Using Connected Boiler Data to Accurately Quantify Overheating and Energy Savings from Outdoor Air Reset (OAR) Curve Changes in Multi-Family Buildings

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ABSTRACT

Many multi-family buildings heated by boilers suffer from overheating caused by poor thermostatic valve (TV) regulation. This compromises comfort and can increase space heating energy consumption dramatically (e.g., up to 20-30%). Prior studies found that decreasing heating water supply temperatures (HTWS) based on outdoor temperature (Tout) can reduce overheating and modestly improve boiler efficiency, but couldn't accurately predict energy savings. We use connected boiler heat output (Qout) data to 1) quantify the degree of overheating and 2) accurately predict energy savings from outdoor air reset (OAR) curve changes, i.e., HTWS(Tout) by modeling the bounding cases of fully controlled and fully uncontrolled heat flows. When applied to 12 connected boiler systems that underwent 19 HTWS(Tout) changes to predict changes in energy consumption, the average modeled and observed changes were 12.8% and 11.3%, respectively (average difference = 4.3%; 13 within ±5%, 16 within ±10%). Thus, the model can be applied to connected boiler data to accurately identify buildings experiencing significant overheating, quantify the energy impact of overheating, and derive accurate estimates for the energy impact of reducing HTWS(Tout).

Introduction

Building operators have realized for several decades that boiler energy consumption for space heating can be reduced by reducing (aka resetting) the heating water supply temperature (HTWS) as the outdoor air temperature (Tout) increases (see Figure 1, from Landry et al. 2021).

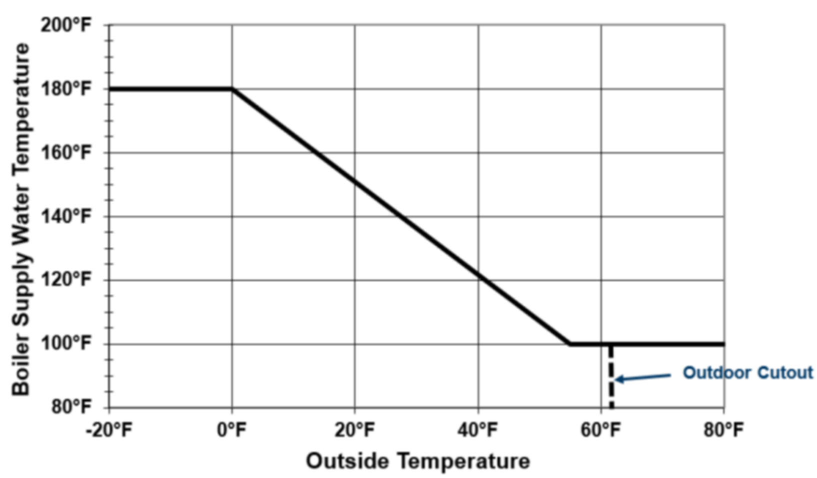

Figure 1. Example of an outdoor air reset (OAR) curve; from Landry et al. 2021

For condensing boilers, this can increase the portion of the space heating load met by heating water return temperatures (HTWR) that occur in the condensing regime, increasing boiler efficiency, η. Although condensing boilers can realize large efficiency-related savings when replacing non-condensing boilers, the efficiency-driven savings from improved outdoor air reset (OAR) optimization is quite modest. For example, modeling of the expected efficiency-driven savings for 17 monitored commercial condensing boiler systems found that improved reset curve parameters would reduce space heating energy consumption by less than 2% at all sites (Landry et al. 2021), while another study found an average of ~1.5% efficiency-related savings at 10 sites from reset curve changes (range: 0-4%; Landry et al. 2016).[1]

In both condensing and non-condensing boilers, reducing HTWS at a given Tout can also reduce space heating energy consumption by reducing indoor temperature (Tin) and, thus, effective space heating loads, Qin. As a field study by Hewett and Peterson (1984) found, boiler systems are prone to overheating spaces due to a combination of high Tin preferences by inhabitants (sometimes accompanied by window opening), failed thermostatic zone valves (TVs), and/or poorly or uninsulated distribution piping that result in uncontrolled heat flow to spaces. They showed that reducing HTWS(Tout) in multifamily buildings served by cast-iron boilers decreased space heating energy consumption by between 4 and 16%, with a corresponding 1 to 4°F decrease in Tin measured in hallways. Figure 2 below shows boiler energy consumption as a function of daily Tout before (top curve) and after (bottom curve) applying HTWS reset and warm-weather shut-down [WWSD] at Tout = 55°F in the building that achieved the greatest savings (when combined with a; Hewett and Peterson 1984).

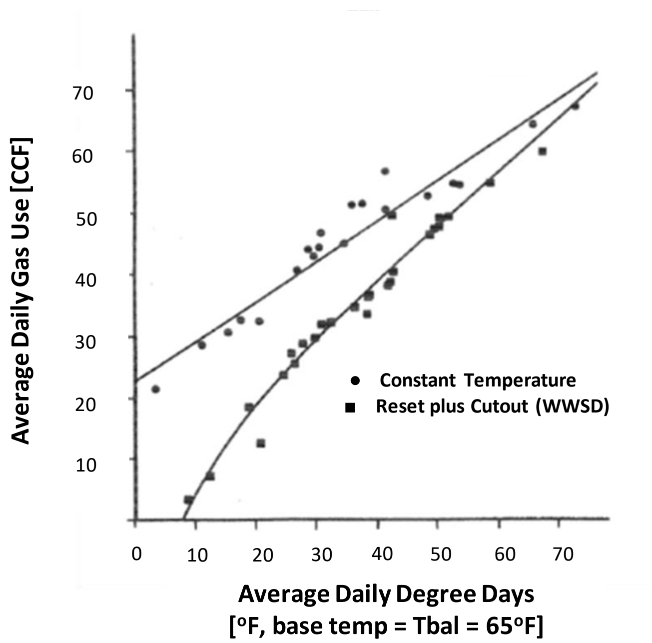

Figure 2. Field data for boiler daily energy consumption as a function of heating degree days for boilers with constant (top curve) and reset (lower curve) control; recreated from Hewlett and Peterson (1984).

[1] We found similar results when analyzing OAR curve changes for >10 buildings, using manufacturer data for boiler efficiency, η(HTWS), hourly TMY Tout data, and assuming space heating loads decreased linearly from the design temperature, Tout,design, to a balance temperature, Tbal = 60°F.

Existing industry rules of thumb range from 1% savings per 1°F reduction in HTWS to "reduce 4°, save 1%"[2]. Beyond such basic approaches, Landry et al. (2021) attempted to model the energy savings from decreasing OAR curve parameters based on the energy savings found in prior studies for OAR curve changes, including Hewett and Peterson (1984). They found a limited correlation between modeled and actual savings, on average underestimating savings by 40% (see Figure 3). This likely occurs because that model does not model the *actual* building overheating ("load reduction savings") occurring in specific buildings.

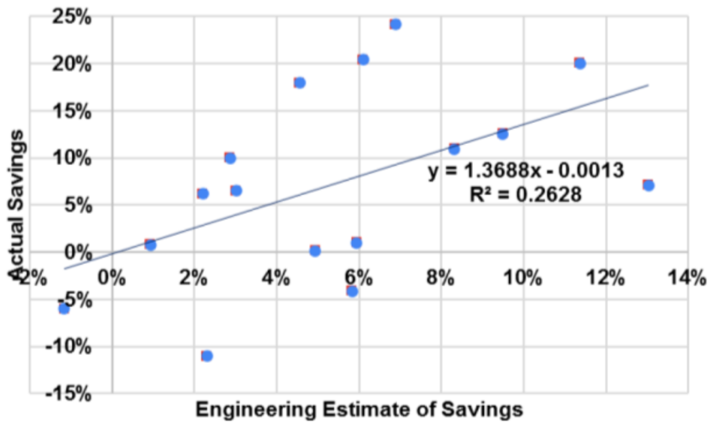

Figure 3. Engineering estimates versus actual savings for commercial boiler systems, from Landry et al. (2021). The engineering estimates underestimated actual energy savings by an average of 40%.

Clearly, the energy savings potential from reducing overheating and the resulting high space heating loads can greatly exceed those from increasing boiler efficiency. Furthermore, the prevalence appears to be acute in the roughly 2 million multi-family building with hydronic heat[3], i.e., monitoring of >100 multi-family boiler systems in colder climates by New Ecology (2018) found that in 80% of them HTWS could be lowered without compromising comfort. Although the savings potential can be large from OAR curve changes, the realized savings varies greatly among buildings (Hewett and Peterson 1984, Davey and Connelly 2018, New Ecology 2018). Presumably, this varies with the degree of uncontrolled heat flow of that specific boiler system. The challenge then becomes: how does one accurately quantify the expected energy savings from potential changes to the OAR curve?

A Physics-based Model for Hydronic Heat Transfer

The fundamental problem with the existing approaches is that they do not take into account the actual control of boiler distribution systems in a specific building, i.e., the extent of uncontrolled heat flow-driven overheating that occurs. To address this, we developed a basic model for heat transfer from the hydronic distribution loop to indoor spaces and how heat distribution unit (HDU) control – or the lack thereof – impacts effective space heating loads and

[2] See: https://www.heat-timer.com/outdoor-reset-control-savings/ for the latter; the 1°F = ~1% savings comes from discussions with practitioners.
[3] The 2020 DOE EIA RECS estimated that 2.8 million buildings with 5+ units have steam or hot-water heating systems, primarily in colder climates; we expect that a sizeable majority are hot-water systems.

boiler energy consumption. Figure 4 shows the basic model for heat transfer to and from a hydronically heated room.

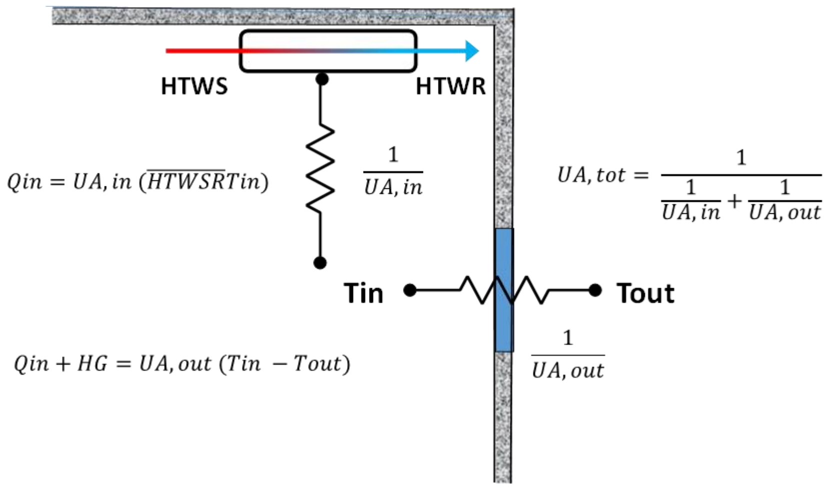

Figure 4. Conceptual model of room heat transfer with boiler system and outdoors.

Heat transfer from the heating loop to the space, Qin, equals:

$$Qin \simeq UA_{in}(\overline{HTWSR} - Tin)VRT \tag{1}$$

where the variables are:

- HTWS: Heating loop supply water temperature, i.e., temperature entering the radiator/convector (from now on referred to as a heat distributing unit, or HDU).
- HTWR: Heating loop return water temperature, i.e., temperature leaving the HDU.
- $\overline{HTWSR}$: The average of HTWS and HTWR, i.e., 0.5*(HTWS + HTWR)
- Tin: Room temperature.
- UA_{in}: the overall heat transfer coefficient for an HDU, which varies as a function of HTWS and Tin.
- VRT is the % of time the thermostatic valve (TV) is open.

A heat balance on the fluid flowing through the HDU shows that the change in flow thermal energy equals the heat transferred to the space; here, *m* equals the water mass flow and cp the water thermal capacitance:

$$mc_{\ p}(HTWS - HTWR) = \ UA_{in}\ (\overline{HTWSR} - Tin) \tag{2}$$

Similarly, the overall heat balance for the room equals:

$$Qin + HG = UA_{out}(Tin - Tout) \tag{3}$$

where HG equals internal plus solar heat gains while UA_{out} is the overall heat transfer coefficient from the building to the outdoors from conduction, radiation, and infiltration.[4] When Qin = 0, i.e., when Tout equals the balance temperature, Tbal, at the indoor design temperature, Tin,design:

$$HG = UA_{out}\ (Tin, design - Tbal) \quad (4)$$

At Tbal, internal and solar heat gains exactly balance heat losses from conduction and convection, i.e., space heating is required below Tbal.[5]

Once values for some variables are known or estimated, we can solve for the other variables. For example, if we can estimate Tin,design, Tbal, and UA,out, and assume VRT = 100% at design conditions, we can solve for UA,in (at design conditions) and *m*:

$$UA_{in} = \frac{UA_{out}\ (Tbal - Tout, design)}{\overline{HTWSR(Tout, design)} - Tin, design} \quad (5)$$

$$mc_p = \frac{UA_{in}\left(\overline{HTWSR(Tout, design)} - Tin, design\right)}{\overline{HTWSR(Tout, design)}} \quad (6)$$

The temperature difference for the water flowing through the HDU, dT, at other conditions equals:

$$dT(HTWS, Tin) = HTWS - HTWR \cong dT_{design} \frac{(HTWS[Tout] - Tin)}{(HTWS, design - Tin, design)} \frac{UA_{in,new}}{UA_{in,design}} \quad (7).$$

The last term takes into account that HDU output scales with $(HTWS\text{-}Tin)^n$, so UA_{in} scales with $(HTWS - Tin)^{n-1}$, where n depends on the type of HDU. Based on ASHRAE (2020), n = 1.31 for baseboard units (1.375 for SlantFin products) and 1.2 for cast-iron radiators. Although Tin decreases as HTWS decreases (assuming VRT is constant), the change in Tin is typically small relative to that in HTWS (see subsequent discussion).

To model how boilers can inadvertently overheat spaces, we next discuss system performance with controlled and uncontrolled heat transfer from the boiler distribution system to the room.

Well Controlled Case

Thermostatic valves (TVs) regulate heat flow from the boiler supply loop to rooms that shut off water flow through the HDU when the room achieves[6] its target temperature set-point, Tset. That is, TV *should* turn on and off the valve such that Tin ~equals Tset. In that case, for any HTWS and HTWR, the space heating load, Qload, and the controlled Qin, Qin,contr, both decrease linearly from the heating load at Tout,design, Qin(Tout,design), to Tbal:

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[4] This basic HDD formulation (i.e., PRISM) for space heating loads lumps conduction and infiltration heat losses into a single UA term, assuming both conduction and infiltration vary linearly with Tin – Tout. Actual building infiltration tends to exhibit appreciable nonlinearity, with an average exponent of ~0.65 (ASHRAE 2023).

[5] In practice, Tbal can vary appreciably depending on the actual SHGs experienced by a building, as well as with nonlinear wind-driven infiltration.

[6] Or, in the case of thermostats with anticipation action, approaches Tset.

$$Qload = Qin, contr = UA, out(Tin - Tout) - HG = UA, out\ (Tbal - Tout)$$
$$= Qin\ (Tout, design) * \frac{(Tbal-Tout)}{(Tbal-Tout,design)} \quad (8)$$

Uncontrolled Case

If the TV does not modulate effectively to control heat flow to the space, e.g., if the TV is stuck open, the dynamics change appreciably as the heat flows continuously from the boiler system into the room, i.e., VRT = 1.0 *under all conditions*. Since Tin is no longer controlled, it increases to an equilibrium temperature, Tin,eq, where the heat flows balance:

$$Qin + HG = UA_{in} mcp\ dT + HG = UA, out\ (Tin, eq - Tout) \quad (9)$$

Qin now equals the uncontrolled heat input into the space, *Qin,uncontr*, which is proportional to the difference between $\overline{HTWSR}$ and Tout:

$$Qin, uncontr = Qin = UA, out\ (Tin, eq - Tout) - HG. \quad (10)$$

Viewed another way, in the uncontrolled case heat transfer from the HDU at $\overline{HTWSR}$ to the outdoors at Tout occurs through two heat transfer resistances, $1/UA_{in}$ and $1/UA_{out}$. The total UA, UA,tot, equals:

$$UA, tot = \frac{1}{UA_{in}(Tout)} + \frac{1}{UA_{out}} \quad (11)$$

Consequently, Qin,uncontr is approximately proportional to the difference between HTWS and Tout:

$$Qin, uncontr\ \sim UA_{tot}(HTWS - Tout)\ C_{TV}. \quad (12)$$

Here, the C_{TV} factor takes into account how UA,in varies as a function of the difference between $\overline{HTWSR}$ and Tin,eq (see prior discussion and Appendix A). This expression neglects both internal heat gain and the reality that heat transfer between the HDU and Tin,eq occurs at $\overline{HTWSR}$[7]. As shown later, these simplifications do not appear to have a significant impact on the accuracy of data-driven assessments of the degree of overheating from uncontrolled heat flows for a specific boiler system or the predicted energy savings from decreasing HTWS. If we assume that the HDUs would just meet the design heat load as design conditions, i.e., when Tout = Tout,design and Tin(Tout,design) =Tin,design, VRT(Tin,design) = 100%, then Qin,uncontr is also approximately proportional to Qin,design:

$$Qin, uncontr(Tout) \cong Qin, design\ \frac{HTWS(Tout)-Tout}{HTWS(Tout,design-Tout,design}\ C_{TV} \quad (13)$$

[7] Although hydronic systems are often designed for dT~20ºF, field data collected by New Ecology for >100 multifamily buildings found that dT did not approach that value for most boiler systems.

We can also solve the energy balance and dT(HTWS,Tin) equations simultaneously to obtain Tin,eq, where $UA_{in,design}$ and $UA_{in,new}$ are calculated for the HDU at the design and new HTWS values:

$$Tin,eq = \frac{UA_{out}Tout + HG + \frac{mcp\ HTWS\ dT\left(HTWS_{design}, Tin_{design}\right) UA_{in,new}}{\left(HTWS_{design} - Tin_{design}\right) UA_{in,design}}}{\left(UA_{out} + \frac{mcp\ dT\left(HTWS_{design}, Tin_{design}\right) UA_{in,new}}{\left(HTWS_{design} - Tin_{design}\right) UA_{in,design}}\right)} \quad (14)$$

Unsurprisingly, a perpetually open TV can significantly increase indoor temperatures. Figure 5 shows Tin,eq as a function of Tout based on this methodology based on the following assumptions: Tdesign = 0°F; Tset,design = 75°F Tout; VRT(Tout,design)=100% (for the controlled case); HG = 10°F and a HTWS reset curve of (10,180) and (60,120).[8] In that case, our model shows the building experiences significant overheating, with the expected Tin,eq often exceeding 80°F. Heat transfer from the room to the outdoors, which scales with Tin-Tout, increases, so effective space heating loads do as well.

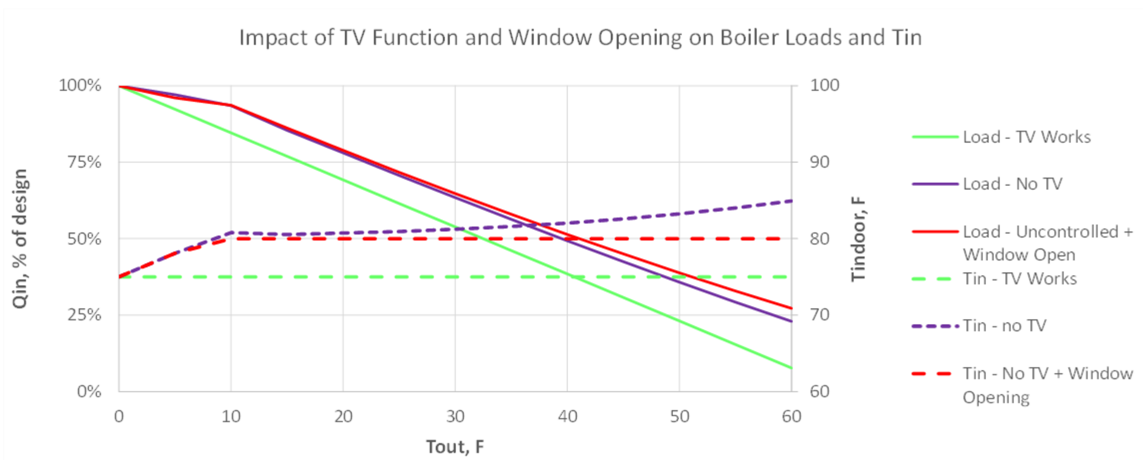

Figure 5. Example of modeled Tin and boiler output (Qin) as a function of Tout for three control scenarios: TV Works, No TV (= failed TV), No TV + Window Open.

Elevated Tin,eq makes it more likely that inhabitants will open windows to moderate Tin, which increases UA_{out} and UA_{tot} for the entire system. We can estimate the increase in UA_{out} by assuming people would operate windows to achieve a maximum, marginally acceptable indoor temperature, Tin,max, In that case, the window-controlled Tin, Tin,cont, equals:

$$Tin,cont = MIN\ (Tin,equ\ ,\ Tin,max). \quad (15)$$

Since Tin is now fixed and VRT = 100%, we can readily solve for dT and then $UA_{out,new}$ from a room energy balance:

$$dT = dT_{design} \frac{HTWS - Tin,cont}{HTWS_{design} - Tin_{design}} \frac{UA_{in,new}}{UA_{in,design}} \quad (16)$$

[8] The first term of the reset curve parameters specifies Tout (10°F) when HTWS reaches its maximum value (180°F) while the second specifies the Tout (60°F) when HTWS reaches its minimum value (120°F).

$$UA_{out,new} = \frac{mcp\ dT + HG}{(Tin,cont - Tout)} \quad (17)$$

Calculations made for $UA_{out,new}$ indicate that UA_{out} increases ~10-15% when Tout ~25-30^{o}F, and by >40% when Tout is 50^{o}F relative to the windows closed case.

Estimating the Fraction of Controlled and Uncontrolled Heating Energy Consumption

As shown, uncontrolled heat flow can greatly increase Tin, effective building loads, and boiler energy consumption. We now present an approach that uses data from connected boilers to estimate the *degree* of overheating occurring in a building. Connected boilers acquire a range of time-series data about boiler performance, such as boiler firing rates (BFR), outlet and return temperatures, status and error codes, etc. and communicate it to the cloud. Building operators can then access those data remotely (see Lochinvar 2023). *We use the $\overline{HTWSR}$, FiringRate, and Tout data from connected boilers to evaluate the degree of overheating occurring for a specific boiler system.*

As shown earlier, a building with well-regulated heat flows from the boiler system will result in space-heating *loads* that decrease approximately linearly from Tout,design to Tbal. In contrast, space heating loads in buildings with uncontrolled Tin regulation will scale with ($\overline{HTWSR}$ – Tout), with an abrupt drop-off around the warm-weather shut-down (WWSD) temperature (when the system automatically locks out the boiler from firing). **Thus, we can analyze the *shape* of the boiler gas consumption (derived from BFR data) versus Tout curve to identify systems that have appreciable overheating. Specifically, we expect boiler plants with Load (= Qin * η) vs. Tout slopes that scale with ($\overline{HTWSR}$ –Tout) and do not converge to negligible average BFR (i.e., negligible space-heating gas consumption) at Tbal (e.g., around ~55-65^{o}F) indicate significant overheating.**

Uncontrolled heat flow yields a gas consumption vs. Tout curve similar to that shown in Figure 2 from Hewett and Peterson (1984), who reported Tin values in many buildings they investigated ranging from the mid-70s to mid-80s, indicative of significant overheating relative to typical design temperatures and likely window opening.

In practice, many buildings have a mix of controlled and uncontrolled heat flow from HDUs. Then, the actual Qin to the building, Qin,actual, equals the product of the controlled and uncontrolled cases with the fraction of HDU UA associated with each case, where SC equals the fraction of HDUs with well-controlled heat flow.

$$Qin, actual = SC * Qin, contr(Tout) + (1 - SC)Qin, uncontr(Tout, HTWS) \quad (18)$$

Figure 6 show conceptually to apply these basic models to estimate the actual extent and energy impact of overheating in a building by comparing actual average hourly heating loads at different Tout values to the fully controlled and uncontrolled cases. As in Figure 2, the upper red line represents the Qin(Tout) curve for the uncontrolled case, the lower green curve the controlled case, and the middle blue line a curve for an actual boiler system with some fraction of uncontrolled heat flow, *SC(Tout)*. As noted earlier, this assumes that the controlled (i.e., ideal) and uncontrolled curves converge at Tout,design, i.e., that the HDU TVs are always fully open to attain Tin,design at Tout,design. For the analysis that follows, this is likely a conservative assumption for many buildings that have spare boiler and HDU capacity at design conditions.

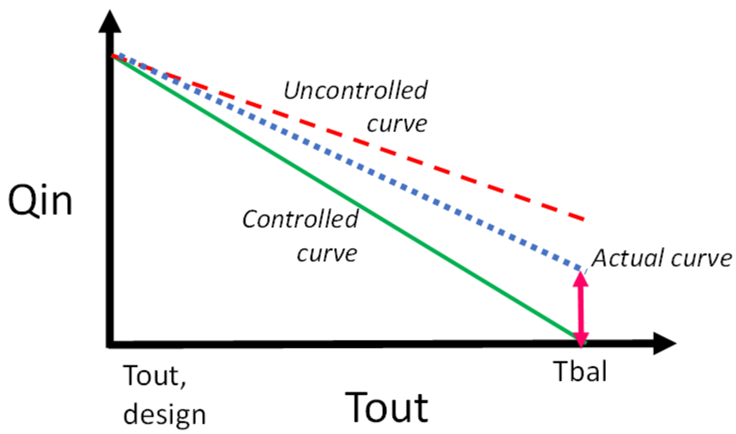

Figure 6. Conceptual diagram of boiler Qin versus Tout curves for ideal HDU control and uncontrolled HDUs, with an example of an actual boiler system with uncontrolled heat flow in ~60% of spaces.

Modeling Energy Impact of Uncontrolled Heating Energy Consumption and OAR Curve Changes

Using BFR and HTWS data from connected boilers and Tout weather data, we can assess SC(Tout) for each 5^{o}F Tout bin by calculating the difference between Qin,actual and Qin,ideal(Tout) divided by the difference between Qin,uncontr(Tout) and Qin,contr(Tout) given the boiler system's HTWS(Tout):

$$SC(Tout) = \frac{Qin{,}actual(Tout) - Qin{,}contr(Tout)}{Qin{,}uncontr(Tout) - Qin{,}contr\ (Tout)} \quad (19)$$

We can then calculate Qin for any conditions:

$$Qin(Tout) = Qin(Tout, design)\left[\frac{SC * C_{TV} * (HTWS(Tout) - Tout)}{HTWS(Tout{,}design) - Tout{,}design} + \frac{(1 - SC)\ (Tbal - Tout)}{Tbal - Tout{,}design}\right] \quad (20)$$

We can use this expression to model and predict the energy impact of changes to the OAR curve parameters, i.e., HTWS(Tout). *Crucially, changes in HTWS(Tout) only result in savings from reducing overheating in portions of the distribution system with uncontrolled heat flows, as system portions with well-controlled heat flows effectively modulate Qin as loads change.*[9] Consequently, systems with load curves closer to the uncontrolled case can achieve significant overheating/load-related savings, as decreasing HTWS directly decreases Qin for uncontrolled flows. In contrast, systems with load curves closer to the controlled case will realize smaller savings from the same OAR curves, since a smaller portion of the heat distribution is uncontrolled. Figure 7 show an example of this approach applied to two OAR curves, with Tbal = 60^{o}F and SC = 0.59; the actual SC would be calculated using BFR data.

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[9] In the extreme case where heat flow is perfectly controlled, the savings from modifying the HTWS curve are driven entirely by nominal changes in boiler efficiency as a function of temperature and firing rate.

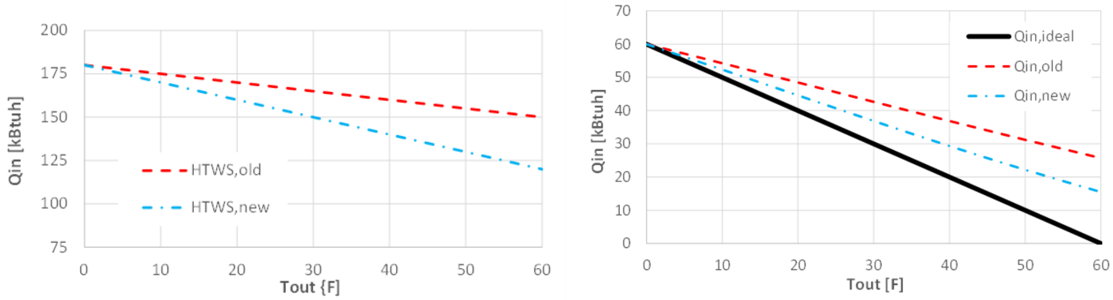

Figure 7. Modeled example of how lowering HTWS (Tout; *left*) decreases Qin,uncontr(Tout), shown relative to ideal (controlled) case (*right*).

Assuming the portion of the system with uncontrolled heat flows does not change when HTWS(Tout) changes, e.g., due to window opening, we can estimate the reduction in space-heating heat into the building from changes in HTWS for each Tout bin, dQin(Tout), and the percentage change in Qin, OAR,save,load (Tout), taking into account changes in C_{tV}:

$$dQin\ (Tout) = \frac{SC*\ Qin\ (Tout,design)*\left[C_{TV,fail,old}\ (HTWS_{old}\ (Tout)-Tout) - C_{TV,new}\ (HTWS_{new}\ (Tout)-Tout)\ \right]}{(HTWS(Tout,design)-Tout,design)} \qquad (21)$$

$$\%OARsave, load(Tout) = \frac{SC*\left[C_{TV,fail,old}\ (HTWS_{old}\ (Tout)\ -Tout) - C_{TV,new}\ (HTWS_{new}\ (Tout)-Tout)\ \right]}{(HTWS(Tout,design)-Tout,design)*\left[\frac{SC*C_{TV,old}\ (HTWS_{old}\ (Tout)-Tout)}{(HTWS,design-Tout,design)} + (1-SC)\left(\frac{Tbal-Tout}{Tbal-Tout,design}\right)\right]}\ . \qquad (22)$$

One thing to note is that if the load curve is linear with Tout and the change in HTWS(Tout), i.e., dHTWS(Tout)/Tout, is constant over a temperature range, the *magnitude* of the hourly savings would be the same for those Tout bins (not accounting for changes in UA_{in} and UA_{tot} that will "bend" down the theoretical uncontrolled load curve). The *percentage* savings will, however, increase as Tout increases, since the magnitude of the baseline load decreases while the quantity of energy saved remains constant. In practice, these calculations can become very sensitive as Tout approaches the estimated Tbal. Since the ideal load becomes small under those conditions, uncontrolled heat flows likely dominate space heating. Consequently, it may be reasonable to assume that SC = 1 when Tout approaches Tbal.[10]

To obtain a representative estimate of annual savings from the OAR curve changes, we apply the SC(Tout) values to TMY data, multiplying dQin(Tout) for each Tout bin by the hours/year in that bin in a typical mean year (TMY). Any incremental savings from increased boiler efficiency would be calculated based on the difference between Qin to obtain a difference in boiler energy, Qgas, i.e., Qin divided by η(Tout), for the baseline and reduced load cases.

[10] If HTWS were decreased below the minimum required to meet the space heating load at a given Tout, with functioning TVs fully open, Tin would fall below Tin,design. The model assumes that HTWS(Tout) is not decreased to an extent that this occurs.

Field Testing Results

We applied this methodology to 19 different OAR curve and WWSD changes made at 12 different sites in Massachusetts[11] with boiler systems monitored using New Ecology's Remote Monitoring & Optimization (ReMO) platform that acquired HTWS, HTWR, BFR, and Tout data (New Ecology 2023)[12]. For more detail on data acquisition, please see Davey and Connelly 2018 New Ecology 2018. To avoid confounding factors, we limited our analyses to sites where the boilers only served space heating loads, i.e., they did not serve water heating loads.[13] For both cohorts, data were divided into "pre" and "post" periods that correspond to periods with different OAR curves. In all cases, we used the "pre" data to model the boiler plant and then apply the model to the "post" period actual weather to predict "post" period performance, ultimately comparing modeled (*predicted*) energy consumption to *actual* post-ECM energy consumption.

Figure 8 presents pre and post hourly Qin data for another site, along with the ideal and uncontrolled curves for the pre and post OAR curves, as well as the average Qin values (triangles) for the 5°F Tout bins. Due to frequent problems with Tout sensor placement, the analysis uses Tout values from weather services instead of values from an on-site Tout sensor.[14]

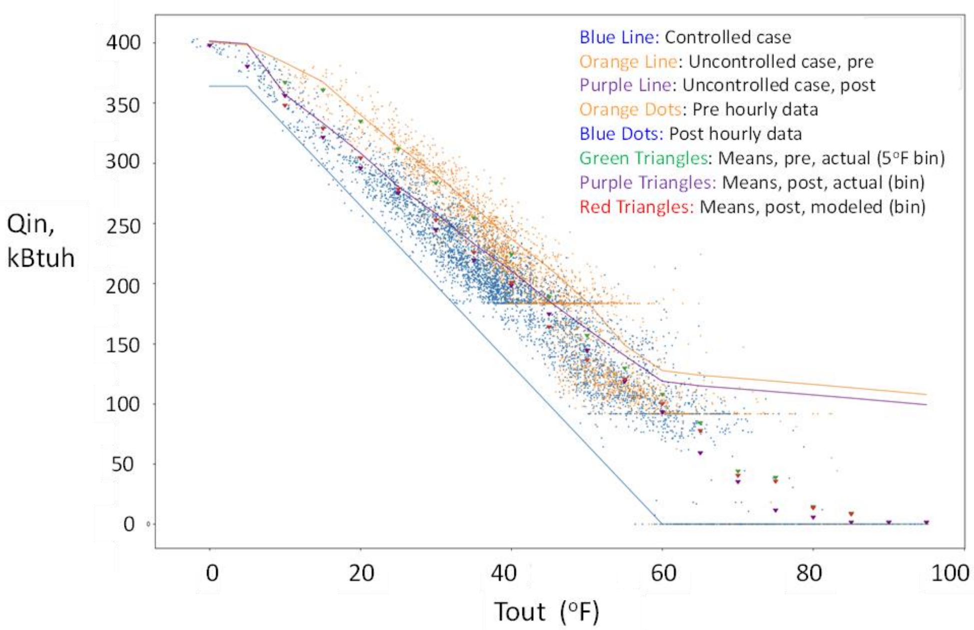

Figure 8. Example of Qin analysis for site 1020, showing pre and post data relative to controlled and uncontrolled heat flow cases.

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[11] Located mainly – but not all – in Greater Boston, the sites included masonry, concrete, and wood-frame buildings constructed between 1900 and 2002 with 15 to >150 units on three to 16 stories. Each building had at least two boiler that could serve space heating loads, with capacities ranging from a few to several hundred kBtuh.

[12] The surface-mounted temperature sensors for HTWS and HTWR were both installed in the boiler room, with HTWS typically located immediately downstream the heating water distribution pump(s) and HTWR downstream of the piping manifold (if any) that combined separate heating water loop returns.

[13] For boilers serving both space and water heating loads, we have developed data-driven techniques to disaggregate boiler energy consumption time series between space and water heating.

[14] New Ecology (2018) found that a large fraction (roughly half) of Tout sensors suffer from suboptimal placement that yield inaccurate values, e.g., due to solar gains (poor placement, lack of solar shield) or heat from exhaust.

Table 1 summarizes the 19 OAR curve changes made to the boiler systems at 12 sites, with several sites having multiple changes.

Table 1. OAR curve parameters for the 19 changes evaluated at 12 sites. OAR parameter format is: Tout/HTWS,max to Tout/HTWS,min (all temperatures in ^{o}F).

	Period		***WWSD***	***OAR Curves***	
Site	**Pre**	**Post**	**Pre to Post**	**Pre (Original)**	**Post (New)**
1020	2	0	65 to 65	8/156 to 64/117	12/150 to 68/109
1020	3	2	70 to 65	0/169 to 64/119	8/156 to 64/117
1020	4	3	70 to 70	16/172 to 63/124	0/169 to 64/119
1020	4	0	70 to 65	16/172 to 63/124	12/150 to 68/109
1007	1	0	83 to 75	10/180 to 70/120	10/170 to 65/115
1023	1	0	70 to 62	11/136 to 60/120	10/140 to 60/101
41	1	0	67 to 67	14/169 to 65/133	20/162 to 60/133
41	2	1	70 to 67	34/169 to 67/142	14/169 to 65/133
41	4	3	70 to 65	29/170 to 62/145	25/161 to 69/131
43	1	0	65 to 65	39/187 to 69/153	8/168 to 64/114
1009	1	0	67 to 62	33/175 to 68/123	14/175 to 60/119
1009	2	1	69 to 67	22/176 to 65 121	33/175 to 68/123
1009	4	3	67 to 67	31/175 to 64/115	18/175 to 68/111
1013	2	0	70 to 62	10/169 to 68/102	5/173 to 60/100
1028	1	0	70 to 65	10/163 to 60/109	25/166 to 60/135
55	2	1	65 to 61	39/151 to 67/138	14/170 to 60/115
1016	1	0	No change.	10/169 to 60/124	2/162 to 61/117
23	2	0	70 to 62	13/168 to 60/137	3/162 to 69/121
24	2	1	70 to 65	15/166 to 63/124	35/165 to 61/120

For the 19 different OAR changes, we modeled the expected energy savings using the following process:

1. Analyze boiler data from the “pre” period to calculate hourly space heating energy consumption.
    a. Calculate the total boiler system gas input (HHV), Qgas,in, for each hour by summing the product of boiler firing rate (BFR) and boiler capacity for all boilers.
    b. Estimate the average boiler efficiency for each boiler during each hour using a curve for η(HTWR,BFR) derived from Lochinvar (2019).
    c. Calculate the hourly Qin = Qgas,in,pre * η(HTWR,BFR)
    d. Calculate the average Qin for each 5^{o}F Tout bin for the entire “pre” period
2. Estimate Tout,design; since the boiler plants analyzed were in Boston, MA and vicinity, we used Tout,design = 5^{o}F.
3. Estimate Qin,design from the hourly Qin data in the vicinity of Tin,design.
4. Calculate the Qin,contr and Qin,uncontr heat flow curves using the respective equations above.
5. Calculate SC(Tout) for each 5^{o}F Tout bin using the equation above.

We then applied the SC(Tout) factors calculated for the "pre" period with the pre and post HTWS values (Tout), i.e., HTWS,new and HTWS,old, to calculate dQin(Tout) and the expected *post* space heating load and gas consumption, Qin,post(Tout) and Qgas,in,post, taking into account the impact of OAR curve changes on both space heating loads and boiler efficiency. Finally, Qin,post(Tout) is applied to the "post" Tout data to calculate the total expected boiler energy consumption for the entire "post" period.[15] At all sites, we used the HTWS(Tout) curves derived from "pre" and "post" field data instead of values specified for the periods. For all sites, we calculated the SC values and two metrics:

- "Modeled Savings": Expected percent savings from OAR, WWSD, Tout sensor[16], and Summer-Winter Switch[17] based on weather data from the "post" period.
- "Observed Savings": Actual savings observed during the post period.

Table 2 and Figure 9 summarize the comparisons of the modeled (predicted) and observed (actual) savings. Although there is some scatter, the absolute values[18] of the modeled and observed savings are 12.8% and 11.3%, respectively, with an average absolute difference of 4.3%.[19] For the 19 changes, the model predicted actual savings within ±5% for 13 of them and within ±10% for 16 of them. Taken together, these results strongly suggests that the new approach effectively models the energy impact of overheating from boiler systems due to uncontrolled heat flows and the impact of changing HTWS(Tout) on boiler energy consumption.

Interestingly, there is not always a strong correlation between SC values and the magnitude of modeled savings. This reflects that the magnitude of changes to OAR curve parameters also has a large impact on expected savings, e.g., the three sites with modeled savings exceeding 20% had larger changes in the OAR curve parameters. In addition, we calculated savings based on the actual Tout conditions during the post period. That is, the post period may include warmer or colder conditions than TMY conditions, which can substantially affect the savings period for that period. Finally, the magnitude of WWSD changes – and their savings – varies appreciably. For these reasons, the typical annual savings from changing boiler control settings can vary appreciably from those shown; our analyses focused on evaluating the accuracy of the algorithms.

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[15] Since sites often implemented changes to WWSD measures, we also modeled their energy impact.

[16] The Tout sensor was also moved at a few sites, which affects the Tout value used by the boiler system to determine HTWS(Tout); we took that into account.

[17] A summer-winter switch (SWS) locks out space heating functionality for a boiler system during a set time of the year, e.g., mid-June through mid-September.

[18] For cases with negative savings, typically due to an increase in OAR curve parameters, we calculated the absolute value of savings by effectively switching the pre and post case, i.e., savings = (% savings)/(1-% savings).

[19] Ignoring the outlier for site 41, between periods 4 and 3, the modeled and expected savings are 12.9% and 10.9%, respectively, with an average absolute difference of 3.8%. At site 41, Tout during period 4 was very warm; as a result, the impact of heat gains not captured by the model on total space conditioning loads increases as conduction and infiltration loads driven by ~Tin-Tout decreases. Specifically, 48% of the post-ECM samples are >62.5 ºF, i.e., a Tout regime with very large savings from both OAR changes and WWSD changes. In short, the post period is not very representative of the entire space heating season.

Table 2. Summary of modeled and observed savings for OAR changes at different sites. Negative numbers represent an increase in energy consumption.

	Period		*Savings*			
Site	**Pre**	**Post**	**Modeled**	**Observed**	**Difference**	**SC**
1020	2	0	10.8%	5.6%	5.2%	0.75
1020	3	2	9.5%	-1.4%	10.9%	0.77
1020	4	3	10.4%	11.7%	-1.3%	0.69
1020	4	0	16.9%	15.8%	1.1%	0.67
1007	1	0	11.1%	1.8%	9.3%	0.83
1023	1	0	12.4%	-1.8%	14.2%	0.33
41	1	0	5.3%	9.0%	-3.7%	0.59
41	2	1	22.5%	19.8%	2.7%	0.65
41	4	3	12.3%	24.6%	-12.3%	0.52
43	1	0	27.4%	27.3%	0.1%	0.18
1009	1	0	17.9%	12.9%	5.0%	0.57
1009	2	1	-8.9%	-2.1%	-6.8%	0.68
1009	4	3	2.7%	2.6%	0.1%	0.60
1013	2	0	9.2%	10.7%	-1.5%	0.82
1028	1	0	20.7%	23.7%	-3.0%	0.34
55	2	1	14.0%	16.0%	-2.0%	0.54
1016	1	0	8.1%	9.3%	-1.2%	0.32
23	2	0	10.1%	12.7%	-2.6%	0.65
24	2	1	-15.1%	-14.7%	-0.4%	0.68

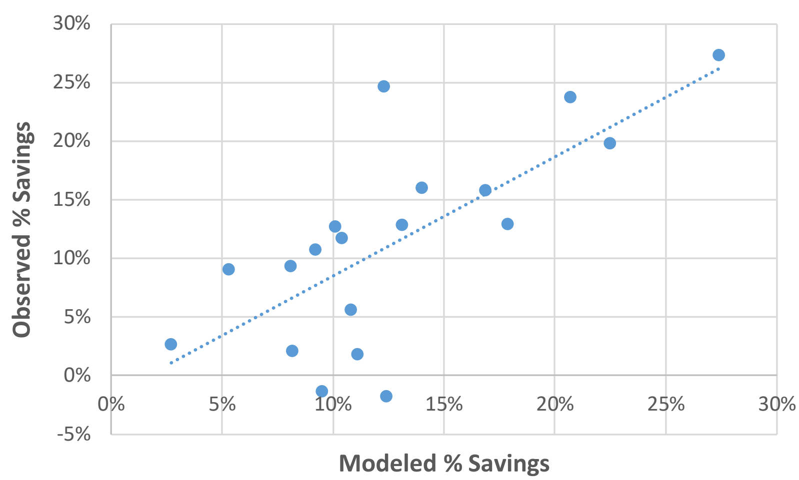

Figure 9: Comparison of modeled and observed savings percentages for the 19 OAR curve changes.

Conclusions and Next Steps

We developed a simple physics-based model that uses connected boiler system data to characterize the extent of overheating occurring in each building due to uncontrolled heat flow. The model can also predict the change in annual space heating energy consumption from changes in OAR curve parameters, i.e., HTWS(Tout). To validate the model, we used data from 12 multi-family buildings that underwent a total of 19 OAR curve parameter changes to predict post-change space heating energy consumption under post-change weather conditions and compared it to actual post-change boiler energy consumption. The absolute values of the predicted and actual savings were 12.8% and 11.3%, respectively, with an average absolute difference of 4.3%. For the 19 changes, the model predicted actual savings for 13 within ±5% and 16 within ±10%. This indicates that the new approach effectively models the energy impact of overheating from boiler systems due to uncontrolled heat flows and the impact of changing OAR curve parameters on energy consumption. To address the pervasive problem of building overheating from high HTWS (New Ecology 2018), the authors worked with New Ecology, Inc. to incorporate the algorithms presented into a boiler system performance analysis tool that automatically analyzes a year's worth of building performance data to detect overheating and several other boiler system energy-wasting faults and calculates the savings from remediation. We also extended the analysis framework to buildings with combination boiler systems, i.e., those where boiler serve both space and water heating loads. Since the tool has a runtime of about one minute per site on a notebook PC, it enables ongoing commissioning of boiler systems.

Acknowledgements

The authors thank Ed Connelly, Neil Donnelly, Sankhanil Goswami, and Joshua Sklarsky of New Ecology, Inc. (NEI) for their collaboration on this project. Dr. Roth particularly appreciates the review and feedback on the model development provided by Henry Harvey (former Director of Engineering at NEI). This work was supported by the U.S. Department of Energy Building Technologies Office Building America Program under Contract # DE-EE0008696 via a subcontract from NEI to Fraunhofer USA.

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Appendix A: UA,in Correction to TV Failed Curve

UA_{in} varies as a function of $\overline{HTWSR - T\imath n}$, so it decreases as HTWS-Tin decreases, causing the heat delivered in the uncontrolled heat flow case (upper curve in Figure 7) to bend downward as Tbal-Tout decreases. The correction factor, C_{TV}, takes this into account and decreases as a function of both the indoor and outdoor overall heat transfer coefficients as follows:

$$C_{TV} = \frac{\left(\frac{1}{UA_{in}(Tout, design)} + \frac{1}{UA_{out}}\right)}{\left(\frac{1}{UA_{in}(Tout)} + \frac{1}{UA_{out}}\right)}$$

However, UA_{in} also varies with Tin. Using UA_{out} estimated earlier and the $UA_{in}(HTWS,Tin)$ model shown below, we can iteratively solve for Tin,equ and UA_{in} as a function of HTWS(Tout) and Tout. For a HDU exponent of n=0.3783, this yields the following curve fit for C_{TV} as a function of HTWS and Tout):

C_{TV} (Tout) = (-9.6*10^{-6}*(HTWS-Tout)^2 + 0.0042*(HTWS-Tout) + 0.562) / (-9.6*10^{-6} * (HTWS,design – Tout[design])^2 + 0.0042*(HTWS,design -Tout[design]) + 0.562) .

and Qin,uncontr is proportional to: (HTWS – Tout) * C_{TV}. The approximate impact of this correction factor increases as HTWS decreases, with ~37% decrease in UA_{in} resulting in a ~25% decrease in UA_{tot} (assuming no change in window opening, i.e., UA_{in}) when going from HTWS,design = 170^{o}F at Tout=0^{o}F to 110/60.