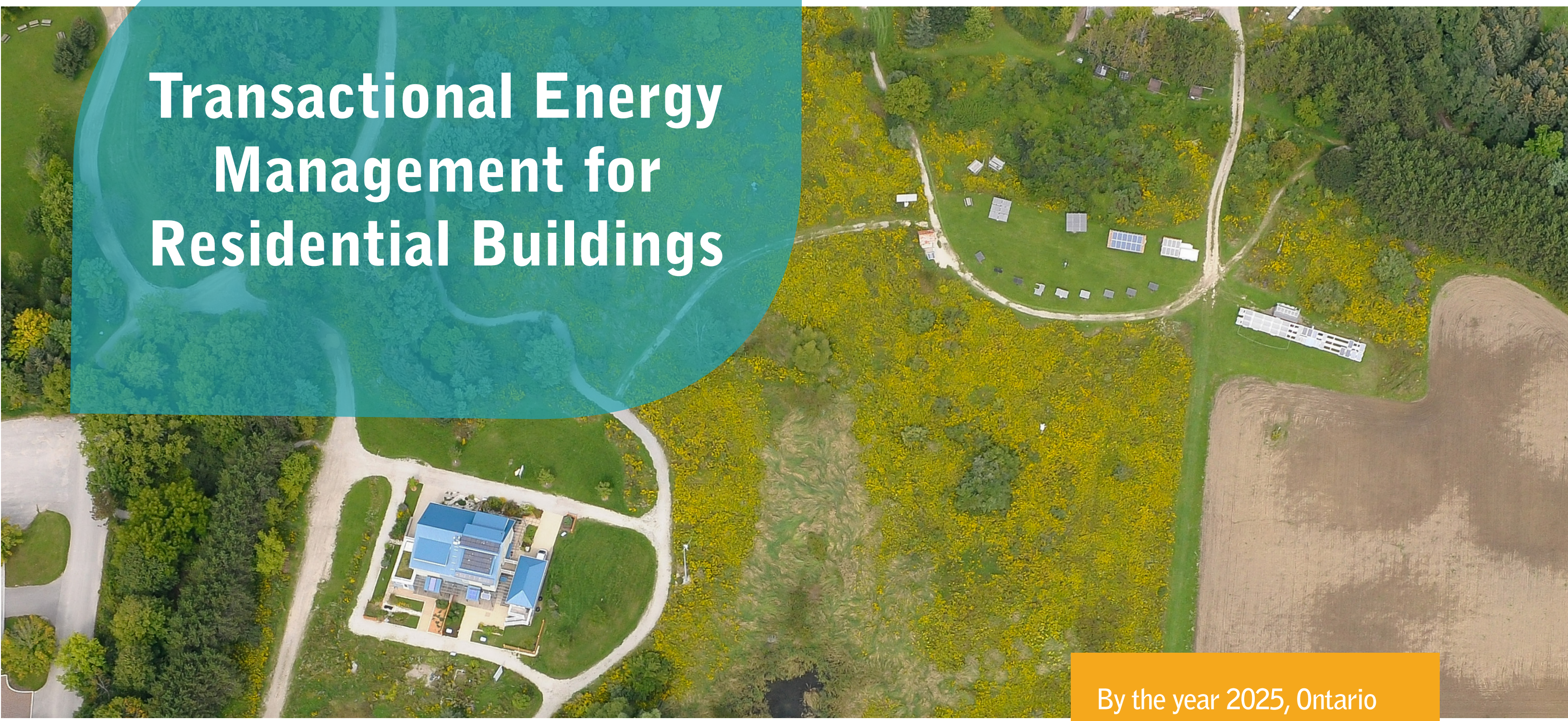
TECHNICAL BRIEF

Sustainable Technologies
EVALUATION PROGRAM

Smart Grid

Transactional Energy Management for Residential Buildings

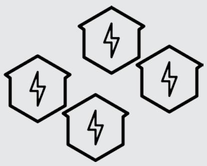


INTRODUCTION

With increasing concern towards carbon emissions and climate change, the ways in which we produce and consume energy are changing. The rise of renewable energy is leading to more distributed generation – moving away from large, centralized generation facilities towards smaller generators spread out over a large area. This distributed generation can lead to more robust, cleaner, and resilient electricity grids. Not only is electricity generation changing, but so is the way in which it is being used. Historical data shows that while the number of households and businesses in Ontario is increasing, the energy *intensity* of buildings (the energy consumed per building) is decreasing due to conservation and efficiency measures (Ministry of Energy, 2013).

These changes to the energy landscape bring about the need for smarter energy management technologies to manage the growth of smart generators and devices on the grid. Some of these technologies are already in use today and can vary in both size and complexity, ranging from individual smart thermostats in homes to widespread demand response (DR) programs across a local distribution network. This work investigates an energy management technique known as *Transactional Energy* and presents results from both real-world demonstration and simulations.

Whether a smart thermostat or simple countertop display, energy management systems (EMS) help us understand where and when we use energy, providing valuable insight that can help identify where savings can be achieved. Knowledge and understanding are critical steps towards smarter energy consumption within buildings and communities.



By the year 2025, Ontario aims to meet 10% of its peak electricity demand with demand response (DR). Time-of-use (TOU) electricity pricing is a form of DR, incentivizing homeowners to use less electricity at peak hours. Electric utilities have also implemented more active DR, sending signals directly to consumers requesting reductions in energy consumption for a brief period. This type of practice will become much more common as a shifting electricity landscape leads to greater interaction between consumers and utilities.

Transactional Energy

Transactional energy is a type of energy management system (EMS) that is highly scalable, with a variety of building-focused applications. Simply put, it involves the exchange of energy between participants via the negotiation of virtual energy contracts. Participants within the "energy market" of a transactive network can include smart or flexible loads (e.g. adaptive thermostats), distributed generators (DGs), entire buildings, or the grid itself. There is no single, rigid model in which a transactive energy system must operate, but many guidelines for their design and implementation have been proposed (PNNL, 2014).

A transactive-based building control framework can provide a variety of benefits. For the energy consumer, these include energy cost savings and monitoring and verification (M&V) services. For the utility, this framework allows for active two-way communication with consumers, acting as a means to provide grid services such as peak load reduction and distributed generation management. Another interesting benefit for consumers is that it considers the thermal comfort of the buildings' occupants while providing grid services, such that demand response (DR) signals, for example, do not compromise the needs of the consumer.

As an example, transactive-based thermostats operating on a summer day in a community of buildings would each programmatically request energy for space cooling (kWh) in the form of a bid ($/kWh) that is proportional to the "need" of the device. The relationship between a device's need and its bid is illustrated in Figure 1. In this case, as the zone gets hotter, the thermostat would be willing to pay more and more for cooling energy. A transactional system can help to coordinate multiple thermostats throughout a community such they do not all come online at the exact same time, reducing peak loading situations by respecting a utility-defined community "demand cap" (kW).

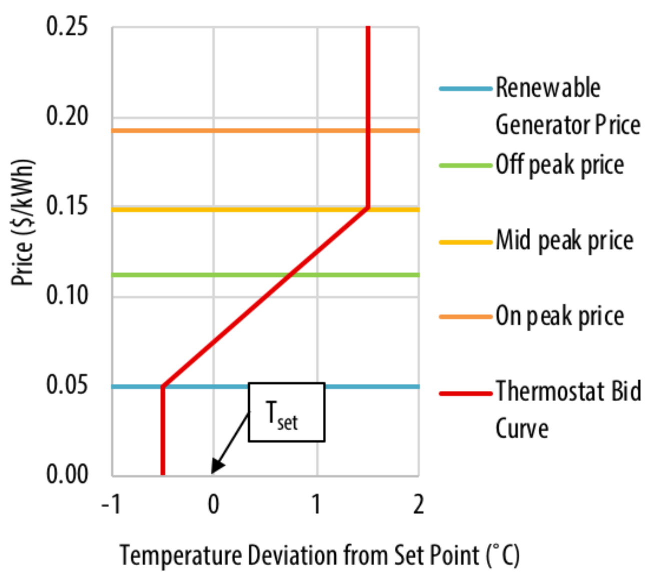


Figure 1. An example of a thermostat bid curve based on a zone's deviation from its set point relative to TOU energy prices. The upward slope of the line indicates that the bid price of the thermostat increases as the deviation from the set point increases, up to a point at which it will bid whatever the current cost of energy may be in order to satisfy its call for heating or cooling. The intersection of the bid curve with each price curve indicates the point at which it would be willing to pay for each respective energy source.

The basis of the transactive energy management system investigated in this work follows the principles of the given examples. However, there are many potential applications for this type of system not explored in this work.

Energy Marketplace

The *energy marketplace* is the software platform in which virtual contracts are negotiated. The marketplace, illustrated in Figure 2, was developed based on simple economic supply and demand principles.

At regular intervals (minutes to hours in length), the marketplace collects and evaluates all supply and demand bids that have been made since the previous market evaluation. It then calculates the market-clearing price, the point at which the supply and demand bid curves intersect. All loads on the demand curve are then awarded virtual contracts if they lie *above* and to the left of the clearing price, while all generators are awarded virtual contracts if they lie *below* and to the left of the clearing price. If a load did not receive a contract, it is because a consumer deemed it as low-priority and was not willing to pay very much for the energy to power it.

Not pictured in Figure 2 are critical loads. A critical load is anything that *must* have its demand bid awarded. For building operation, a critical load could be an appliance like a stovetop, a refrigerator, or a heating/cooling system whose zone temperature has deviated well beyond its thermal comfort threshold. For any of these devices, it is unrealistic to expect the needs or comfort of an occupant to be sacrificed. For the purposes of this work, critical loads have been neglected.

It should be noted that the marketplace would not drive up the cost of electricity set by the utility. Rather, it would allow consumers to selectively (and programmatically) turn off their non-critical loads over the course of a day as electricity prices increase. The relatively low operating cost of renewables is reflected in the marketplace, allowing lower priority loads to come online as renewable energy penetration increases.

STUDY SITE & APPROACH

The Archetype Sustainable House (cover image) is comprised of two semi-detached houses, named House A and House B, which have been awarded LEED™ Platinum, EnergyStar, and GreenHouse certifications. More information on the Archetype Sustainable House is available at sustainabletechnologies.ca.

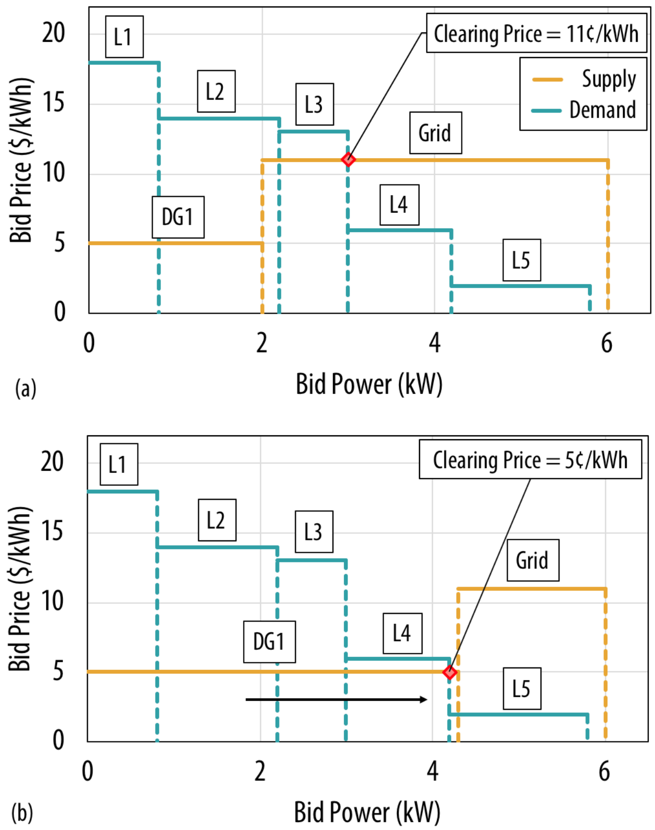


Figure 2. An example of supply and demand curves evaluated in the Energy Marketplace at two consecutive points in time. The bid price of a load (L1 – L5) or supplier (DG1, Grid) is indicated by the height of the respective section of the curves, while the requested or available power is the width of each section of the curves. From (a) to (b) DG generation increases with time, lowering the market clearing price and allowing L4 to power on. Loads can also modify their bids over time.

This work focused on the control of a subset of the systems at the two houses. Simulations were performed in MATLAB on a calibrated model of House A, investigating the impact of a transactional energy system on the air source heat pump (ASHP) used by the house for both space heating and cooling. Simulations also considered the 4 kW of roof-mounted PV on House B and a 25 kWh battery bank located on site. The transactional energy system was also demonstrated in the real world using integrated LabVIEW-MATLAB software. The real-world system operated on House B's heat pump water heater (HPWH) and 4 kW of roof-mounted PV.

FINDINGS

The transactional energy control system was successfully implemented in the real world. Three controllers were run separately and simultaneously, responsible for the bidding and control of the marketplace, HPWH and PV. Throughout the demonstration, the PV and HPWH agents were removed from and re-added to the marketplace. This did not halt operation and validated the plug-and-play nature of this control system. This system was designed to be flexible so that it may be used for additional transactional experiments in the future.

A transactional energy control system can easily account for thermal comfort preferences, potentially leading to reduced energy consumption and costs. Figure 3 illustrates a range of bid curves that represent varying thermal comfort preferences. As the steepness of a bid curve decreases, the homeowner's thermal comfort flexibility, or "willingness to participate" increases. Table 1 summarizes the simulated cost savings associated with each of these bid curves. As an example, the ASHP represented by Bid curve 4 will not pay for electricity, even at off-grid electricity prices, until the indoor temperature raises beyond 2˚C above the desired set-point.

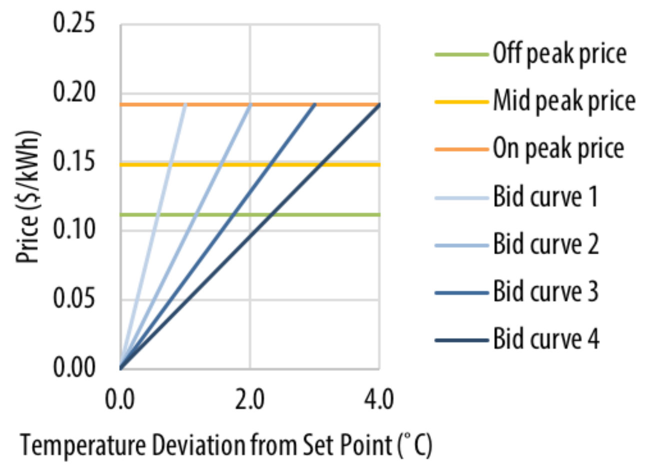


Figure 3. Four example ASHP bid curves compared to variable electricity prices (as of May 2017) used in space heating simulations. From 1 to 4, the curves represent an increasing "willingness to participate", or a greater threshold for thermal *dis*comfort.

Table 1. Summary of simulated direct annual electricity savings for a homeowner and average zone temperatures associated with transactional energy-enabled temperature setbacks. Note that these numbers do not capture the benefits to the utility that transactional systems are capable of achieving.

Control	Annual Consumption (kWh)	Annual Variable Cost ($)
Non-transactional thermostat	5183	$729.73
Bid curve 1	5021	$700.28
Bid curve 2	4676	$645.03
Bid curve 3	4353	$593.74
Bid curve 4	4057	$547.62

In reality, a homeowner's willingness to participate would vary with time depending on their particular needs. Some modern smart thermostats are already equipped with artificial intelligence that learns a homeowner's thermal comfort preferences overtime, meaning that the willingness to participate (i.e. the bid curve) can be learned over time without any direct action required by the user.

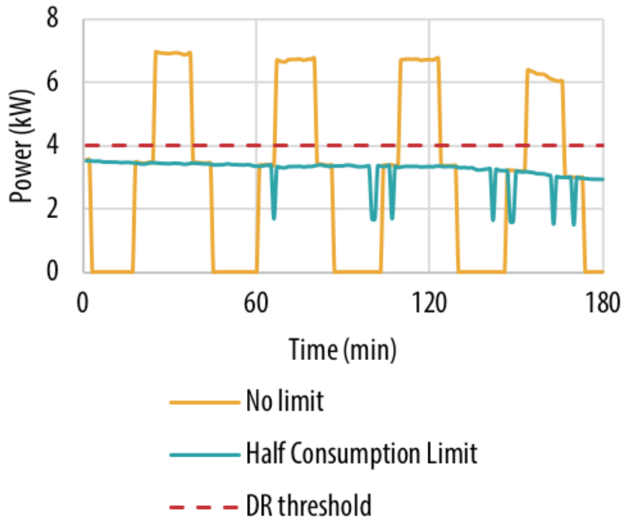


Figure 4. Total simulated ASHP power consumption for a four-house community. Data in yellow indicates transactive control with no demand cap. Data in blue-green shows the response of the system to a DR signal requesting a 50% power reduction. This shows that the transactional system effectively managed the four-house community such that a maximum of two heat pumps would come online at one time, reducing peak loads.

A Transactional energy system can reduce peak community heating and cooling loads through demand response requests. Figure 4 illustrates an example of the system's simulated reaction to a demand response signal. Where houses under normal operation would have uncoordinated calls for heating and cooling, a transactional system can be used to stagger heating and cooling consumption, lowering the community's potential peak demand. Actual DR capabilities of a community will vary depending on local weather conditions, building insulation levels, and the number of participants in the Marketplace, as all of these factors impact the flexibility of the system.

Transactional control can increase the amount of on-site renewable energy utilization. A transactional energy framework inherently attempts to align demand with the most cost-effective energy available. Taking on-site renewable generation to be the cheapest source of electricity enables the system to match demand with local, renewable generation as often as possible, subject to other system constraints. Table 2 summarizes the simulated on-site renewable energy utilization under normal conditions and using transactional systems. By aligning local generation with loads, a transactional system can help to flatline a community's load from the grid's perspective, creating more self-sustaining and resilient communities.

Table 2. Comparison of on-site renewable energy utilization with different systems.

System	On-site Renewable Utilization (kWh)
Zero-export non-transactive PV	821
Transactional PV	987
Transactional PV and battery bank	1645

CONCLUSIONS

This report summarizes work conducted at the Archetype Sustainable House investigating transactive energy management for residential buildings. Both simulations and real-world demonstrations were used to examine transactive control protocols and their impact on building energy consumption. Further details on the experiment are available in the thesis upon which this work is based (Brookson, 2017).

While this project focused on transactional energy for individual buildings, future transactional energy work at the Archetype Sustainable House will incorporate much greater utility involvement, with a focus on both energy conservation and resilience. The system will also be further enhanced by implementing direct peer-to-peer energy transactions, significantly increasing the scalability of the system.

REFERENCES

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