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CASE STUDIES: BALANCING WIND GENERATION USING ELECTRIC THERMAL STORAGE AND ELECTRIC WATER HEATERS

Canada

CASE STUDIES: BALANCING WIND GENERATION USING ELECTRIC THERMAL STORAGE AND ELECTRIC WATER HEATERS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Integrating a large proportion of variable renewable energy, such as wind, is a challenge for power grid operators, who must ensure a constant balance between the supply and demand of power, according to different time frames and different contingencies.

Recent studies [1] and experiments [2] [3] with wind power integration have shown that it is possible to integrate a high penetration of energy from various sources on most power grids. However, as mentioned in previous studies, when wind power penetration reaches approximately 20% of a grid's peak demand, the cost of this resource increases by up to 10% [2].

Depending on the region, wind power integration of over 20% may require improvements to a power grid's flexibility[1]. According to the IEA [1], this flexibility may increase by improving the generating system, by interconnecting with other markets, or by storage and demand management.

The introduction of dynamic rates and the development of demand management programs (*Demand Response*) reward clients who adjust their energy use in order to reduce stress on the grid. These programs may be offered on the wholesale market [4], as well as on retail markets by public utilities.

The industry's fascination with smart grids has led to the marketing of consumer products that include equipment with the possibility for smart management of their use [5]. In the commercial sector, power management solutions have been added onto building automation systems for easier interaction with the grid [6]. Over the long term, it is expected that smart electric vehicle charging may also be used to balance wind generation [7]. All of these applications could one day make it possible to increase power grid flexibility and absorb greater wind power penetration [8].

Although new technologies are in development, a large capacity for heat storage in client homes can already be used to offer power grid services. Many demonstration projects are already underway in this field [3] [9].

In this report, the possibility of controlling water heater load and thermal storage units in order to balance wind generation will be explored in three case studies. The proposed control approach focuses on smoothing out wind generation variations, storing surplus and recovering heat during low production periods. In one case, the distributed resource is also used to reduce grid peak. In addition to balancing wind generation, this approach will also help postpone grid investments or prevent polluting or expensive power plants from operating.

The methodology required to model the system and the simulation results will be presented in this document. However, the results of these studies are only valid for the given context.

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[1] Ability to increase or decrease production over time in order to follow load and intermittent production variability.

2 WIND GENERATION BALANCING

Many power plants are needed in order to maintain a grid's frequency. Primary, secondary and tertiary continuous regulation capacity [10] is needed in order to follow the continuous variations in demand and grid production.

In many power grids considered to have low flexibility, existing plants can barely increase or reduce their production in order to follow variations in both wind and load. These load variations and fluctuating production can sometimes be asymmetrical and require a much larger than normal regulation reserve. For these power grids, integrating a high wind power penetration may incur additional costs.

The grid's balance is maintained in different time frames and requires different complementary grid services, and optimal production distribution. De Cesaro's article [2] summarizes recent experiences in integrating wind energy in the United States and the additional costs incurred by this type of energy in different markets. The authors separate and quantify the economic impacts of grid balancing according to three different time frames:

- From seconds to minutes (primary regulation, secondary regulation)
- From a few minutes to a few hours (load-following plants)
- From a few hours to a few days (unit commitment)

Recent experiences in the United States seem to demonstrate that as the time frame increases, so too will the additional costs incurred by wind generation. In other words, the costs associated with unit commitment, including reserving resources or their impromptu distribution, would be higher than the costs associated with regulation (seconds to minutes) and those associated with load following (minutes to hours).

As part of this study, water-heater and thermal-accumulator control will be adjusted to follow wind energy variations over long periods of time, i.e., in order to avoid costs associated with the reservation or impromptu start-up of power plants. This particularly long time frame also corresponds to the duration of certain grid peaks.

3 PRESENTATION OF CASE STUDIES

The goal of the three case studies is to offset long-term wind generation variations using water-heater and electric thermal storage (ETS) load control. The heat storage capacity of these resources is used to store or release energy as needed.

In the first two case studies, the water heaters or the ETS will be used to offset the variations over a few hours of wind generation. The third case study focuses more specifically on ETS load control in order to reduce peak on cold winter days with low wind generation. The control strategy specific to each of the three cases is presented in the respective sections.

In all three cases, it is considered that the resource would be dispatched according to a direct load control by the grid operator (or a public utility) and would therefore not be under client control. No dynamic power rates would be required, but a financial incentive would be given to the client to take part in the program. It is therefore implied that there is a type of market for providing complementary services[2] in place and that this market is open to clients or third party aggregators.

As part of this study, the operator has no bi-directional link and load control occurs through a signal that is widely broadcasted, and not point to point. In the absence of client information, margins are added in order to take into account variations in the use of these loads.

As part of the three scenarios, we expect to offset long-term wind energy fluctuations, i.e., over a 6-hour time frame. This time corresponds approximately to the start-up time of the coal-fired power plant [1]. We therefore assume that the regulation and other complementary services that consist in following the load variations over a shorter term are offset by other plants.

The modelling of the wind resource common to each of the three scenarios is set out in the following section.

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[2] Consult the IRC – ISO/RTO Council “North American Wholesale Electricity Demand Response Program Comparison” [4] study for more details on comparable programs in each North American region

3.1 Wind Generation Modelling

Real wind generation data were used. These values come from Ontario and were found on the website of the Independent Electricity System Operator, IESO [11]. Data spread over a one-week period were used, specifically a period when significant low and high wind generation was recorded. The installed wind capacity at this time in Ontario was 1083.6 MW. The wind generation curve appears in Figure 3.1.

A six-hour rolling average (three hours on each side of the data) is applied to these data in order to smooth the curve and retain only the long-term fluctuations.

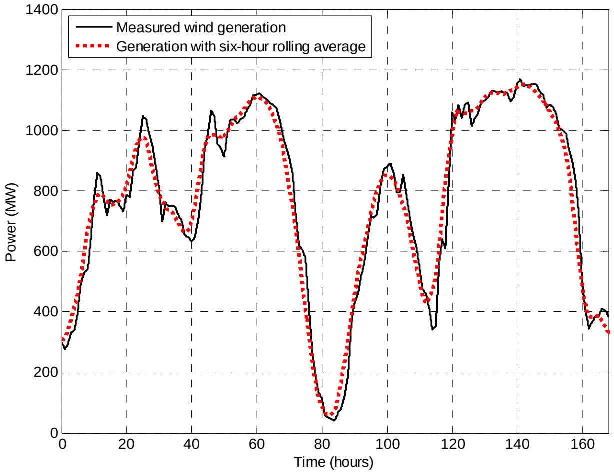

Figure 3.1: Wind generation in Ontario and six-hour rolling average applied to these data for one week

Figure 3.1 shows that wind generation variations are spread over several hours. Over a space of about 20 hours, i.e., between hours 60 and 80, the power supplied by wind energy decreases by 1,000 MW, i.e., stabilizes for about half a day and then increases by 800 MW in about 18 hours.

This week was chosen because it contains significant variations in generation occurring within a fairly short time frame. It represents a major case of wind generation variation.

Table 3.1 sets out the typical variations of wind generation between each six-hour period, for one year. The percentage reflects the variation in comparison to the previous period.

Table 3.1: Wind generation variations over a six-hour period for one year

Generation variation over six hours	± 0-10%	± 10-20%	± 20-30%	± 30-40%	± 40-50%	> 50%
Number of hours in the year	5567	2115	780	230	55	13
Percentage of hours in the year	63.6%	24.2%	8.9%	2.6%	0.6%	0.1%

It was noted that for about 60% of the time, wind energy varies only from 0 to 10% from one 6-hour time frame to another. Meanwhile, variations of over 50%, such as those retained for the case studies, occur 0.1% of the time.

4 CASE STUDY: WATER-HEATER CONTROL TO BALANCE WIND GENERATION

The first simulation case consists of controlling electric water heater loads in 20,000 typical homes. This control changes the setpoint temperature of all water heater thermostats at the same time for these 20,000 clients. The purpose of the control is to increase the setpoint temperature in the event of high wind energy production and to lower the setpoint temperature during low production. The simulated water heaters run at 4,500 W. This case study was done in Matlab.

4.1 Water Heater Model

According to *U.S. Department of Energy* data [12], a water heater consumes an annual average of 4,770 kWh of electricity, making it the household appliance with the highest energy consumption. There are several methods for modelling a water heater. The method used in this case is taken from a case study set out in appendix [13] and is summarized by the following equation:

$$\frac{dx}{dt} = -a(x(t) - x_a(t)) - A(t)q(t) + Rm(t) \qquad (4.1)$$

where: a is the thermal resistance of the walls and, therefore, represents the water heater's heat loss, x is the temperature, x_a is the room temperature, A is the rate of energy extraction per minute during hot water demand, q is the ON/OFF state of water extraction, R is the power of the heating element, and m is the state of the thermostat.

The water consumption model is represented by a Markov chain in two states:

$$P[q(t+h) = 1 \mid q(t) = 0] = \alpha_0 h, \qquad (4.2)$$

$$P[q(t+h) = 0 \mid q(t) = 1] = \alpha_1 h, \qquad (4.3)$$

where h is a sufficiently small unit of time based on the value of α. In this case, a time step of h = 1 minute is used.

As shown in equations 4.2 and 4.3, when q(t) equals 0, meaning that no water is drawn at the t moment, the probability that at time t+h water is drawn, therefore, change in state, is $\alpha_0 h$. Likewise, the probability of a change in state when q(t) = 1 is $\alpha_1 h$. Table 3.2 shows the parameters used during the simulation:

Table 4.1: Parameters used for simulating a water heater [13]

Parameter	Value
x_a	20°C
a	0.000156/min
R	0.3279°C/min (4,500 W)
A	1.29°C/min
α_0	0.012/min
α_1	0.32/min

The values of α_0 are changed depending on the time of day, based on Ontario water heater consumption data for the average of week-ends and week days available on the Ontario grid operator's website [11]. The following chart shows the overall water heater consumption standardized to 1 MW for a typical day.

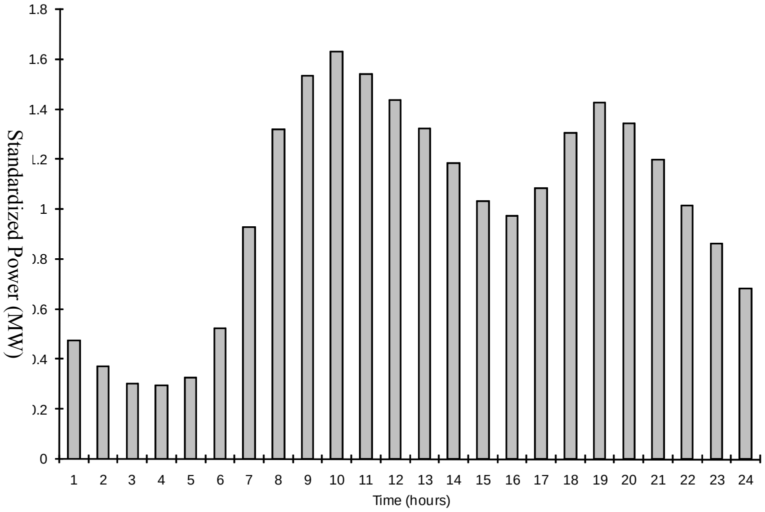

Figure 4.1: Standardized Ontario water heater consumption curve

Equations 4.1, 4.2 and 4.3 and the different parameters have made it possible to recreate water heater electricity consumption using the Matlab software. The following is an example of the consumption of three simulated water heaters for one day, with random water drawing modelled by equations 4.2 and 4.3. The simulation time step is 1 minute, and the duration is 1,440 minutes, i.e., one entire day.

In the proposed model, there are two states for each water heater: they either consume 4,500 W, or they do not consume any energy. Figure 4.2 sets out these typical curves for 3 water heaters.

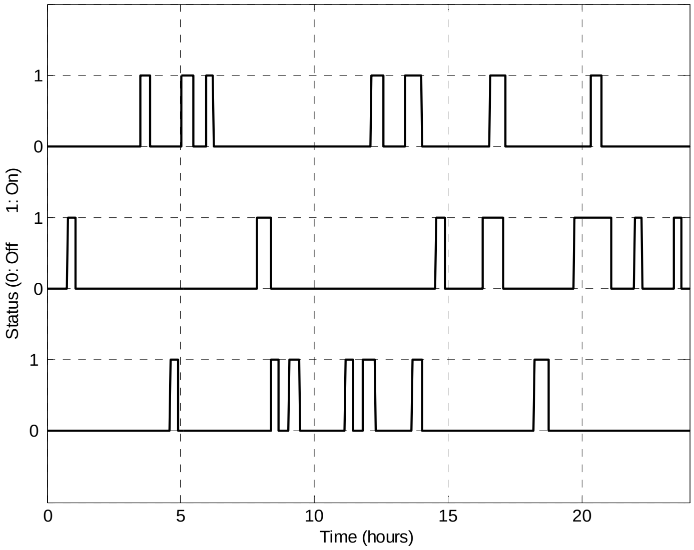

Figure 4.2: Example of typical operating curves for three simulated water heaters with random water drawing for one entire day

Of course, this profile changes with all simulations given the random aspect of the water drawing, but it makes it possible to recreate the load profile presented in figure 4.3 for 1,400 water heaters. When a water heater is simulated for an entire year, the total energy value obtained is approximately 4,900 kWh. This is comparable to the typical value provided above.

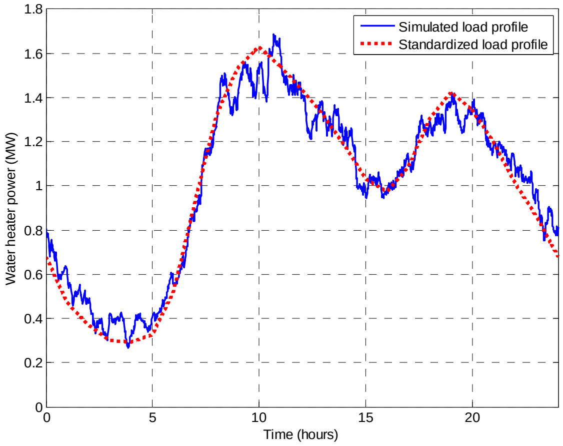

Figure 4.3: Consumption profile for 1,400 water heaters (normalized)

The consumption profile follows the typical consumption curve in Figure 4.1. It was noted that the peak demand of 1,400 units is at 1.6 MW in the morning and 1.4 MW in the afternoon. Knowing that the water heaters are either active (4,500 W) or inactive (0 W), one can conclude that 25% and 22% of water heaters, respectively, would operate simultaneously during these two periods.

4.2 Control Strategy – Water Heaters

A water heater control is applied to overcome wind generation variation over a six-hour period, based on the profile set out in Figure 3.1. Wind generation data are, however, divided by a ratio of ten to adjust this generation to the load level considered in the analysis.

The control strategy is applied to 20,000 water heaters and focuses on taking advantage of power storage in heat form inherent to the temperature range possible inside a water heater. For the purposes of the study, it is considered that a one-way control signal is sent by the electricity system operator at the desired moment. The simulation period is one week for a 1-minute time step.

The quantity of theoretical thermal storage supplied by the water heaters can be calculated as follows:

$$\mathrm{Q} = \mathrm{mc}\Delta\mathrm{T} \qquad (4.4)$$

For a 60-imperial-gallon (272.8 L) water heater, specific heat capacity of the water of 4,186 J/(kg°C) and a temperature variation of 10°C[3], we have:

Q = 272.8 x 4,186 x 10 = 11.4 MJ = 3.2 kWh per water heater

Since wind generation variation is usually distributed over several hours, the control used is aimed at making the setpoint temperature of the water heaters vary based on the value of the wind generation's rolling average.

The variation of the water heater setpoint temperature is based on the method presented by Callaway [14][4], i.e., the application of a rolling average, in this case, in order to retain only high-frequency variations (regulation service). In our case, we are interested in low-frequency variations (reducing the allocation cost for generation resources). This method has also been adapted for water heaters. The equation connecting the variation in the setpoint temperature to generation variation is as follows:

$$\Delta u_t = \frac{-\Delta y_{t+1}\delta}{P_{TOT}} \qquad (4.5)$$

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[3] The model used assumes a uniform water heater temperature. More detailed modelling would make it possible to better characterize the temperatures at the top of the water heater (at the outlet) and at the bottom (at the inlet), and thereby take into account a tolerance level greater than 10°C.

[4] Callaway had estimated the regulation potential of a stock of thermostat-controlled air conditioners. The results show that a load of 3.4 MW of thermostat-controlled air conditioning was needed to balance 1 MW of wind generation (installed capacity).

Where Δu_t is the variation in the setpoint temperature in °C, Δy_{t+1} is the variation in wind generation between two time steps, δ is the dead spectrum of the setpoint temperature (5°C) and P_{TOT} is the total maximum power of the load, i.e., 20,000 homes at 4,500 W, which is equal to a load of 90 MW.

To enhance the control results, the variation of Δy_{t+1} is taken on the smooth curve of wind generation. In a real time control, forecasts would therefore need to be included.

4.3 Results

Figure 4.4 presents the variation of the preset temperatures applied over a one-week period. These variations are determined with equation 4.5.

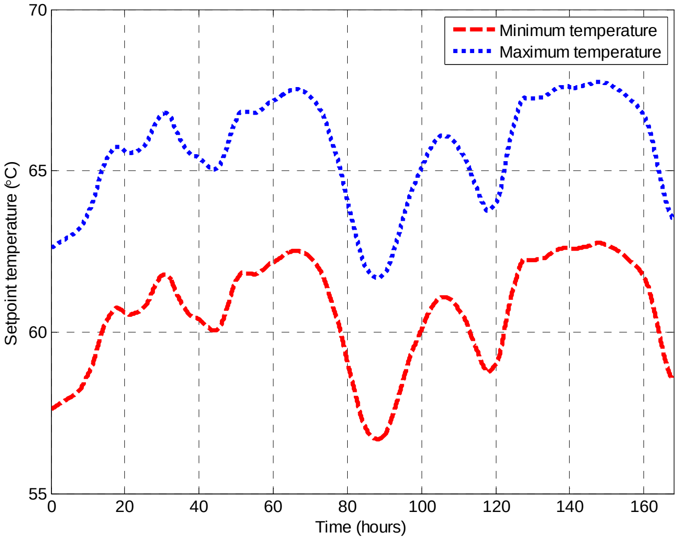

Figure 4.4: Maximum and minimum preset temperatures evolution during the week

Figures 4.5 and 4.6 present the simulation results. Figure 4.5 presents the impact of load control on the total water heater load.

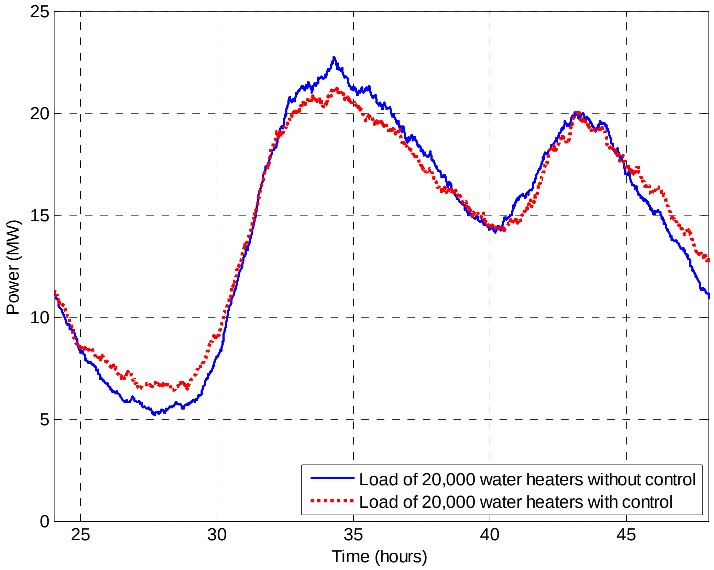

Figure 4.5: Impact of setpoint temperature control on the total load of 20,000 water heaters for a typical day

The results set out in Figure 4.5 are for the second day. It was noted that, without control, the water heater peak is 23 MW, whereas with the control it is 21 MW. If all water heaters are working at the same time, their peak would be 90 MW.

For a minor change to the load curve for the 20,000 water heaters, the control makes it possible to obtain maximum variations of about 2 MW. This balancing potential is significant, but can also differ depending on the moment when the resource is required. In fact, we notice that the diversified water heater load with control varies between 7 MW and 21 MW.

Figure 4.6 shows the results over a six-day period.

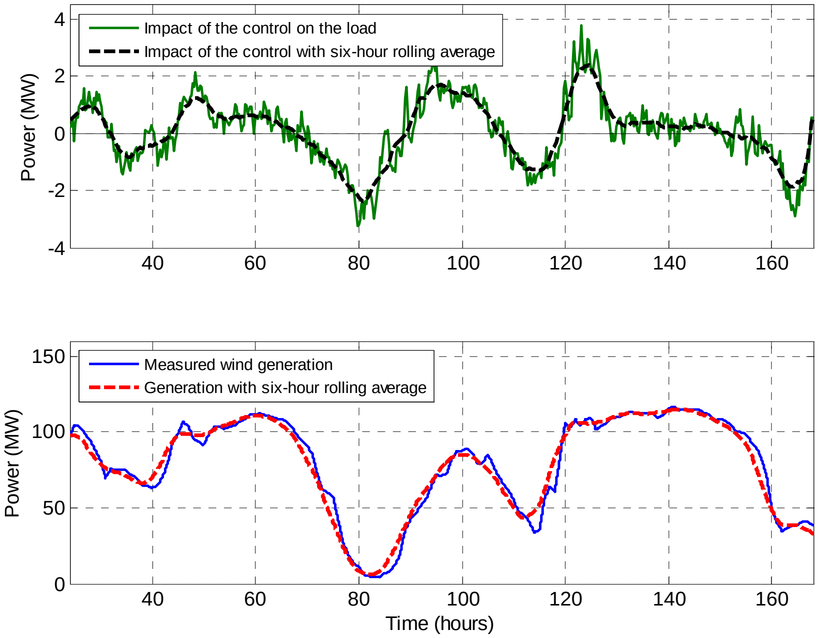

Figure 4.6: Effect of controlling 20,000 water heaters on the energy demanded by them (top) and wind generation fluctuation over time (bottom)

This figure shows the impact of the control on loads, against the corresponding wind generation fluctuation. Note the control effect, i.e., that the water heater load variation follows wind generation[5]. Between hours 65 and 71, there was a 24-MW decrease in wind generation. During the same 6 hour period, the water heaters decrease their respective consumption by 0.65 MW, i.e., 32.5 W per water heater. However, the wind continue to drop for a few more hours, as does the water heater load, providing balancing for the following periods. During the following hours, wind generation resumes, and the water heaters increase their consumption, this time by the same 0.65 MW over a period of 6 hours. In other circumstances, water heaters can release or absorb more energy, depending on the temperature of the water inside the tank.

During the 20 hours event, the 3MW drop in water heaters demand suggested that each water heater provided 150 W of balancing. Considering that 150 W of power was provided for 20 hours, the balancing energy provided could be estimated as follow :

Balancing energy (kWh) : (150 W X 20 hours) /2 = 1.5 kWh

Providing balancing service requires managing both charging and discharging episodes of electric water heater as a “storage device”. To provide such service, the storage set point should be somewhere in the

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[5] As mentioned above, wind generation is divided by 10 in comparison to previous values in order to adjust generation and the load to scale.

middle (half loaded[6]). During the 20 hours wind reduction event, the 1.5 kWh of balancing energy or "storage" provided was about half (1.6 kWh) the electric water heater storage capacity found in equation 4.4 (3.2 kWh). In other words, during that event, the storage capacity of electric water heater was well used, using 1.5 kWh of a theoretical value of 1.6 kWh.

However, over the course of the week, during the 6 hours periods, the balancing energy provided was different. The Table 4.2 sets out the balancing need filled by the water heaters over the 6 days.

Table 4.2: Mean variation of water heater power for a six-hour period

Power variation per water heater (W)	< -150	-150 to -100	-100 to -50	-50 to 0	0 to 50	50 to 100	100 to 150	>150
Percentage of time	1.2%	6.0%	17.7%	34.4%	22.4%	10.0%	5.6%	2.7%

During 56.8% of the blocks of time for this period, the water heaters provided up to 50 W of positive or negative balancing. They provided from 50 W to 100 W 27.7% of the time, 100 W to 150 W 11.6% of the time, and, finally, over 150 W of balancing 3.9% of the time.

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[6] Forecast tools may allow better storage capacity management of electric water heater, with pre-heating or pre-cooling prior to the anticipated event.

5 CASE STUDY – HEAT ACCUMULATORS FOR WIND BALANCING

This second case study looks at balancing wind energy by using Electric Thermal Storage devices or ETS. These devices have a much greater storage capacity than water heaters (> 150 kWh).

In this case study, 500 ETS will be simulated among a group of 20,000 homes, 10,000 of which are heated by electricity. Therefore, grid modelling includes 9,500 homes heated with a conventional system and 500 homes using a heating system with thermal storage.

5.1 Electric Heating Modelling

The heat accumulator control scenario involves building modelling. Using this technology for wind balancing means properly modelling heating-related electrical consumption based on outdoor temperature. The model will make it possible to estimate the amount of energy needed to maintain the dwelling temperature within a comfortable range, but also to determine the drop in indoor temperature when the heating is off. The Trnsys software was used for this modelling.

5.1.1 Trnsys Software Presentation

The *Trnsys* software [15] *(Transient System Simulator)* was developed by the University of Wisconsin's Solar Energy Laboratory in the 1970s. It was originally developed to calculate solar thermal processes. It was then expanded to calculate CVAC systems, multizone buildings, renewable energy systems, co-generation, etc. *Trnsys* is currently in its 16th version. For this paper, we used primarily applications for multizone buildings. In fact, *Trnsys* includes a model for defining this type of building, called the *TRNBuild*.

TRNBuild makes it possible to define zones, i.e., volumes with a very specific orientation and insulation. Different zones can then be juxtaposed to recreate a building. For each of these zones, different types of windows, heating and ventilation can be added.

After defining the building, the *Trnsys Simulation Studio* module makes it possible to simulate a building under different conditions. The software contains typical hourly temperature and sunlighting data for different cities on the continent on an annual basis (TMY – *Typical Meteorological Year* file). In this case, given that the building's behaviour is to be modelled based on outdoor temperature, several simulations reproducing a variation of the outdoor temperature were carried out. These simulations were done, on the one hand, when heating is on, and, on the other hand, when heating is off. The results were recorded in CSV files, and the results were analyzed using *Matlab*.

5.1.2 Building Description

Here now are the average specifications for a house in eastern Canada used in this study [16]:

- Total window surface: 18.9 m^2
- Total number of windows: 12
- Average window surface: 1.6 m^2
- Percentage of homes with a basement: 91.4%
- RSI value (thermal resistance) of the wall: 2.3
- RSI value of the ceiling: 4.2

The following are the simulation parameters used in *TRNBuild*:

- Number of areas: 2 (living room and attic)
- Living space: 115 m^2
- Volume of the living room area: 287.5 m^3
- RSI value of the wall: 2.3
- RSI value of the ceiling: 4.2
- South-facing window: 7 m^2
- Window facing other direction: 4 m^2
- Living room infiltration: 0.4 (equivalent to an ACH50Pa value of 6.9)
- Attic infiltration: 0.7 (slightly more than in the living room)

5.1.3 Outdoor Temperature

Temperature values are taken for a week in January when temperatures are very low (between -15°C and -25°C) over several consecutive days. The data come from the National Climate Archive of Canada [17]. The following are the temperatures for the chosen week (Figure 5.1).

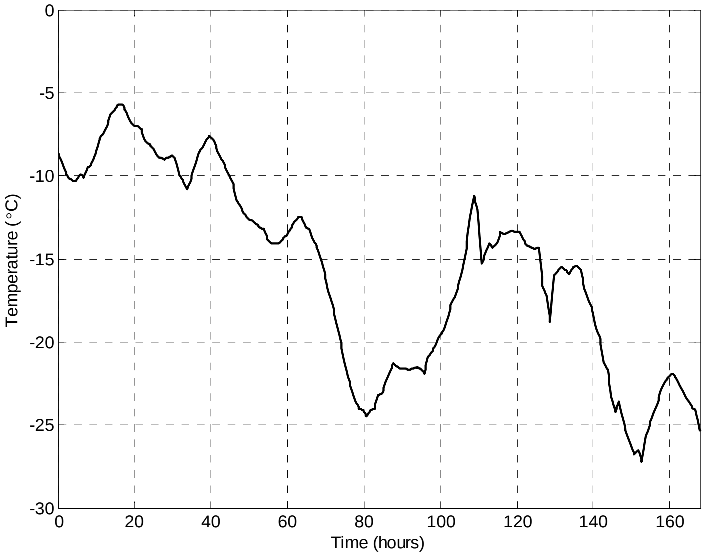

Figure 5.1: Temperature for a cold week in January

In this first study with ETS, these temperature variations will influence ETS control flexibility for wind balancing. In the second study with ETS, this particularly cold week will make it possible to determine the ETS impact on the grid peak. It is actually under such winter conditions that the grid power peak occurs with high electric heating penetration.

5.1.4 Heating-related Electricity Demand

Simulations are carried out to determine the electrical heating needs of a building based on outdoor temperature. In order to do this, 10 consecutive days are simulated, with a constant outdoor temperature. In order to calculate heating needs, an integrator is added to the model to help find heating needs in kWh. This energy total is then converted to kWh/day and average kW per hour. Table 5.1 sets out the results of these simulations.

Table 5.1: Heating energy depending on temperature

Outdoor temperature (°C)	Daily heating energy (kWh)	Equivalent power (kW)
-35	186.2	7.8
-30	168.7	7.0
-25	151.2	6.3
-20	133.8	5.6
-15	117.8	4.9
-10	101.5	4.2
-5	85.2	3.5
0	68.8	2.9
5	52.21	2.2
10	35.79	1.5
15	19.78	0.8

A home's need for electric heating based on temperature may be practically modelled along a straight line, and therefore defined by only two parameters.

These figures set out the average electrical demand required to maintain a home's temperature. A home's peak heating demand is more variable. Demand variability depends on the type of heating used (centralized with one or several elements, or several baseboard heaters).

Several factors may affect these results: insulation, wind effect, net heat gain from the sun, household appliances and residents, individual actions, variation in thermostat setpoints, etc.

5.1.5 Simulations without Heating

Simulations without heating are used to determine the decrease in a building's indoor temperature over time. We can therefore evaluate the maximum heating shutdown time in the event that a heating load cycle is desired. The model used in *Simulation Studio* is roughly the same, except that the heating is turned off. As with simulations with heating, the outdoor temperature is varied. Table 5.2 presents the different parameters, as well as the resulting decrease in indoor temperature during the first fifteen minutes without heating. The initial temperature is 21.1°C (70°F):

Table 5.2: Decrease in indoor temperature based on outdoor temperature

Outdoor temperature (°C)	A	B	Decrease in temperature during the first 15 minutes (°C)
-30	-3.29	20.91	1.00
-25	-2.97	20.93	0.90
-20	-2.65	20.95	0.80
-15	-2.36	20.96	0.71
-10	-2.06	20.98	0.63
-5	-1.77	21.00	0.54
0	-1.46	21.01	0.44
5	-1.16	21.03	0.35
10	-0.85	21.05	0.26
15	-0.54	21.06	0.16

Parameters A and B correspond to the following equation:

Tint (°C) = A*t + B, where t is the time in hours. Tint is the building's indoor temperature.

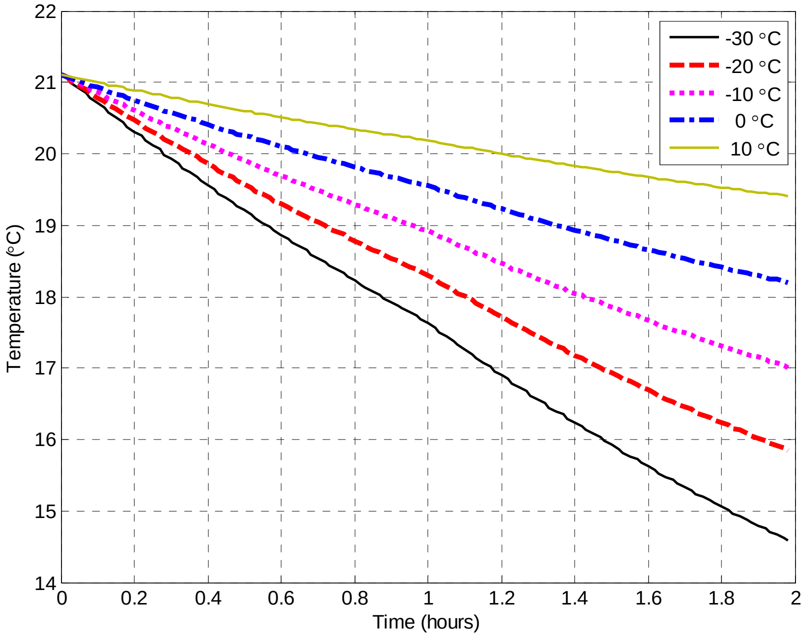

Figure 5.2: Decrease in indoor temperature over time, based on outdoor temperature

Figure 5.2 and Table 5.2 show that interrupting electrical heating to reduce grid peak (i.e., when the temperature is very cold) leads to a significant decrease in temperature over a short period of time, i.e., about 1 degree for the first 15 minutes.

5.2 Modelling of the Electric Thermal Storage (ETS)

A heat accumulator is a heating device for storing heat. It is recharged during off-peak periods, when there are base electricity surpluses or when prices are low, and restores heat, without electricity demand, during peak periods. Moreover, storing heat energy enables cost savings for commercial or industrial clients subject to power measuring. Finally, an additional benefit of this equipment is that it enables[7] heat to be supplied for several hours during power grid outages. Its use as a means of storage to facilitate the integration of renewables was recently studied [18] and is being demonstrated in the city of Summerside, Prince Edward Island [19].

This type of device comes in several forms. First, there are wall-mounted heat accumulators to replace electric baseboards. There are also hydronic (hot water) systems. Finally, ETS are used in electrical systems where air is forced through ducts. This type of accumulator is examined in the following two case studies. Heat accumulators can also be used as a heat pump supplement.

For this paper, the ETS model used is central and is geared to a residential market. The model in question is the DLF30B by Steffes. The features of this device are as follows [20]:

Table 5.3: DLF30B Operating specifications

Outdoor temperature (°C)	Load level	Initial electrical power (kW)	Maximum internal temperature of the equipment(°C)
12.8	1	9.6	260 (500 °F)
1.7	2	19.2	482 (900 °F)
-9.4	3	28.8	732 (1350 °F)

Other equipment specifications are as follows:

- Rated voltage: 240 V
- Load circuits: three 50-A loads
- Maximum fan load (blower): 6 A at 240 V
- Storage capacity: 180 kWh
- Total brick weight: 2,160 lbs (980 kg)
- Total ETS weight: 2,750 lbs (1,247 kg)
- Number of bricks: 84 whole and 12 half

The equations describing the thermal behaviour of this ETS are taken from work performed at the Hydro-Québec Research Institute (LTE) [21]:

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[7] According to the manufacturer and presence of back-up energy for the fan.

$$C\frac{\left(T_S^{t+1}-T_S^t\right)}{\Delta t}=P_{electric}^t-P_1^t-P_2^t \qquad (5.1)$$

$$P_1=4{,}64\times10^{-6}T_S{}^2+1{,}14\times10^{-3}T_S-0{,}024 \qquad (5.2)$$

$$P_2=4{,}88\times10^{-2}T_S+0{,}39 \qquad (5.3)$$

where the symbols are defined as follows:

C: Specific heat of the device's storage mass (0.336 kWh/°C)

T_S: Temperature of the storage mass (°C)

Δt: Time interval between two simulations (hours)

$P_{electric}$: Electric power for recharging (9.6 or 19.2 or 28.8 kW)

P_1: Standby losses (kW), i.e., heat that escapes from the ETS at all times

P_2: Heat power restored by the fan (kW) (limited to 15 kW by internal controls)

These equations describe the thermal behaviour of the ETS and allow for modelling with Matlab. The ETS's standby losses vary according to equation 5.2. At maximum temperature (732 °C), "losses" therefore amount to 3.3 kW. Of note is that the power of the "losses" is not lost since it is used to heat the house. However, the ETS must be properly dimensioned and well controlled according to the house's specifications so that these losses are not too high at a time when heating needs are lower.

5.3 Control Strategy – Heat Accumulators

The control algorithm used for the 500 ETS is based on that of the water heaters. It involves varying the maximum temperature of the storage mass and, therefore, the amount of energy that can be stored. As a result, increased wind generation means each ETS stores more power.

Equation 5.4 presents the variation in the storage mass temperature according to wind generation.

$$T_{MAX}=400+200P_{wind}(pu) \qquad (5.4)$$

P_{wind}(pu) represents the percentage (*pu: per unit*) of wind generation at this moment depending on the total maximum installed power (1,200 MW). Also, if the internal ETS temperature drops below the 100°C limit, recharging is allowed to ensure clients have heating. Figures 5.3 and 5.4 present the results obtained.

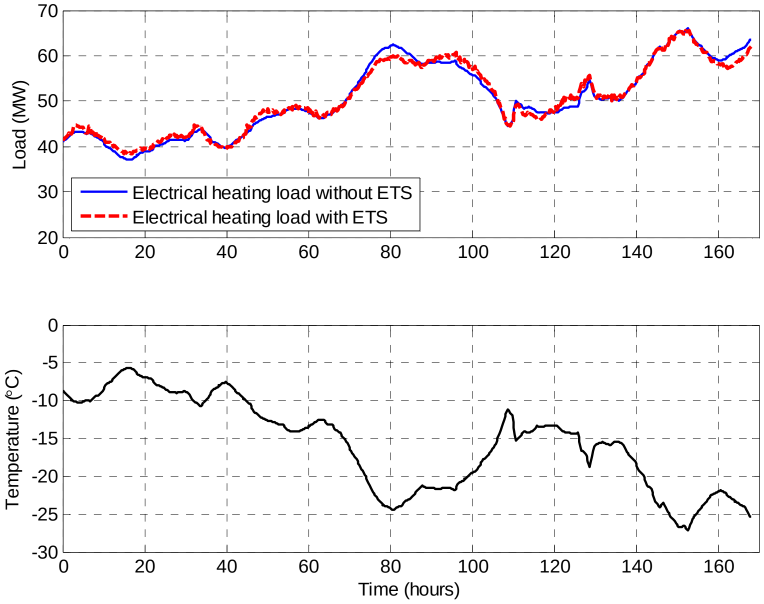

Figure 5.3: Impact of maximum temperature control of 500 ETS on a typical heating load (top) and outdoor temperature for one week (bottom)

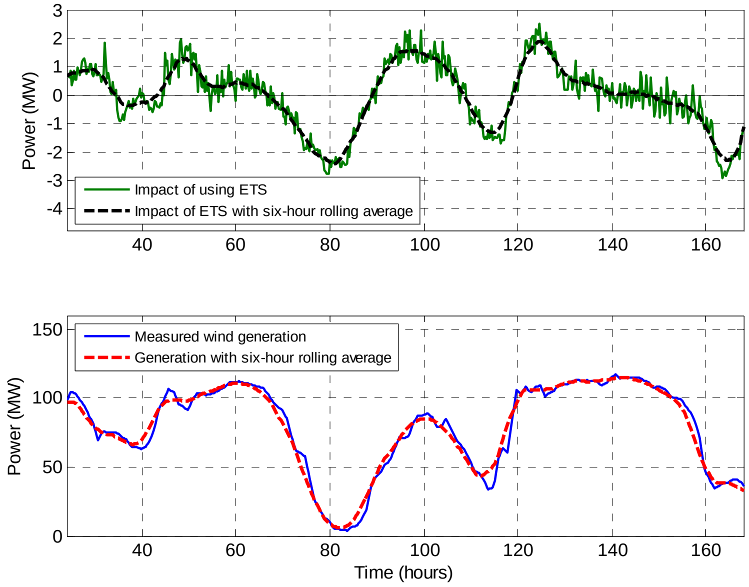

Figure 5.4: Effect of controlling 500 ETS on heating power (top) and wind generation fluctuation over time (bottom)

The simulation results presented are spread over a six-day period between hour 24 and hour 168. In order to compare these results to those obtained with the water heaters, the same hours are used.

Between hours 65 and 71, there is a 24-MW drop in wind generation. During that same period, the ETS make it possible to decrease the total load by 0.9 MW, i.e., 1.8 kW on average per ETS.

6 CASE STUDY – HEAT ACCUMULATORS FOR WIND BALANCING AND PEAK REDUCTION

This third case study focuses on managing ETS load to partially balance wind generation, but also power system peak. The operator could use this resource during load peak caused by very cold outdoor temperatures combined with low wind generation.

The goal of this scenario is to analyze the total load prior to control, as well as the total load after control, and to assess its impact on both peak reduction and wind balancing. In this scenario, again 20,000 homes are examined. Of these 20,000, 10,000 are electrically heated. For the case with control, it is assumed that 1,000 of these 10,000 homes use a heat accumulator.

For the following simulation, the total house load will be examined in order to determine the impact on the grid's peak. The load of the base and of the home's electrical appliances must be modelled given that the water and air heating load where already modelled in the previous cases.

6.1 Modelling of Other Loads

Residential loads, such as the washer, dryer, dishwasher, refrigerator and range, are modelled according to the load curves set out in [5]. The data for so-called « base » loads, such as small appliances and lighting, come from GridLAB-D [22]. Figure 6.1 sets out the cumulative effect of these loads for 20,000 typical North American residences.

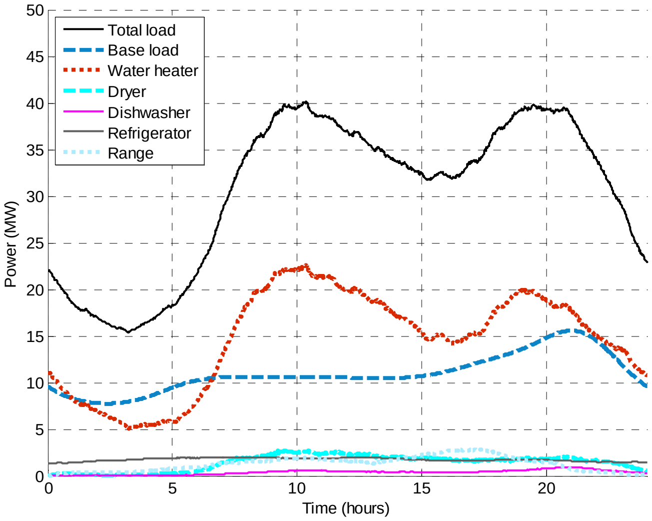

Figure 6.1: Daily load profile of 20,000 typical homes based on the main household appliances

First and foremost, the importance of the water heater is noteworthy in relation to other household appliances. The base load, which is quite significant, represents the rest of the electrical consumption of a typical residence (lighting, small appliances, televisions, computers, electronic devices, etc.)

The total load curve (in black) for one day will be used for this third case study. For homes with ETS, heating consumption will be added.

6.2 Simulations – ETS Control

The ETS control strategy consists in preventing recharging if wind generation is too low, i.e., below 40 MW.

The ETS state (storing or not storing energy) can therefore be defined as follows:

Storage if:

- The ETS internal temperature is lower than 100°C
- Wind power at that moment is over 40 MW

No storage if:

- The ETS internal temperature is higher than its maximum setpoint temperature (see Table 5.3)
- Wind power at that moment is under 40 MW

The results are set out in Figure 6.2.

In the complete load chart, we note that with load control, load peak (A) can be reduced by about 6 MW, i.e., about 6 kW per installed heat accumulator. This 6-MW drop represents a 7% peak drop. Since this peak coincides with the low wind generation period, the ETS cannot recharge. We then note that shortly after hour 90 (B), a new peak is created by accumulator control. However, at that moment, wind power is higher by several MW compared to the previous peak. This means that, from the grid's point of view, this load increase causes fewer problems since it is compensated by increased wind generation.

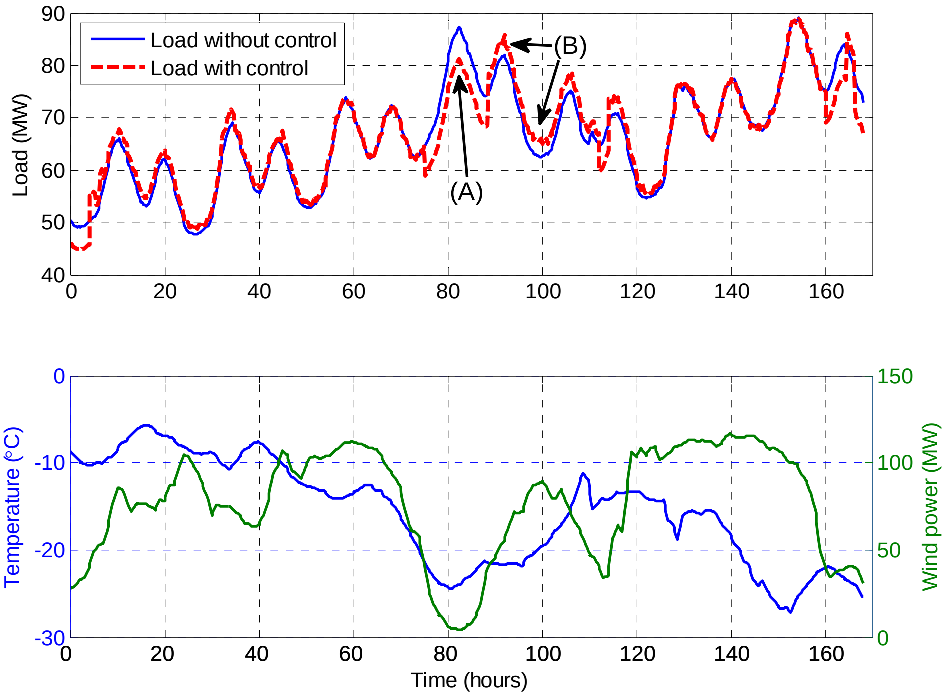

Figure 6.2: Impact of the load control of 1,000 heat accumulators on the total load of 20,000 homes (Top) Temperature and wind power generation during the period (bottom)

7 DISCUSSION

Wind generation variation becomes increasingly significant as the time frame studied increases. Possible wind energy variations are anticipated by grid operators, who reserve certain plants for planned generation drops or request emergency plant start-up for unplanned wind generation drops. Whether or not these variations occur, or occur as planned, they cause an increase in the costs associated with the allocation of generation resources. It is with the goal of offsetting these long-term variations that a water heater and heat accumulator load control was simulated over a week of wind generation with major variations.

In the first scenario presented, the 20 hours drop in wind generation and the associated 3MW load drop suggested that each water heater provided 150 W of balancing during that period. During that event, the storage capacity of each electric water heater was well used, using 1.5 kWh of a theoretical value of 1.6 kWh (without pre-heating or pre-cooling). The simulations for the week chosen indicated that, 84.5% of the time, water heaters have a flexibility range that can reach up to ± 100 W over a 6-hour period. The second scenario indicates that, in order to offset the wind generation variations over the week chosen, each ETS allowed 1.8 kW to be released during the six-hour period. In the third study, each ETS contributed to an average 6-kW decrease per house with ETS installed, while enabling the wind energy to be partly balanced. The wind power nominal capacity was 120 MW.

To ensure to use the full potential of those thermal storage devices, the following facts must be taken into account:

- Water heater flexibility is only highlighted if correlated with a balancing need. The water heater setpoint must be properly chosen in order to minimize cases where the “battery,” i.e., the temperature range, is “full” or “empty” at the wrong time. In the case studied, the control algorithm applied did not use any demand forecasting or wind generation forecasting. The set point was maintained somewhere in the middle (half loaded). Forecast tools may allow better storage capacity management of electric water heater, with pre-heating or pre-cooling prior to the anticipated event.

- A common control for all water heaters does not allow to take advantage of larger water consumers (to absorb more power) or smaller water consumers (to release more power).

- One way information exchange, without feedback loop, could limit the control’s flexibility. Without measurements, it was impossible to know which water heater population was truly affected by the setpoint variation. Also two-way communication could help managing the energy recovery period after the event, also called the “payback”.

- The storage capacity is over 3,200 Wh if there is also a balancing need when the water is used. Of note, however, is that hot water use responds to daily cycles (e.g., greater consumption in the morning and evening) that may differ from wind generation cycles (e.g., if generation is on average greater during the night). There are, however, different water use profiles that could be utilized with a more customized control or with feedback on the state of the water heater.

- The water heater model with single heating element and standard temperature was used. This resource can be modelled differently, in particular the interaction of the top and bottom element based on the way heat is dispersed in the tank.
- The temperature variation range was conservative (10°C). Using a greater temperature range, with or without mixing valves, could also produce more significant results. In this case, the theoretical storage potential would be greater than 3.2 kWh.

The following should be considered when analyzing the ETS results:

- Choosing to study only one high-capacity heat accumulator per home instead of many baseboard accumulators may produce different results. Management per room may offer more management flexibility, but multiplying these lower capacity devices may result in higher costs.
- A sole house model was tested. Using a variable-efficiency group of homes would help to change electricity demand and benefit from their individual characteristics.

From all three scenarios, it should be mentioned that a single week of wind generation was used. That week was chosen for its significant generation variations. Replication of this study over a one-year period could produce different results and, above all, more statistical information.

In the first two scenarios, control followed long-term wind generation variations and not the “net” balancing need, which would take into account variations in demand and wind generation. In the third scenario, a trade-off between peak needs and wind balancing was applied.

Finally, the study of extremes or the “worst case scenario” in variation may not be the best approach for quantifying the water heater or ETS balancing potential on an integrated system. In fact, on large power grids, reserves are maintained in order to account for exceptional events and other resources may be drawn upon.

8 CONCLUSION

This report presented three case studies of the use of water heaters and ETS to offset wind generation variability. Simulations over a week of particularly variable generation showed that controlling these devices may provide some balancing over a time frame of at least six hours.

These case studies were conducted in a specific context. The results are therefore closely linked to this context and cannot be generalized. Other scenarios, a different climate or wind resource, as well as new load control approaches may be explored in the future. To this end, the modelling is presented so that other studies may complement these results.

Considering the high electric water-heater capacity installed on Canadian power system, the potential is there to use this capacity for wind balancing. A demonstration project is currently underway to examine this potential [15]. The installation of heat accumulators, still not largely deployed in Canada, could be considered further by public utilities, producers or grid operators. This equipment offers the triple benefit of reducing peak, balancing wind energy or supplying emergency heat during power outages.

This study sheds light on certain limitations of centralized, non-customized management of these heat storage resources. Smart grid development involves the use of information technologies to maintain power grid operation. Although load control has been in use for several years, improving existing communications by developing customized bi-directional links should allow for better management of the storage available on the grid or in buildings.

Developing distributed energy resources through smart grid implementation should open the door to new grid management opportunities, but also represents a major integration challenge.

APPENDIX 1 – CODE EXAMPLE FOR ETS

The following is an example of a Matlab code used for modelling ETS:

```
% Parameters of the heat accumulator
Pmax_ACC1 = 28.8; % Pmax load  = 28.8 kW (under -9.4 degrees C)
Pmax_ACC2 = 19.2; % Pmax load = 19.2 kW (between 1.7 and -9.4 degrees C)
Pmax_ACC3 = 9.6; % Pmax load = 9.6 kW (over 1.7 degrees C)
Pmax_ACC4 = 0; % Pmax load = 0 kW (over 12.8 degrees C)
T_ACC_MAX1 = 732; % Maximum brick temperature (under -9.4 degrees C)
T_ACC_MAX2 = 482; % Maximum brick temperature (between 1.7 and -9.4 degrees C)
T_ACC_MAX3 = 260; % Maximum brick temperature (over 1.7 degrees C)
T_ACC = zeros(1,length(T)); % Brick temperature vector
T_ACC(1) = 150+rand()*350; % Initial random temperature
C = 0.336; % Specific heat of the storage mass (kWh/degrees C)
E_ACC = 0; % Total energy consumed
P_ATC = zeros(1,length(T)); % Power at each moment

for i=1 : length(T) % Vector T contains the outdoor temperatures
    if T(i) < -9.4 % Temperature under -9.4
         Pacc = Pmax_ACC1;
         T_ACC_MAX = T_ACC_MAX1
    end
    if T(i) >= -9.4 && T(i) <= 1.7 % Temperature between 1.7 and -9.4
         Pacc = Pmax_ACC2;
         T_ACC_MAX = T_ACC_MAX1
    end
    if T(i) > 1.7 % Temperature over 1.7
         Pacc = Pmax_ACC3;
         T_ACC_MAX = T_ACC_MAX3
    end
    if T(i) > 12.8 % Temperature over 12.8
         Pacc = Pmax_ACC4;
    end
    if T(i) < 1.7
    T_ACC_MAX = 400 + (1-(Eol_moy15(i)/MaxEol))*200; % Control
    end
    if T_ACC(i) < T_ACC_MAX && Eol(i) > 40 || T_ACC(i)<100
         tmp = 1;  % If the wind is blowing or if the brick temperature is too
                   % low, recharging is required
    else
         tmp = 0;
    end

    Pe = Pacc*tmp; % Electric load power
    P1 = (4.64e-6*T_ACC(i)*T_ACC(i) + 1.14e-3*T_ACC(i) - 0.024); % Losses
    P2 = (-3.23*T(i) + 70.67)/24 - P1; % Heating power at this time
    T_ACC(i+1) = T_ACC(i) + (Pe - P1 - P2)/(4*C); % Variation in the ETS
                                                  % temperature
    P_ATC(i)= Pe;
end
```

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