaters run on natural gas, 21% of hot water heaters in Michigan are electric [10]. Commonly, electric hot water heaters cycle once each hour to ensure hot water is continuously available [12,13]. These cycles last about six minutes and draw approximately 5500 W [12,13]. Load control programs have been initiated by a number of utilities and programs that prevent electric hot water heaters from turning on for a set period of time during the day; commonly this is an approximately 6-h power interruption, often during peak electricity consumption (1–7 pm) [13]. In this study, we use a 6-h power interruption with a preferred shut off time of 1–7 pm in order to test the emissions reduction potential of load shifting in a hot water system.

2.1.2. Refrigerator defrost cycle

The refrigerator defrost cycle, like an electric hot water heater, is a prime candidate for an automated controller that allows the equipment to run when emissions are lowest. This controller could be incorporated into existing technology that allows refrigerator defrost cycles to avoid periods of peak electric demand [14] or high emissions. The defrost cycle varies widely for different ages and models of refrigerators. A draw of 450 W for the defroster is used by the U.S. Department of Energy (DOE) for a variety of models [15] and is assumed for this study. A defroster typically runs every 12 h of compressor run time. Depending on weather, insulation, and door openings, this can vary in time from 12 to 84 or more hours [15]. The default for the US EPA refrigerator analysis (ERA) is every 10 h, and for refrigerators equipped with higher efficiency adaptive defrost, the defrost cycle runs every 38 h [15]. For the purposes of this project, we use the midpoint between 10 and 38 h, or every 24 h. The US EPA refrigerator analysis model assumes a run time of 10 min, which we also apply here [15]. The average Michigan home has 1.24 refrigerators [10].

2.1.3. Dishwasher

Dishwasher use is not as invisible to consumers as the hot water heater and refrigerator defrost cycles, but use of dishwashers can reasonably be shifted in time. The dishwasher was assigned an energy use of 1200 W with a cycle length of 1.9 h [16]. The average