High-resolution residential electricity consumption trends under fixed and time-of-use rates

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Abstract

Efforts to alter building electricity consumption by reducing peaks and filling valleys via time-of-use rates is now commonplace among utilities as they attempt to reduce required peak generation capacity and integrate renewable electricity generators. These schemes affects consumer behaviour and drives the implementation of new technologies such as programmable thermostats, cycle start delays on electric appliances, or more significantly, electric thermal storage (ETS). The objective of this research is to provide trends of residential electricity consumption to inform building simulationists as they apply and modify standardized operating schedules. Here a full year (2012) of measured 15-minute electricity demand data from 48 houses located in Nova Scotia is evaluated. Three groups emerge: (i) non-electric HVAC, (ii) fixed rate electric HVAC, and (iii) time-of-use rate electric HVAC. Major trends are investigated, including the increase in non-heating loads in the winter, variations in the timing of load peaks, both through the week and through the year, and systematic errors in the response of residential load-shifting equipment to time-of-use rates.

1 Introduction

Buildings are a major end-use consumer of electricity, and notably impact the provincial electricity demand profile. Electricity may be used to service all end-uses within the sector, including space heating, space cooling, domestic hot water, appliances, and lighting. In the province of Nova Scotia, 29% of households use electricity for space heating. (Statistics Canada 2013). This, combined primarily with appliance and lighting, results in the sector consuming approximately 35% of the 11.5 - 12.5 TWh of electricity produced each year in Nova Scotia (Statistics Canada 2012). The seasonal, weekly, and sub-hourly nature of un-controlled residential electricity consumption is of great interest to electricity grid managers as they work to integrate and coordinate it with new non-dispatchable generation (e.g. wind turbines, solar photovoltaics). This has led to the support and use of new technologies (e.g. electric thermal storage, ETS) and new rate structures (e.g. time-of-use/day) aimed at modifying the hourly demand profile. Primary objectives of these tools are: (i) clipping demand peaks, which reduces the need for gross dispatchable generating capacity, and (ii) filling of demand valleys, which keeps demand from declining precipitously to the level of non-dispatchable generation and causing widespread system instability.

Electricity grid system operators are interested in building sector modeling and simulation that accurately estimates the impacts that new technologies and policies will have on electricity consumption and demand profile. As such, building simulationists must increase the fidelity of electricity schedules and profiles used within their models from simple fixed values (e.g. ASHRAE) to representative inter-hour variations. This present research paper attempts to inform building simulationists on specific features and relationships of these electricity profiles, to aid them in modifying said schedules. It is intended in the future that a new set of profiles, similar in format to (Armstrong, Swinton et al. 2009, Swan, Ugursal et al. 2009), will be created and disseminated so as to add to the tools available for such purposes.

This paper examines the electricity profiles from measured residential units and compares them across several groups and rate structures. The provincial electricity utility Nova Scotia Power has two domestic rates: a flat rate which is constant at 14.25¢/kWh throughout the year, and a time-of-day/use (TOD) rate (18.6-, 14.25-, and 7.3¢/kWh) which varies seasonally, daily, and hourly roughly following times of high, medium and low load. Details of the TOD schedule are presented graphically in Figure 1.

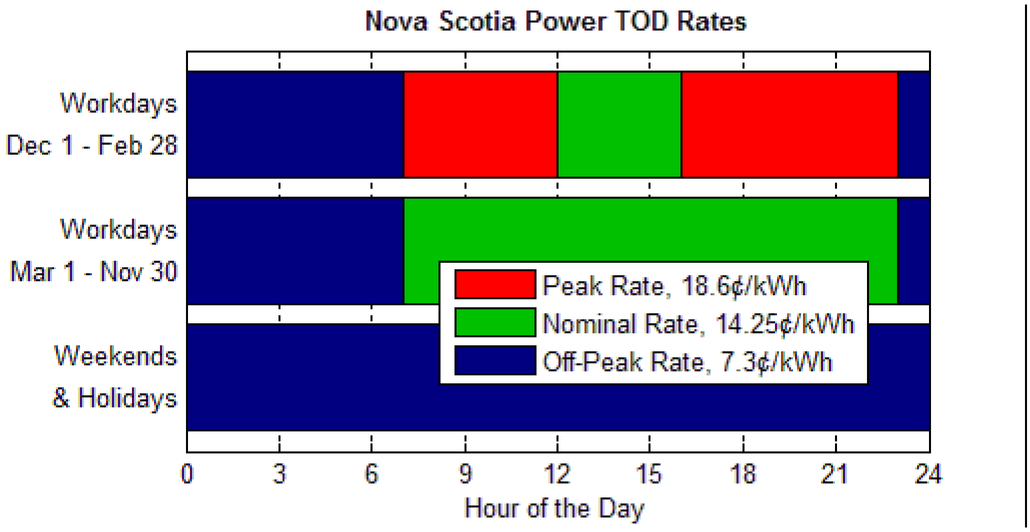

Figure 1: Nova Scotia Power domestic service time-of-use/day electricity tariff schedule

2 Data

A sample of houses throughout Nova Scotia were randomly selected for monitoring by Nova Scotia Power. Within the study, average electricity demand over 15-minute periods was measured and recorded throughout calendar year 2012. This sample represents the length and breadth of Nova Scotia, but given the ubiquity of a shoreline on the North Atlantic, there is fairly little climactic diversity in the province; Heating degree days in January and February (the amount the daily mean temperature is less than 18°C) average from 20 – 28 per day across the province, and cooling degree days (the amount the daily mean temperature is greater than 18°C) average from 0 – 4 per day in July and August.

The houses were divided into three classes based on primary heating technology, specifically 1) houses heated by means other than electricity, 2) electrically heated houses on a standard (flat) rate plan, and 3) houses equipped with ETS and subject to TOD electricity rates. General electrical characteristics of these three classes are given in Table 1. Differences between these classes may exist, including those related to housing age, size, insulation, as well as economic factors. Such differences were not recorded in the dataset.

Table 1: Summary of measured residential electricity consumption groups

Class	**1**	**2**	**3**
Heating Fuel	Not Electricity	Electricity	Electricity
Billing Rate	Flat	Flat	TOD
Number in Sample	9	14	25

Max. 15-Minute Demand (kW)	16.2	23.0	31.4
Ave. 15-Minute Demand (kW)	1.6	2.8	3.3
Max. Daily Consumption (kWh)	158	248	349
Ave. Daily Consumption (kWh)	39	66	79
Min. Daily Consumption (kWh)	27	32	12

3 Analysis

The data described in this paper reveal a number of interesting trends in electricity consumption. In this section, several of these trends will be presented in figures of timeseries load, and briefly described. The significant findings will be discussed in greater depth in the following section.

3.1 Seasonal load variations.

Figure 2 shows the seasonal variation in provincial and residential load. Changes in load timing driven by TOD pricing will have negligible effect on energy consumption over time periods of several days or weeks, so for this analysis the two classes of housing with electric heat (classes 2 and 3 in Table 1) have been aggregated into a single group. Thus the three lines in Figure 2 represent total provincial load (red, right hand y-axis), residential loads from houses with electric heat (blue, left hand y-axis) and those with other heating fuels (green, left hand y-axis). Values measured on 15-minute intervals are averaged over half a month to give 24 values.

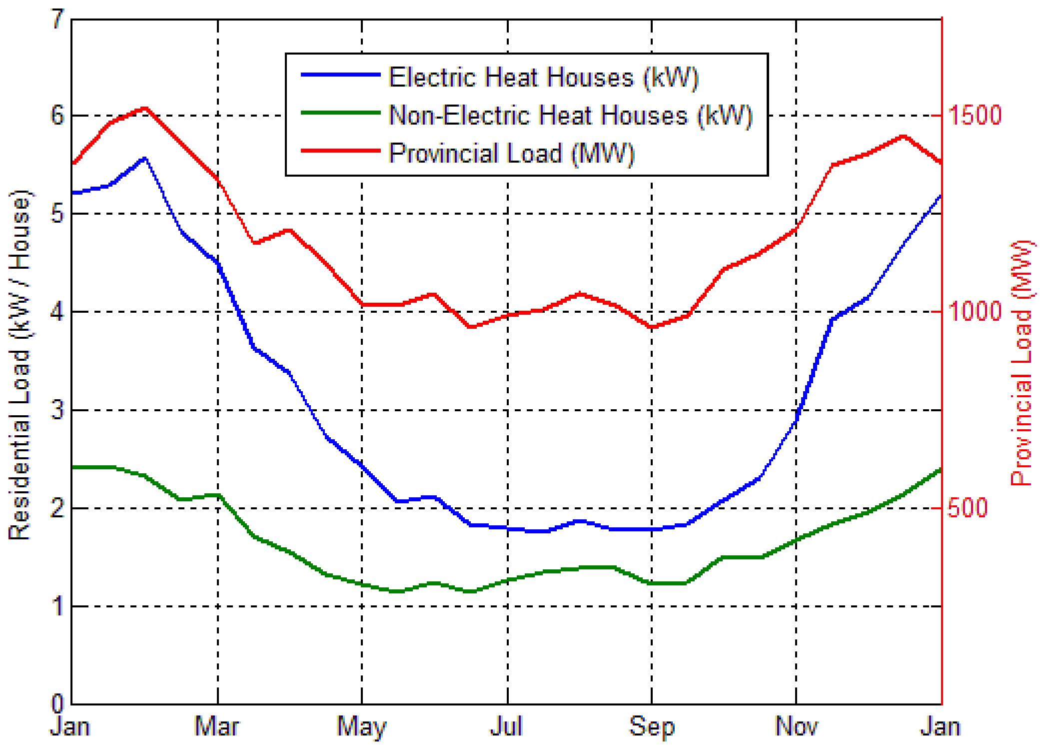

Figure 2: Monthly average electricity demand of the three house types in comparison with total provincial load

The differences in average load due to residential heating can clearly be seen as the difference between the green and blue lines in Figure 2 (though some of this difference may be accounted for by characteristic differences in the housing stock, such as age, size, household income etc.). Also of interest is the distinct variation in average load through the year of the non-electrically heated houses (green line). In contrast to assumptions often made about non-heating electric loads (ASHRAE, 2005), these data show that such loads vary by a factor of 2 through the year.

Of importance to grid managers is the great similarity between residential electricity demand and the provincial electricity demand. This suggests that appropriate management of residential loads would be of great significance to total regional loads. In fact, the total load of electrically heated houses (blue line) varies by about a factor of three throughout the year, far more than the provincial load as a whole (red line). This result emphasises the importance of a good understanding of residential loads, both for heating and other purposes, to the provincial grid.

3.2 Hourly and weekly load variations

The primary focus of TOD rates and associated load-shifting technology such as ETS is modifying the load profile on timescales of several hours to a day. Specifically, thermal storage systems are generally sized to store less than 18 hours' worth of heat (Steffes 2008, Arteconi, Hewitt et al. 2012, Arteconi, Hewitt et al. 2013). As a consequence, the most important results of this data derive from an investigation of loads through the day. These are presented in Figure 3, where the monthly average hourly demand profiles are given. In Figure 3, three columns of plots represent the load on weekdays on the left, Saturdays in the middle, and Sundays on the right. The three rows of plots depict total provincial load in Nova Scotia on top, the residential load of flat rate customers in the middle, and the residential load of TOD customers on the bottom.

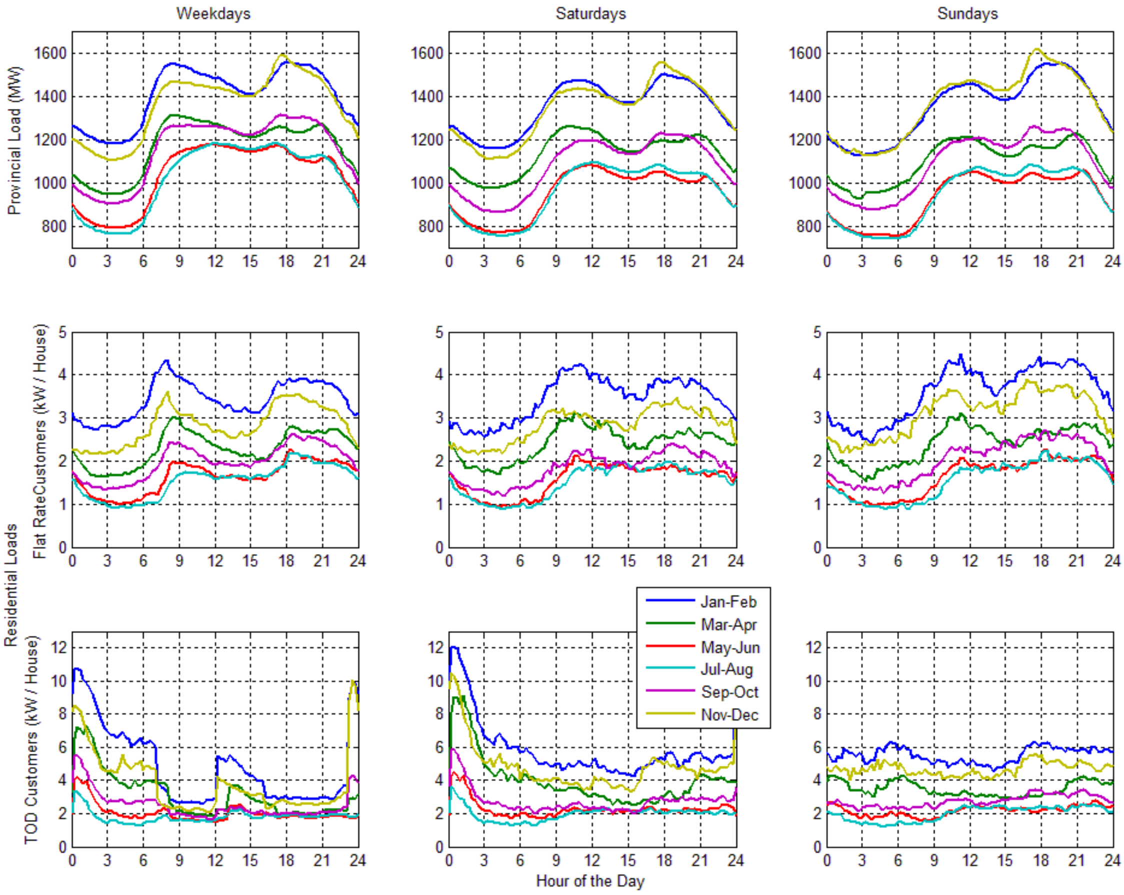

Figure 3: Detailed annual average daily electricity demand profiles (by day type) of specific residential groups and total provincial load

Note that while for Figure 2 the three housing classes were grouped according to whether they used electricity for heat or not, here they are grouped according to whether they are subject to TOD rates. As described previously, the objective of TOD is to shift loads within a day, so for this 15-minute analysis, this grouping is more appropriate. Another difference in the treatment of data lies in grouping weekdays, which include statutory holidays, separately from Saturdays and Sundays. Initial research found this grouping produced more consistent results, particularly with respect to the loads of TOD rate customers.

4 Results, significant observations, and trends

From Figures 2 and 3, several significant trends are identifiable that could be of benefit to building simulationists.

4.1 Non-Heating loads double in the winter.

As discussed in section 3.1, the average load of houses not heated with electricity is not constant through the year. Loads for lighting, appliances etc. increase during the winter by roughly a factor of two. While the collected data do not resolve to the level of individual appliances or circuits, we speculate that several seasonal factors contribute to this. For one, when daylit hours grow shorter, the reliance on artificial light must increase. Secondly, as cold and wet weather makes outdoor activities less pleasant, a greater proportion of leisure hours may be spent at home.

4.2 Morning peak loads shift through the week and the season

Of particular interest to energy modeling is that for houses on flat rate electricity, the timing of morning load peaks (and evening peaks to a smaller extent) is a function of the day of the week, and the season of the year.

4.2.1 Loads peak earlier in the winter

The farther into winter, the earlier the demand peak gets, appearing as early as 7:30am in January and February. In warmer months, morning ramp-up of load (to call it a peak would be inaccurate, as load plateaus but does not fall during the day) occurs later in the day, as late as 9:00 am in July and August (times on the plots are local time, which includes Daylight Savings). We speculate that this trend likewise relates to doing more things indoors, and needing more artificial light to do them.

4.2.2 People sleep in on the weekend

The middle row of plots in Figure 3 shows the intra-day load of houses on flat electrical rates throughout the year, which include houses that heat with electricity and others that do not. Such houses have a double load peak, fairly characteristic of heating regimes when morning and evening activity at home driving up demand for electricity. These data show that while the height (amplitude) of these peaks are reasonably consistent between weekdays and weekend days, on weekends they occur significantly later in the day. January and February morning peaks occur at about 7:30 am on weekdays, but don't occur until at least 10:00 am on Saturdays and Sundays. The seasonal shift in morning peak loads discussed in section 4.2.1 are additive to this weekend effect, pushing summer weekend morning load peaks to near noon.

4.3 Non-Heating Loads are Shifted under TOD Rates

Summer TOD rates can be compared to summer flat rate loads. Even for months when space heating loads will be all but non-existent, the load profile charts for houses on TOD electric rates (July and August aqua lines; bottom set of plots in Figure 3) still show a pattern that corresponds to the times of day of low rates. This suggests that household loads other than spacing heating are also being affected by the economic drive of lower prices. These loads may include dishwashers and laundry, as many modern large appliances include start time delay options.

4.4 TOD response is largely effective

Contrasted with the loads of houses on flat rates (middle row of plots in Figure 3), the hourly load profile of houses on TOD with ETS (bottom row of plots in Figure 3) are dramatically different. Those differences are highlighted by a spike in load at 11:00 pm, when electric rates switch to off-peak regardless of season or the time of week (Figure 1). The 11:00 pm peak lasts much of the night (at least in winter), and is followed by a dramatic drop in loads during morning peak times of 7:00 am – noon, and evening peak periods of 4:00 pm – 11:00 pm. For the most part, this load profile is exactly as grid managers would wish it, as it is almost diametrically opposed to the loads of houses on flat rate, and to the provincial loads as a whole (top row of plots in Figure 3).

4.5 TOD response is often incorrect

A closer examination of the residential loads of houses on TOD rates (bottom set of plots in Figure 3), show that the response of load-shifting equipment such as ETS heaters is not necessarily exactly matched to TOD rates (Figure 1). Four examples of this are:

- Daylight savings time has a clear impact on load timing. This can be identified in the load response for March & April (dark green lines in Figure 3), which are shifted forward an hour relative to the January – February loads (Daylight savings moved clocks forward on 11 March, 2012, and back on 4 November).
- Many holidays exhibit variations in load profile corresponding to a workday TOD rate response (not shown).
- Similarly, variations in load do not vary identically with the seasonal shift away from high peak rates, which only apply in December, January, and February. The jump in load in the middle of the day in March and April for TOD houses on weekdays (dark green lines in Figure 3) does not correspond to a change in electricity rates.

These examples suggest that the controlling signal of the dominant load-shifting equipment are not programmed with, or do not receive, very sophisticated or comprehensive schedules. Holidays, and even the non-winter rate structure (which should apply 1 March – 30 November) seem to be absent at least in some cases.

5 Discussion

The application of these results to the broader southeast of Canada and the US northeast must be made with care. While electricity is the predominant heating fuel in 29% of Nova Scotia's housing stock, electric residential heat in Prince Edward Island is almost non-existent, while in New Brunswick 66% of households rely primarily on electricity for heat (Statistics Canada 2013). Across the US boarder in the state of Maine only 4% of homes use electricity as their primary heating fuel (EIA 2013b). As a result, the 35% of electricity production that serves the residential sector in Nova Scotia falls between the corresponding fractions in PEI, NB, and ME, where 20% and 58% 39% of electric load (respectively) is residential (Statistics Canada 2013, EIA 2013a)

6 Conclusion

We have presented research findings from a new, detailed, diverse and precise set of residential load data, collected on 15-minute timesteps in Nova Scotia, Canada. These data can facilitate more accurate residential electricity consumption modeling, as they demonstrate several characteristics and patterns of residential energy use not customarily represented in standardized schedules. These include the increase in non-heating loads in the winter by a factor of 2 over summer the summer minimum, from an average of 1.25 kW to roughly 2.5 kW per house. Secondly, for houses on flat rate electricity pricing structure, the timing of load peaks varies significantly, both through the week and through the year, with weekends and warmer weather both driving morning and evening load peaks later in the day. Third, though the effect of automated load-shifting equipment is very effective at modifying the residential load profile, there remain systematic errors in this with respect to the precise TOD rate structure.

Acknowledgements

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References

Armstrong, M., Swinton, M.C., Ribberink, H., Beausoleil-Morrison, I. and Millette, J., 2009. Synthetically derived profiles for representing occupant-driven electric loads in Canadian housing. Journal of building performance simulation, 2(1), pp. 15-30.

Arteconi, A., Hewitt, N.J. and Polonara, F., 2013. Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. Applied Thermal Engineering, 51(1-2), pp. 155-165.

Arteconi, A., Hewitt, N.J. and Polonara, F., 2012. State of the art of thermal storage for demand-side management. Applied Energy, 93(0), pp. 371-389.

ASHRAE Handbook; Fundamentals (SI Edition). 2005. Atlanta, GA,

EIA, DOE, 2013. Monthly Electric Utility Sales and Revenue Report with State Distributions. f8262012. Washington, DC: US Department of Energy.

EIA, DOE, March 27, 2013, 2013-last update, U.S. Department of Energy - Clean Energy in My State; Maine Residential Energy Consumption; [Homepage of US Department of Energy], [Online]. Available: http://apps1.eere.energy.gov/states/residential.cfm/state=ME [Jan 4, 2014, 2014].

STATISTICS CANADA, 2013. Households and the Environment: Energy Use 2011. 11-526-S. Ottawa, Canada: Statistics Canada.

STATISTICS CANADA, 2012. Energy Statistics Handbook; First quarter 2012. 57-601-X. Ottawa, Canada: Statistics Canada.

Steffes, P., 2008. Renewable energy and electric thermal storage, November 13-14, 2008.

Swan, L.G., Ugursal, V.I. and Beausoleil-Morrison, I, 2009. A database of house descriptions representative of the Canadian housing stock for coupling to building energy performance simulation. *Journal of Building Performance Simulation,* 2(2), pp. 75-84.