BUILDING ENVELOPE OPTIMAZATION METHOD AND APPLICATION TO THREE HOUSE TYPES IN A PROPOSED SOLAR DISTRICT ENERGY SYSTEM

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ABSTRACT

A simple cost optimization method was applied to determine the appropriate investment in energy efficiency for houses to be built as part of a large scale solar community planned for construction near Calgary, Alberta. The cost effectiveness of individual house envelope energy efficiency upgrades was determined using energy simulation results and builder contributed costing information. These results then guided the combination of house energy efficiency upgrades. Finally, the incremental costs of these combined upgrades were compared to the estimated incremental cost of providing space heating using the planned solar district heating system to determine the appropriate house energy efficiency upgrades.

INTRODUCTION

Of the myriad uses of energy simulation, cost optimization is one of the most common. The solution described herein was developed to determine how much effort should be invested in energy efficiency upgrades for houses which will be part of a large solar community planned to be built near Calgary, Alberta.

The new solar community in question was planned to comprise close to 1000 dwellings of varied type for which about 90% of the space heating energy and potentially up to 50% of the domestic hot water (DHW) heating energy would be provided using a solar district energy system connected to a borehole seasonal storage system (McClenahan 2011). The cost of providing space heating to the community using the solar seasonal storage system added to an existing district energy system was estimated to be about $720/GJ (Wong 2012). It is hoped that this cost will decrease as the parameters of the system undergo further optimization. Of these parameters, the optimization described here focused solely on the cost-effectiveness of house efficiency upgrades. The question to answer was: is it cheaper to increase supply of renewable energy or reduce demand with energy efficiency measures?

TOOLS

There is a wide array of residential and commercial building energy simulation engines available today. Some, such as NREL's BEopt, combine energy simulation and cost optimization routines into one tool (NREL 2011). For this study HOT2000 v10.51 was used (NRCan 2010). This venerable modified-bin method tool includes the AIM-2 infiltration model (Walker 1990) and the BASESIMP ground conduction model (Beausoleil-Morrison et al. 1997) making HOT2000 better suited to estimating the energy use of Canadian homes than other, more generalized, tools which simulate energy consumption in large commercial buildings in addition to smaller residential homes. HOT2000 is widely used in Canada for both research purposes and program delivery (NRCan 2010) and has been validated using HERS BESTEST (Haltrecht et al. 1997). More than 1 million homes in Canada have been evaluated using the HOT2000 energy analysis tool in the last fifteen years. Although there are many more sophisticated tools available, such as ESP-r (ESRU 2011), or those based on EnergyPlus (DOE 2011), HOT2000 was chosen for its ease of use, speed, integration of the EnerGuide rating system and the models it uses to simulate houses typically found in Canada. The upgrades considered in this study were all well-suited to, and within the modeling capabilities of, HOT2000.

As with energy simulation tools, there are many powerful optimization tools available for use with building energy simulation, such as GenOpt (LBNL 2011) and BEopt (NREL 2011). Unfortunately, many require a continuous cost function. Others require that a specific energy simulation tool be used. GenOpt provides a text based interface with the simulation engine allowing it to be used with a variety of tools. Unfortunately, using a text interface with HOT2000 proved difficult. Some of these limitations could have been overcome, but time constraints prevented pursuit of their solutions for this study. Given the scope of constructible and practical energy upgrades considered in this investigation and the use of HOT2000, the simple optimization technique described herein was used despite its limitations.

OPTIMIZATION METHOD

The optimization method used followed a two step approach. First, the cost effectiveness of a set of individual upgrades was determined. Then these upgrades were combined in order of decreasing cost effectiveness and the cost effectiveness of the combined set of upgrades established. The incremental cost of one upgrade, when added to a combination of others, was subsequently estimated. This method is similar to a simplified version of the sequential search method used by BEopt (Horowitz 2008).

To start, three baseline models were generated to represent the housing segment considered for the solar community. This provided a common reference to compare the effect of an upgrade on a house's energy consumption. For the sake of clarity, only one baseline is considered in the present discussion. Next, one individual efficiency upgrade was added to the baseline model and the energy consumption of that model was determined. If several upgrades are typically applied simultaneously (e.g. thorough air sealing and the installation of a heat recovery ventilator - HRV), then these upgrades would be considered as one for the purposes of the optimization. The cost effectiveness of the individual upgrade would then be calculated by dividing the capital cost of the upgrade by the difference in energy consumption for one year between the baseline and individual upgrade models. This step would be repeated to determine the cost effectiveness of each individual upgrade.

For the cost optimization analysis, only the energy efficiency upgrade initial capital costs were used. The analysis did not consider the utility costs associated with the renewable energy system or any other costs beyond the initial capital costs. More importantly, the goal was to determine if the capital cost of the renewable energy system could be reduced by reducing demand. Thus, the capital cost of the home efficiency upgrades was appropriate for comparison.

An example of this step in the optimization would be a house with a baseline construction BASE and efficiency upgrades A, B, C and D. In this step, the cost effectiveness (CE_X for upgrade X) of the upgrades would be determined as follows (fictitious results included):

$$CE_A = \frac{C_A}{E_{BASE} - E_{BASE+A}} = \$100/GJ \qquad (1)$$

$$CE_B = \frac{C_B}{E_{BASE} - E_{BASE+B}} = \$500/GJ \qquad (2)$$

$$CE_C = \frac{C_C}{E_{BASE} - E_{BASE+C}} = \$400/GJ \qquad (3)$$

$$CE_D = \frac{C_D}{E_{BASE} - E_{BASE+D}} = \$350/GJ \qquad (4)$$

Where C_X is the capital cost of upgrade X, E_{BASE} is the energy consumption of the baseline model and E_{BASE+X} is the energy consumption of the baseline model with upgrade X applied.

To determine the cost effectiveness of the combined upgrades, the individual upgrades were sorted in order of decreasing cost effectiveness and then applied cumulatively in that order. That is, the model with the most cost effective individual upgrade was first chosen. The next most cost effective upgrade was then applied to this model to create one cumulative model. The difference in energy consumption between this new cumulative model (baseline plus two most cost effective upgrades) and the baseline was then calculated, as was the combined capital costs of the two upgrades. Using this information, the cost effectiveness of this set of combined upgrades was determined in the same manner as the individual upgrades. These steps were repeated as each remaining individual upgrade was added, in order of decreasing cost-effectiveness, to the last cumulative upgrade model to create a new cumulative upgrade model. From this information, a cost curve was developed and incremental costs were determined from the slope of that cost curve.

This determination of the cost effectiveness of the cumulative models can be illustrated by extending the previous example. Given the cost effectiveness from equations 1 through 4, the order in which the individual upgrades would be applied is A, D, C, and B. The cost effectiveness of the cumulative upgrades would be calculated as follows:

$$CE_{A+D} = \frac{C_{A+D}}{E_{BASE} - E_{BASE+A+D}} \qquad (5)$$

$$CE_{A+D+C} = \frac{C_{A+D+C}}{E_{BASE} - E_{BASE+A+D+C}} \quad (6)$$

$$CE_{A+D+C+B} = \frac{C_{A+D+C+B}}{E_{BASE} - E_{BASE+A+D+C+B}} \quad (7)$$

Occasionally, individual upgrades in a given category (ex. different amounts of exterior wall insulation) which saved more energy were more cost effective than other upgrades in the same category which saved less energy. In these cases, the less aggressive, less cost effective, upgrade would be skipped when the cumulative upgrades were being generated. An example would be investigating the addition of 3.8cm of external wall insulation and 5.1cm of external wall insulation. If adding 5.1cm was found to save more energy and be more cost effective than adding 3.8cm, then the cumulative models would not include the 3.8cm case and only the 5.1cm case would be considered.

As many of the steps in this optimization were performed manually, the simplicity and lack of required iterations were highly valued. For this optimization method the maximum number of simulations required is 2N, where N is the number of individual upgrades. If some individual upgrades are not included in the cumulative upgrade set then the number of simulations will be less than 2N. In contrast, the total number of simulations required by the basic sequential search enhanced in BEopt (Horowitz 2008) is N(N+1)/2. In the case of this study 22 individual upgrades were considered. This led to a total of 44 simulations as opposed to 231 simulations for the basic sequential search.

However, this optimization has a number of limitations. Chief among these is that the optimization assumes that the relative cost effectiveness of the individual upgrades will be maintained when they are combined. Since houses are complex, non-linear systems, a given upgrade's energy savings and cost effectiveness will change with the characteristics of the house and the nature of the upgrade. Thus, the cost-effectiveness of the upgrades will change as more upgrades are added.

SIMULATION

With the optimization method devised, the task was then to apply it to the housing expected to be found in the large scale solar community being investigated. Larger multi-unit residential buildings were expected to be part of the community; however, this study focused on smaller single family homes. To represent these homes, three existing home designs that have been built in large numbers by the builder partaking in this study were chosen. The three existing designs were the Nebula, the Pinnacle 4 and the Rialta. The Nebula and the Pinnacle 4 are, respectively, small and mid-sized single detached homes. The Rialta is a middle unit of a row house. As existing designs were being investigated, no large modifications to architecture were explored. Furthermore, the orientation used when modeling these houses was chosen so as to yield the highest energy consumption from the houses. This was done to avoid underestimating the energy requirements of the houses which may be built in a variety of orientations. Table 1 summarizes the general characteristics of the three modeled homes.

Table 1 House Characteristics

Rialta	**Nebula**	**Pinnacle 4**
Middle unit, row house	Small detached with full basement	Mid-sized detached with full basement
2 storey	2 storey	2storey
110 m^2	141 m^2	203 m^2
East facing	East facing	Southeast facing

The baseline construction of the houses considered was that typically used by the builder participating in this study (Paget 2011). This construction was found to use on average 11% less energy than the construction dictated in the 2006 Alberta Building Code (NRC 2006). The house construction characteristics pertinent to energy efficiency for houses built to the 2006 Alberta Building Code and those currently typically built in Alberta are shown in table 2. All houses were modeled using the EnergGuide rating system assumptions (NRCan 2011).

There are a wide variety of technologies and constructions now available that reduce a house's energy demand. However, not all of these technologies and constructions were applicable, or practical, for this study. Some limitations were imposed by the nature of the solar community. Since most of the space heating and much of the DHW would be provided using the district heating system, no mechanical systems were considered. Ventilation was the only exception to this. All houses were modeled to use a 92% AFUE condensing gas furnace with a furnace fan powered by an efficient DC motor. In addition, all houses were modeled to use a natural gas, direct vent, 151.4L tank DHW heater with an energy factor of 0.58. Other limitations were imposed by the circumstances in which the houses would be built. Upgrades had to be amenable to application on a large housing development. Thus, a fairly traditional set of upgrades were considered.

Table 2 Baseline House Construction Characteristics

	Typical Alberta Build	2006 Alberta Building Code
Ceiling	38x89mm engineered truss, 0.61m o/c, RSI 6.0 blown cellulose	
Walls	38x140mm, 0.61m o/c, RSI 3.5 Batt	38x89mm, 0.61m o/c, RSI 2.1 Batt
Exposed Floors	RSI 4.9 Batt + 38x89mm strapping w/ RSI 2.1	RSI 4.9 Batt
Joist Header	RSI 3.5	RSI 2.1
Foundation	Interior full height stud wall: 38x89mm, 0.61m o/c, RSI 2.1	RSI 1.4 to 0.61m below grade
Windows	Double glazed, air filled, no coating, vinyl	
Doors	Steel with polyurethane core	
Infiltration	5.5 air changes/hour at 50 Pa	

The upgrades considered are shown in table 3. A code has been added to each upgrade to facilitate referencing. Table 3 lists three window types; however, they only represent one window upgrade. Since the architecture of the houses was not modified the same style of window called for in the building plans was used in the upgrade (eg. a casement window in the baseline would remain a casement window in the upgrade). The air tightness upgrades were performed as a package of upgrades as listed in table 3. All of the upgrades described in the 1.5 air change per hour at 50Pa (ACH@50) infiltration upgrade were applied to the 1.0 ACH@50 upgrade. The exterior dimensions of the houses were held constant. Thus, interior house dimensions were modified to accommodate oversized upgrades (e.g. double walls). All insulation values are nominal. All cost information was provided by the builder (Paget 2011).

With the upgrades defined, their effect on home energy consumption was modeled and their individual cost effectiveness was calculated. The cost effectiveness results and initial capital costs of the upgrades described in table 3, averaged from the three house types, are shown in figure 1. As per the optimization method, the results have been ordered according to cost effectiveness. One measure, D3E2 is the combination of measure D3 and E2. Generally, the cost effectiveness rises fairly steadily; however, changes are more severe at the ends. Most notable is the decrease in cost effectiveness of the F6, A4, S1, S2 and S3 upgrades.

The relative cost effectiveness of the individual upgrades varied somewhat for the three houses. However, one cost effectiveness for each individual upgrade, averaged over the three houses, was used to determine the order the individual upgrades would be applied to generate the cumulative upgrades. This was done because, in practice, the builder would offer the same upgrade packages for every style of house. The builder did this for practical purposes and to avoid potential customer confusion.

With the individual upgrade results determined, the cumulative models were generated. Figure 2 shows the cost effectiveness of the cumulative measures, averaged for all three houses. The upgrades are listed in the same order that they were applied to the houses. The upgrade code listed under each column describes the last upgrade added to generate that cumulative model. The preceding upgrades would also be part of that model. The cumulative upgrades were applied in a rational manner. For example, if the upgrade being added was RSI 16.7 attic insulation, and one of the preceding upgrades included RSI 11.4 attic insulation, the attic insulation was replaced, not added. Not all of the upgrades listed in figure 1 are listed in figure 2. As mentioned, upgrades in a given category that saved less energy than more cost-effective measures were not included in the cumulative upgrade models. From figure 1, upgrades I1, F4, E2, E1 and A4 were all found to be less cost effective and save less energy than other measures in their respective categories; consequently, they were not considered further.

DISCUSSION AND RESULTS ANALYSIS

From figure 2, it is apparent that, generally, the cumulative upgrades became less cost effective as less cost effective measures were added. The only exception to this trend was D3, which is the double wall with RSI 3.9 between the walls. D3 was more cost effective than D2, which differs by including only RSI 2.1 batt between the two wall sections. The increase in cost effectiveness in D3 was likely caused by interactions occurring between measures that were not taken into account when the order of upgrade application was determined. The trend observed from figure 2 provides evidence that the technique described

Table 3 Upgrade Construction Characteristics

<table>
<tr><th>Foundation Upgrades</th><th>Attic Insulation</th></tr>
<tr><td rowspan="2">

F1 - Full height interior basement stud wall offset 19cm from foundation wall using RSI 3.5 in stud wall cavity
F2, F3 - RSI 1.3 and RSI 1.8 full height exterior foundation insulation (3.8cm and 5.1cm of extruded polystyrene-XTPS)
F4, F5, F6 - RSI 1.8, RSI 3.5 and RSI 5.3 below grade exterior foundation insulation (5.1cm, 10.1cm and 15.2cm XTPS)
S1, S2, S3 - RSI 1.8, RSI 3.5 and RSI 5.3 below slab foundation insulation without thermal break between slab and wall (5.1 cm, 10.1 cm and 15.2 cm XTPS)

</td><td>

A1, A2, A3 - RSI 8.8, RSI 11.4 and RSI 16.7 fiberglass batt insulation with heal height increase from 18 cm to 25 cm
A4 - RSI 11.4 sprayfoam insulation with heal height increase from 18 cm to 25 cm

</td></tr>
<tr><td>
Windows

W1 - Triple Glazed, argon filled, low emmisivity coating

Slider: U 1.15 W/m^{2}K, SHGC 0.21
Casement: U 1.02 W/m^{2}K, SHGC 0.19
Picture: U 0.85 W/m^{2}K, SHGC 0.24

</td></tr>
<tr><th>Air tightness</th><th>Walls</th></tr>
<tr><td>

I1 - 1.5 ACH@50 achieved by:

Slab caulking
Upgrade to sealed air barrier from building paper
Upgrade window framing spray foam caulking
Air tight electrical boxes
Structural insulated joist header
Sealed ductwork

I2 - 1 ACH@50 achieved by:

Spray foam joist header
Spray foam in exposed floors

Air sealing measures included HRV

71% efficient at 0C
62% efficient at -25C

</td><td>

E1, E2 - RSI 1.3 and RSI 1.8 exterior wall insulation (3.8 cm and 5.1 cm XTPS)
D1 - Double wall basic construction

Exterior wall: 38x140mm, 0.61m o/c, RSI 3.9 in cavity
Staggered stud inner 2nd exterior wall: 38x89mm, 0.61 m o/c, RSI 2.1 in cavity

D2 - D1 with RSI 2.1 batt between walls
D3 - D1 with RSI 3.9 batt between walls

</td></tr>
</table>

yields a reasonable first approximation for optimization.

To establish the most appropriate set of upgrades to apply to the houses in the solar community, the change in cost with the change in energy saved between measures, called the incremental cost, is required. To determine this, the total cost of the cumulative upgrades was plotted against the total energy saved by those cumulative upgrades. This is shown in figure 3. The three separate curves correspond to the three house types investigated.

One striking feature of the curves in figure 3 is that they increase fairly steadily up to a point after which their slope increases drastically. This transition point appears to precede a jump in cost to the next upgrade, after which energy savings become difficult to realize. The transition point was the same for all three house types and corresponds to the application of upgrade D3, which is a double wall with RSI 3.9 batt insulation placed between the walls. Table 4 provides the full set of upgrades applied up to, and including, D3.

Two lines, labeled by adding 1 or 2 to the end of the house name, were fit to each curve in figure 3. One line (Rialta 1, Nebula 1, Pin 1) was fit to the points from upgrade I2 (the third point) to the transition point. The next line (Rialta 2, Nebula 2, Pin 2) was fit to the points after the transition point. Table 5 lists the slopes and regression fitness (the R^2 value) for both lines for each house type. Line segments were used to fit the curves because they produced the closest fit to the data.

The slope of these lines was used to estimate the incremental cost of the measures they covered. This was done to avoid the large fluctuations in incremental cost that occurred when it was calculated by dividing the difference in cost and energy savings between two neighboring points. The fluctuations were due to small differences in the simulation results between neighboring points being magnified in the incremental costs because the energy results were used in the denominator of this calculation.

Upon attempting to fit lines to the curves in figure 3, finer detail in the cost curve trends became apparent. The first three points of the cost curves (baseline to upgrade W1) were not very linear. Also, the slopes of the cost curves were lower in that region than anywhere else on the curves. When the Rialta 1, Nebula 1 and Pin 1 lines included those first three points, their slopes and fitness were reduced. Thus, the Rialta 1, Nebula 1 and Pin 1 lines are fit from the I2 upgrade point to the transition point.

Using one slope to determine incremental cost for several upgrades at once rests on the assumption that the curves are linear. This implies that the incremental cost of the measures covered is constant. From the R^2 values given in table 5 it appears that this assumption holds true for the Rialta 1, Nebula 1 and Pin 1 curve fits. The Rialta 2, Nebula 2 and Pin 2 fits are clearly non-linear. However, the slope of these lines can still be used to give a rough estimate of the incremental costs for these measures.

Table 4 Transition Point Upgrade Construction

	Transition Point Upgrades Applied to Typical Alberta Build
Ceiling	38x89mm engineered truss, 0.61m o/c, RSI 11.4 fiberglass batt insulation, 25cm heal height
Walls	Double wall with insulated middle area between: • Exterior wall: 38x140mm, 0.61m o/c, RSI 3.9 in cavity • RSI 3.9 batt between walls • Interior wall: 38x89mm, 0.61m o/c, RSI 2.1 in cavity
Exposed Floors	RSI 8.1 sprayfoam
Joist Header	RSI 3.5 sprayfoam
Foundation	Interior full height stud wall: 38x89mm, 0.61m o/c, RSI 2.1 RSI 25.4 full height exterior foundation insulation (5.1cm XTPS)
Windows	Triple Glazed, argon filled, low emissivity coating
Doors	Steel with polyurethane core
Infiltration	1.0 ACH@50 Pa with HRV

Table 5 demonstrates that the incremental costs of the upgrades applied after the transition point, which averaged $3005/GJ, were much higher than those before. The incremental costs for the single detached homes, the Nebula and Pinnacle 4, are fairly close together at $389/GJ and $408/GJ, respectively, averaging $399/GJ. The Rialta, a middle unit of a row house, has a higher incremental cost of $532/GJ. In both cases, the jump in incremental cost after the transition point, and the diminishing energy savings, are strong disincentives to implement the additional upgrades. Given that the incremental cost of space heating provided by the solar seasonal storage system when added to an existing district heating system has been estimated to be $720/GJ (Wong 2012), it would be appropriate to pursue the transition point upgrades as described in table 4.

Table 6 lists the energy savings and initial customer capital cost information (including builder markup) for the transition point upgrades. These energy savings are based on total energy use which includes space heating, DHW and electrical loads, including plug loads.

Table 5 Slope and R^2 Value of Lines fit to Cost Curves

	Incremental Cost from slope ($/GJ)	**R^2**
Rialta 1	532	0.99
Nebula 1	408	0.99
Pin 1	389	0.99
Rialta 2	3842	0.64
Nebula 2	2775	0.71
Pin 2	2397	0.76

Table 6 Energy Savings and Consumer Cost for Transition Point Upgrade

Transition Point Upgrades Costs and Energy Savings	**Rialta**	**Nebula**	**Pinnacle 4**
Total Energy Savings	30 GJ	55 GJ	72 GJ
Total Energy Savings	31%	42%	43%
Upgrade Customer Cost	$10123	$20121	$26130
Upgrade Customer Cost Relative to Standard Construction House Cost	3.6%	5.6%	5.4%

From table 6, the total energy savings yielded by the transition point upgrades are 42% and 31% for the single detached and middle unit row houses, respectively. For these energy savings, the relative consumer cost increases of roughly 5.5% for the single detached homes and 3.6% for the middle unit row house, are fairly small. However, consumers may be sensitive to the upfront costs of these upgrades.

CONCLUSIONS

House simulation combined with a simple and fast energy efficiency cost optimization method was applied to three houses to be included in a planned large solar community. The analysis found that total energy savings of 42% and 31% could be achieved for the single detached homes and the row house middle unit, respectively. These energy savings could be realized for incremental costs of $399/GJ averaged for the single detached homes and $532/GJ for the row house middle unit. Since the incremental cost of adding the solar seasonal storage heating system to an existing district heating system is estimated at $720/GJ, it would be appropriate to pursue these energy savings. However, upgrades beyond this had an average incremental cost of $3005/GJ and produced few energy savings.

Given the faults of the cost optimization method and the scope of upgrades investigated, future work would be to use a more sophisticated optimization method along with a wider set of upgrades to pursue higher energy savings with reduced cost.

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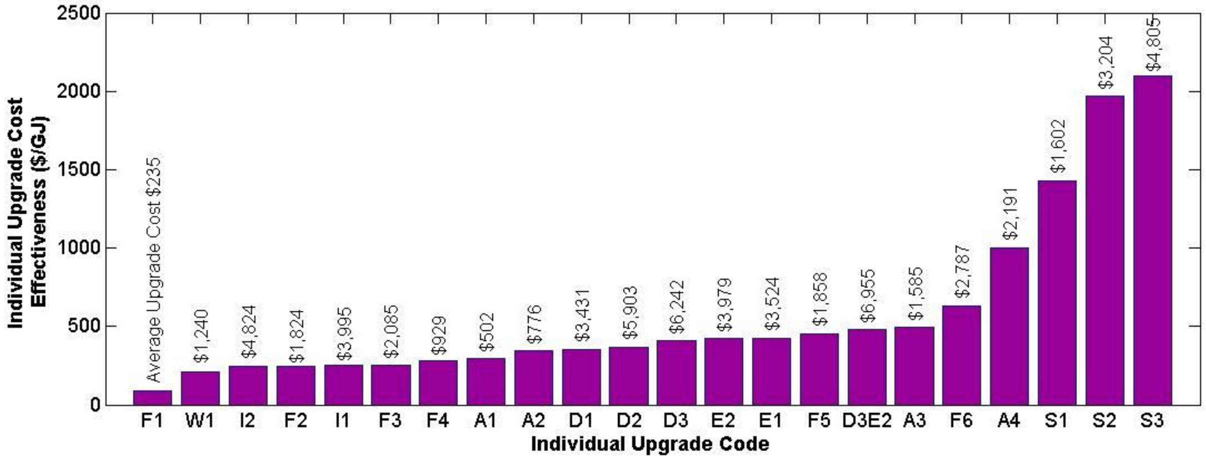

Figure 1 Cost effectiveness of individual measures

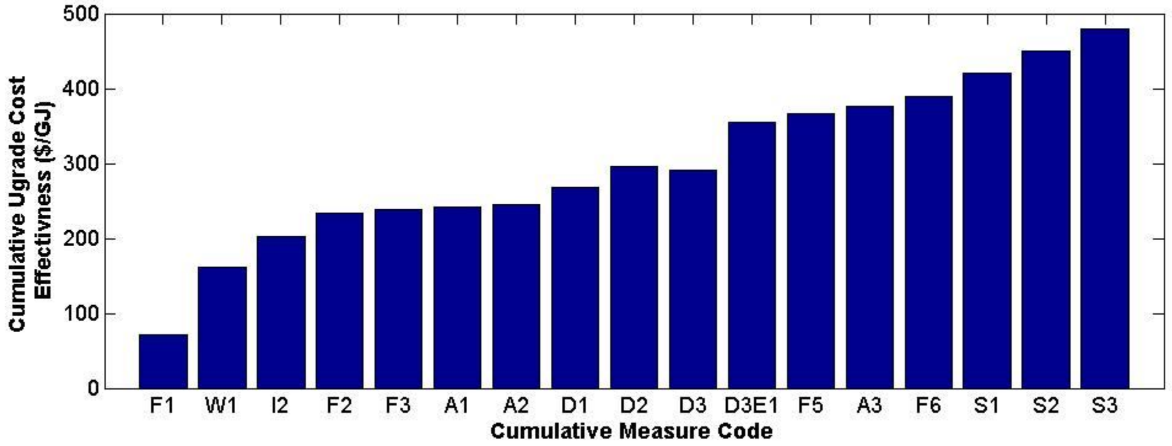

Figure 2 Cost effectiveness of cumulative measures

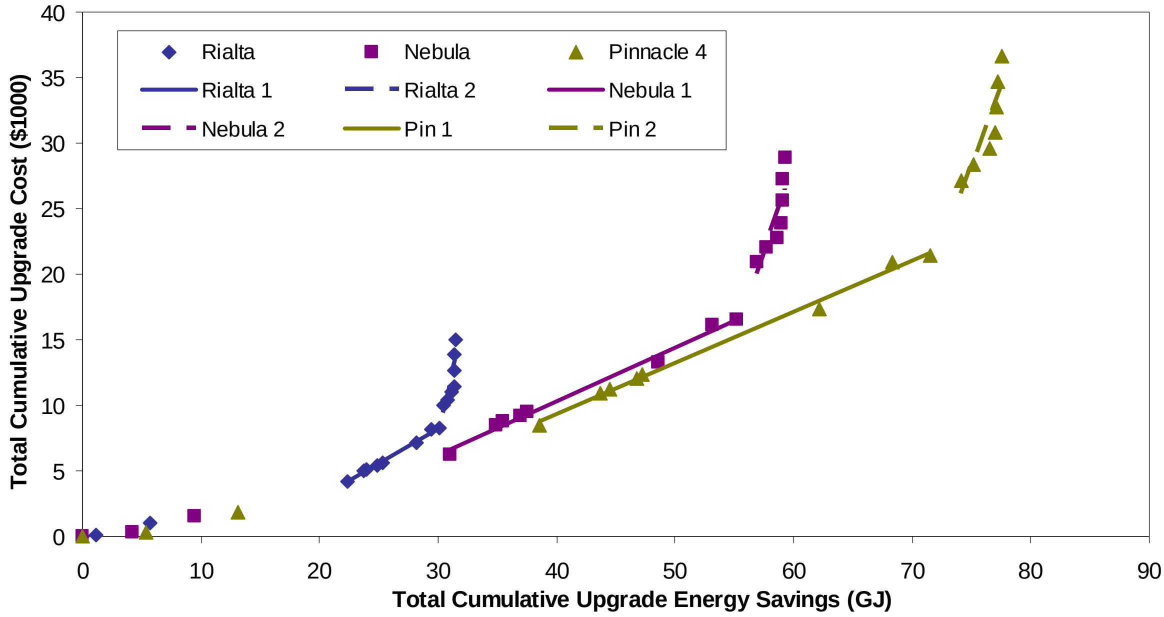

Figure 3 Cumulative capital costs of upgrade measures versus cumulative energy savings