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# Energy, cost, and emission end-use profiles of homes: An Ontario (Canada) case study

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## HIGHLIGHTS

- Hourly electricity consumption data of seven end-uses from 25 homes are analyzed.
- Hourly load, cost, and emission profiles of end-uses are developed and categorized.
- Side-by-side analysis of energy, cost, and environmental effects is conducted.
- Behaviour and outdoor temperature based end-uses are determined.
- Share of each end-use in the total daily load, cost, and emission is determined.

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## ABSTRACT

Providing information on the temporal distributions of residential electricity end-uses plays a major role in determining the potential savings in residential electricity demand, cost, and associated emissions. While the majority of the studies on disaggregated residential electricity end-use data provided hourly usage profiles of major appliances, only a few of them presented analysis on the effect of hourly electricity consumption of some specific end-uses on household costs and emissions. This study presents side-by-side analysis of energy, cost, and environment effects of hourly electricity consumption of the main electricity end-uses in a sample of homes in the Canadian province of Ontario. The data used in this study are drawn from a larger multi-stakeholder project in which electricity consumption of major end-uses at 25 homes in Milton, Ontario, was monitored in five-minute intervals for six-month to two-year periods. In addition to determining the hourly price of electricity during the monitoring period, the hourly carbon intensity is determined using fuel type hourly generation and the life cycle greenhouse gas intensities specifically determined for Ontario's electricity fuel mix. The hourly load, cost, and emissions profiles are developed for the central air conditioner, furnace, clothes dryer, clothes washer, dishwasher, refrigerator, and stove and then grouped into eight day type categories. The side-by-side analysis of categorized load, cost, and emission profiles of the seven electricity end-uses provided information on when the maximum usage of specific end-uses occurs and which end-uses are "behaviour based" and which are "outdoor temperature based". The share of each end-use in total household load, cost, and emissions is determined and load, cost, and emission share distributions are compared. The results of this study present valuable information to homeowners for reducing their electricity consumption and to system operators for reducing peak loads.



## 1. Introduction

The energy consumption of the Canadian residential sector accounted for 17% of the nationwide energy use and was responsible for 14% of the total greenhouse gas (GHG) emissions in 2011 as presented in the Energy Use Data Handbook of Natural Resources Canada (NRCan) [1]. The electricity consumption for space and hot water heating equipment, appliances, lighting, and space cooling equipment in Canadian single detached homes represented 35% of the total household energy consumption [1]. In Ontario, where about 2.9 of the 7.6 million single detached homes in Canada are located, the average annual electricity consumption per household was

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8114 kW h in 2011 with almost half of the electricity consumed by appliances[1] and lighting [1], and the remainder by space heating, space cooling, and water heating. Due to the improvement of the building envelope standards and technological advances in appliances and lighting system designs, a decrease in electricity consumption of single detached homes was observed in the last 20 years in Ontario [1].

The electricity supply in Ontario is a diverse mix of sources and represents a significant change since the 1990s. The share of coal power plants has fallen from 22% in 1990 to 2.1% in 2013 [3,4]. The remaining coal power plants have been converted to use other fuels or shut down by the first half of 2014. In 2013, 59.2% of electricity generated in Ontario came from nuclear power plants, while 23.4% came from hydroelectric facilities, 11.1% from natural gas, 3.4% from wind, 2.1% coal, and 0.8% other fuel type plants [4]. The residential sector accounts for about one-third of the electricity consumption in Ontario [5]. Due to changes in hourly electricity demand, the electricity supply mix of Ontario changes hourly and consequently, the GHG intensity of electricity generation also changes hourly. The hourly electricity generation data obtained from Independent Electricity System Operator (IESO) [4] show that the shares of the natural gas and coal power plants increase substantially at peak hours, whereas the nuclear share decreases, and wind and hydro shares do not change. Thus, hourly GHG intensity reaches higher values during the periods in which the demand in Ontario is higher.

In Ontario, virtually all residential electricity customers pay time-of-use (TOU) prices [6]. There are three TOU price periods: off-peak (when demand is lowest, and thus the least expensive period), mid-peak (when demand is moderate), and on-peak periods (when demand is highest, and thus the most expensive period). Residential electricity consumers in Ontario have the opportunity to reduce their electricity costs by shifting their consumption from on-peak and mid-peak periods to off-peak periods [7]. Due to the wide use of air conditioning systems during hot and humid summers and the limited amount of electric space heating, the maximum electricity demand in Ontario usually occurs on summer weekday afternoons [8].

While an understanding of the annual total and end-use household electricity consumption patterns is important, the temporal distributions of the end-use loads play a major role in determining the potential savings in residential electricity costs and emissions. Many electricity utilities have conducted end-use load monitoring campaigns to determine the hourly profile of various end-uses since the 1980s. One of the first published end-use hourly load research studies was conducted by Pratt et al. [9] in which 13 end-uses at 288 homes in the Pacific Northwest, USA were monitored. In addition to determining the annual end-use loads and the effect of homeowners' demographics on the loads, the average hourly load-curves of the main end-uses were determined.

In a study by Sidler et al. [10], electric cooking appliances, clothes dryers, and irons were metered in ten-minute intervals for a month at 98 homes in central France to determine the annual load and the share of standby consumption of each appliance. In a later study conducted in 1997, Sidler et al. evaluated the saving potential in the residential sector of four European countries using ten-minute interval metered data of various appliances and lighting fixtures of 400 houses [11,12]. The saving potential was estimated based on reducing the share of standby electricity loss, replacing cold appliances and dryers with the most efficient models, and replacing existing lamps with compact fluorescent ones.

In addition to monitoring space heating and cooling, domestic hot water heating, clothes drying, range, and pool end-uses of 204 homes in Central Florida, indoor and outdoor temperatures were also recorded in 15-min intervals for a year in a load research project reported by Parker [13]. Hourly load shapes of the monitored end-uses by month and day of week, and the impact of outdoor temperature on space heating, cooling, and domestic hot water (DHW) heating were examined. The weather sensitivity of space heating, cooling, DHW, and refrigerators/freezers was also studied by Hart and de Dear [14] using 18 month monitored data of 136 homes in Sydney, Australia.

Providing information to homeowners on the amount of actual hourly consumption at the appliance level is one of the ways to encourage the implementation of electricity savings measures at homes. Ueno et al. [15] examined the effect of installing in-house monitoring and information systems at nine Japanese homes. The use of in-house systems that monitored appliance electricity consumption and room temperatures and displayed actual hourly/daily electricity costs of various appliances and appliance specific energy saving tips resulted in, on average, a 9% reduction in total electricity consumption.

The reduction in energy consumption due to energy efficiency improvements can be lower than the estimated values as a result of the increase in demand for energy services. For example, lower than expected energy savings can be achieved after replacing a less efficient furnace due to longer heating periods and/or higher heating temperatures [16]. This pattern is termed the rebound effect. The range of rebound effects for end-uses varies between 0% and 30% based on socio-economic characteristics of the users [17]. The studies on the effects of various interventions on the homeowners' energy use behaviour are examined by Abrahanse [18]. These intervention studies include commitment and goal setting, providing information and feedback on energy use and/or savings, and rewards.

Monitored end-use electricity consumption data can also be used together with survey data to examine the effect of behaviour and socio-economic characteristics of the consumers on the specific appliance usage patterns, to determine the potential in electricity savings, and to develop sustainable and applicable energy and environment policies for the residential sector [19–22]. Simulation models are also used by researchers to develop the optimal savings in demand and consequently cost and GHG emissions. Pietila et al. simulated the hourly electricity consumption of a residence in Toronto, Ontario, Canada, using monitored data [23]. The simulation results show that a reduction of about 50% in demand can be achieved using several architectural, control, efficiency, and occupant behaviour measures during peak demand hours on summer weekdays. The effects of using price-responsive smart appliances and time based electricity tariffs on the household electricity cost and peak load reductions were studied by Gottwalt et al. using a simulation model for a residence in Germany [24]. In another study, a demand model that utilizes data from smart meters to develop appliance profiles is introduced by Gruber et al. [25]. The use of smart appliances, meters, and/or in home displays is expected to stimulate innovative approaches to the evaluation of monitored end-use data [26].

Another approach in providing end-use level energy consumption data is Nonintrusive Load Monitoring (NILM) where only a single whole-house meter and software that runs on signal processing and/or machine-learning algorithms are used [27]. NILM was first introduced by Hart [28], and has been used for over 20 years with many advancements being achieved in software development [29–31]. Other advantages of NILMs are its low cost, easy installation, removal and maintenance, and not requiring any in-house wiring

[1] Includes cooking appliances (gas stoves and ovens, electric stoves and ovens, microwave ovens, and propane or gas grills); cooling appliances (evaporative coolers, attic fans, window or ceiling fans, and portable or table fans); and refrigerators, freezers, clothes washers, dishwashers, and other appliances such as televisions, video cassette recorders, digital video disc players, radios, computers and toasters [2].