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Building energy retrofits under capital constraints and greenhouse gas pricing scenarios

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ABSTRACT

This study demonstrates that capital availability needs to be considered while developing retrofit measures. Specifically, this study established a methodology using building energy simulations to determine optimal retrofit options over a range of NIST greenhouse gas pricing projections, full and half-price measure costs, and capital availability ranging from $1/ft^2-yr ($10.76/m^2-yr) to $100/ft^2-yr ($1076.39/m^2-yr), representing no capital constraint. The demonstration considers a sub-metered office building in Philadelphia with central heating and cooling equipment nearing replacement. When capital is restrained, measure installation occurs over several years, reducing energy and cost savings over the investment lifetime. This effect is as significant as the greenhouse gas price. Furthermore, changing measure installation order matters most when capital availability is constrained to $1/ft^2 ($10.76/m^2), resulting in a difference of $0.34–0.43/ft^2 ($3.66–4.63/m^2) between the least-optimal and optimal measure ordering. All but $0.05/ft^2 ($0.54/m^2) of this difference is explained by when fast-payback measures are installed; load-reduction benefits were insufficient to justify delaying fast-payback measures. This suggests that capital availability is a determinant of retrofit financial performance, and ordering measures for optimal load reduction is inferior to ordering measures with fast-payback when these strategies conflict. Therefore, increasing investment in energy retrofits is key to reducing greenhouse gas emissions.

1. Introduction

Governments and institutions are focusing on building energy efficiency as an area for sizable, cost-effective energy use reduction and greenhouse gas mitigation [1,2]. Commercial buildings are important to consider, as they are capital intensive and long-lasting, with a median lifetime of 70 years [3]. Without considerable efforts to retrofit the current building stock for energy efficiency, as much as 80% of 2005 thermal energy consumption can remain past 2050 [4]. Currently, while 86% of construction costs go to building renovation, little of that goes to improving the energy efficiency of buildings [5]. Renovation rates are around 2.2%, with an 11% average energy savings [6]. This rate needs to grow several-fold, with average savings around 55%, to approach modest emission reduction targets and Architecture 2030 goals [6]. Few renovation projects in the U.S. have achieved this savings level, with one recent study identifying only 50 such projects, known as deep or advanced energy retrofits [7,8]. The lack of major deep or advanced retrofit projects suggest that it is necessary to consider the influence of major setbacks in the building retrofit market, such as the limited annual retrofit budget or capital constraints, when a project is in the process of decision making with respect to building retrofit options.

Lack of access to capital, insufficient payback, and energy savings uncertainty are top barriers to making energy retrofits more prevalent [9,10]. Most projects are funded with limited internal capital, sometimes with assistance from grants, rebates, and other incentives. These projects have tended toward individual lighting, controls, and Heating, Ventilating, and Air Conditioning (HVAC) equipment measures with reliable savings, as it can be very expensive to go through an extensive energy audit that may not significantly reduce the energy savings uncertainty. While the practice of single measure ranking by simple-payback results in good financial payback on a per-measure basis, it does not take advantage of measure integration that can yield greater energy savings. Most notably, heating and cooling load reduction measures enable downsizing central mechanical equipment for significant replacement cost savings. This means that choosing measure with optimal payback individually may not yield the optimal retrofit decision. Overall, uncertainty and capital budgets make energy retrofits an economic problem, not just a physical one.

Several studies investigated and established methodologies for choosing energy retrofits, summarized in the literature [11].

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A subset of the retrofit literature considers the integrative aspect of measure selection. A study showed performance of measure packages with uncertainty of technology performance, capital costs, energy prices, carbon tariffs, and grid decarbonization [12]. This study also evaluated the range of outcomes under three decision criteria: (maximum weighted average of options, maximum under the most pessimistic scenario, and the smallest regret to minimize difference in expected outcome. This approach captures the interactions among retrofit measures, and found that technology performance, capital costs, and energy prices caused the most significant difference in financial performance. This study implemented all measures at once, which is not always feasible, depending on available capital. Another study demostrated a process to implement measures in a package ordered depending on capital availability [13]. This approach reduced financial risk exposure of a large retrofit project by staying within an internal budget, but it did not consider what measure package would result in the optimal savings. Both of the approaches, measure integration and packaging, are important. Interestingly, extending the project timeline incorporates major equipment replacements that are already embedded in capital plans into a comprehensive retrofit package. This allows targeted load reductions to precede equipment replacement, and to account for the cost of waiting. There is a trade-off between sacrificing expected life of equipment by replacing it now with other measures, or waiting until end-of-life and forgoing possible energy savings from implementing measures sooner.

This study established a methodology for evaluating the impacts of (1) the capital cost constrains, (2) uncertainty associated with measure costs, (3) future energy and carbon tax escalation on the retrofit decision making. The methodology was demonstrated for a case study of an actual building with sub-metered energy data including interval data for different end-uses deployed to calibrate a baseline building energy model. The calibrated model enabled considerations of different retrofit scenarios to include intrinsic and extrinsic uncertainties associated with the decision making for a building retrofit. Furthermore, this study also developed software for interoperability with OpenStudio [14,15] based on R scripts [16], allowing deployment of the methodology to retrofit decision making for many buildings. Finally, the case study for an office building in Philadelphia, PA, demonstrated the significance of the difference in capital availability to the optimal retrofit measures.

2. Methodology

Energy retrofit measure selection is dependent on capital availability, financial criteria, and uncertainties in energy savings and energy costs. Including measure interactions and savings uncertainties is necessary to properly account for a measure's impact on overall building performance. This measure integration and packaging increases the number of options to consider, and requires energy simulations to handle the complexity of measure interactions. Installing measures longitudinally based on a fixed capital budget adds further complexity, as the order in which measures are installed becomes significant. Load reduction measures allow equipment downsizing, and there is a performance difference for different sized systems with the same energy efficiency measures. This consideration greatly increases the number of energy simulations. Fig. 1 shows the analysis process of all the possible retrofit path-options, including the downsizing difference, under capital constrains to calculate their impact on the optimal retrofit measure option. As indicated in the figure, the established methodology comprises of five steps including (1) develop a calibrated energy model, (2) Select energy efficiency measures (EEMs), (3) generate unique simulations for measure combinations, (4) run building energy simulations, (5) analyze retrofit path options for different financial scenarios, and identify optimal options. The code to demonstrate this methodology for the case study presented in this paper is available on Github, a web-based code repository [17].

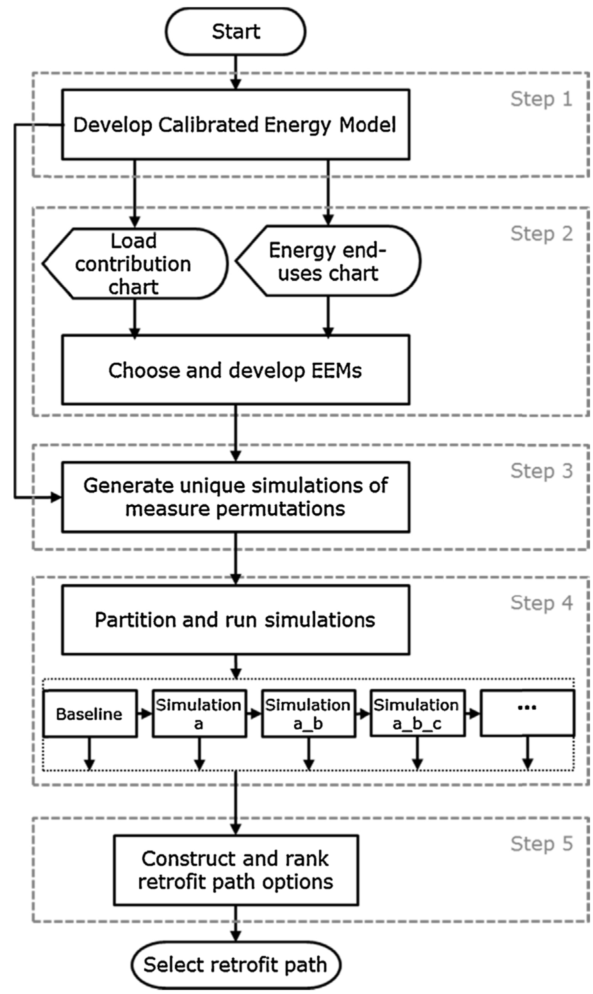

Fig. 1. The flowchart of established methodology for retrofit decision making.

2.1. Develop a calibrated energy model (Step 1)

The first step in the evaluation of different EEMs using building energy simulation tools requires developing a calibrated baseline building energy model. The calibrated baseline energy model needs to meet the requirements of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Guideline 14 2002 [18]. Most commonly deployed calibration of the building energy model uses monthly electricity and gas consumption from the utility bills due to their ubiquitous availability [19]. However, if sub-metered interval data for a building are available, a more accurate calibration method uses the sub-metered interval data to calibrate the building energy model with the 15 min sub-metered building energy data [20,21]. This study uses 15 min sub-metered energy end-uses interval data for the calibration of the baseline building energy model.

2.2. Select energy efficiency measures (Step 2)

The selection of EEMs depends on the building principal functionality, age, size, and financial constraints. Use of the building energy simulations allows identification of energy end-use breakdown, main load contributions, and measures that will most likely reduce peak building loads. These measures may not be financially justifiable on their own, but may be acceptable after including the savings associated with equipment replacement. They include measures for building enclosure, solar control, plug load/lighting control, and HVAC equipment control or replacements. Evaluating multiple measures can be time-consuming if it involves manually creating an energy model for each measure and combination of measures. The OpenStudio Parametric Analysis Tool (PAT) [22] implements measures from the Building Component Library (BCL) [23], and partially automates this process. This study develops new building component library measures and implements them with scripts using the OpenStudio Application Programming Interface (API) [14,15], an open-source software for object-oriented approach to manipulating models to be simulated in EnergyPlus [24] via OpenStudio middleware.

2.3. Generate unique simulations for measure permutations (Step 3)

Energy efficiency measures can be combined together and installed in different order to create unique retrofit paths. To distinguish between retrofit paths, each measure is given a letter "a", "b", "c", etc. A string of letters identifies a unique retrofit path. Particularly, this study looks for the benefit that comes from installing measures that reduce building load prior to replacing the central heating or cooling equipment, which may be downsized depending on the new loads. These HVAC measures are dependent on other measures, whereas building lighting or occupancy sensors are independent of other measures. For example, if HVAC equipment measure "c" is dependent on measures "a" and "b", which are independent, then the measure combination a_b_f will be identical to b_a_f, but not a_f_b. To simulate sequence a_f_b, the process is to (1) simulate the model and auto-size the equipment capacity for a_f, (2) read the HVAC equipment capacity for "f" from the output and hard-size that value in the energy model, and then (3) implement measure "b" and run the energy simulation to get the result for a_f_b. Without this process, if the model is auto-sized and several measures are implemented that reduce load, the energy simulation may run the simulation with a lower equipment capacity than what is present in the building, introducing a small error for the predicted performance.

Once all permutations are generated, a script removes redundant simulations, e.g. a_b_f and b_a_f. Then, another script takes the base model, adds each measure to it in succession, and saves it as a run script for the energy simulation software.

2.4. Run building energy simulations (Step 4)

This study uses OpenStudio and R scripts to implement and run the energy simulations automatically for the selected measures. The developed scripts distinguish between path dependent and path independent simulations to facilitate the process of running multiple simulations in parallel. The 2566 unique energy simulations in this case study are partitioned by the first measure for seven virtual machines on a central server, reducing simulation time by about three-quarters compared to running on a single machine. The energy simulation outputs are collected into a data file on the virtual machines, and then combined together to create a database of all simulation results.

2.5. Analyze retrofit path options for different financial scenarios (Step 5)

The life-cycle cost analysis is deployed to each unique energy simulation combined together in sequence to create a retrofit path for a given measure order and financial scenario. This study considers the impact of three financial variables: (1) measure cost, (2) future greenhouse gas price, and (3) capital availability. It is possible to include many more financial variables to the analysis, as there is no need to rerun the energy simulations and the computational cost of evaluating other financial scenarios is much cheaper than generating the unique energy simulations. However, any measure performance variation, or calibration sensitivity, would require additional measures or choosing a subset of the energy simulations to re-simulate based on most promising retrofit implementation paths. Therefore, it is important to carefully choose the measures and calibrate the model as specified in Steps 1 and 2. The different measure combinations and financial scenarios in this case study generate a half million retrofit path options. These are filtered by financial scenario to generate a ranked list of optimal-path options for a given scenario.

3. Case study

The case study is a commercial office building at the Philadelphia Navy Yard, shown in Fig. 2(a) and (b). The building was originally built as a barracks, and underwent major renovation in 1999 to become an office building. The building is approximately 75,000 ft^2 (6968 m^2), of which approximately 60,000 ft^2 (5574 m^2) is conditioned space, and approximately 40,000 ft^2 (3716 m^2) of that office spreads over 3 stories and a conditioned basement. The Energy Utilization Index (EUI) in this study is referenced to the conditioned floor area only. The building exterior wall is 1.5 ft (0.46 m) thick brick, and has a window-to-wall ratio of 17%. Three variable air volume (VAV) units with direct expansion (DX) cooling serve the building. A gas boiler serves heating coils at each air handler and provides reheat for terminal boxes in each thermal zone. Gas hot water heaters provide service hot water.

3.1. Energy model calibration

The building energy model uses the OpenStudio [14], an interface-type of middleware for EnergyPlus [24]. The model simplifications include an assumption of an identical floor plan on each story, which is nearly the case in the building. The fenestration is modeled with a set window-to-wall ratio on each exterior wall, rather than modeling each window individually, to improve simulation speed with little accuracy loss for load calculations [25].

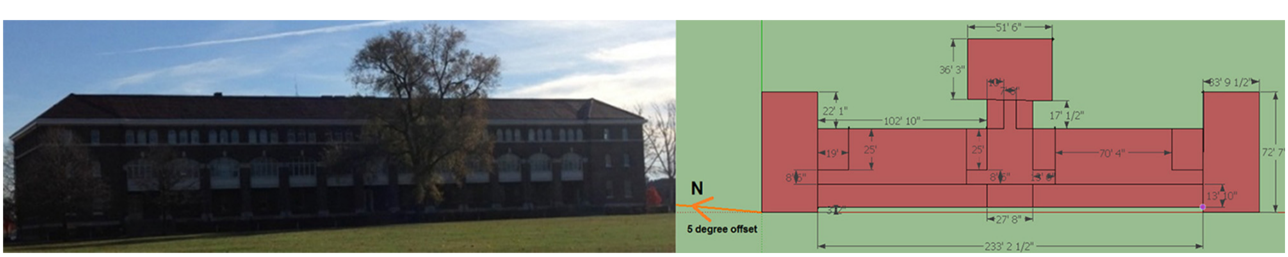

Fig. 2. Office building at the Philadelphia Navy Yard: (a) front side of building and (b) floor plan in the energy model.

Table 1
Building 101 energy end use calibration metrics.

	CVRSME	NMBE	Months
Calibration target	15%	5%	All
All electricity	6.1%	−0.6%	All
Plug loads	5.9%	−2.1%	All
Lighting	4.9%	2.6%	All
Fans	9.3%	−1.2%	Omit December
Cooling	12.6%	3.6%	Omit December
All gas	12.0%	2.3%	Omit December
Heating	12.6%	1.7%	Omit December
Service hot water	9.5%	2.3%	Omit April and May

Mechanical equipment and lighting specifications are detailed from design drawings. Plug loads are modeled with a set area density for office, conference, and lobby areas from sub-meter data, and equipment schedules were then adjusted to match the measured hourly plug load profiles [20,26]. Air infiltration is assumed to be a uniform, constant 0.2 ACH_{nat} across the exterior enclosure [27,28]. The model uses actual meteorological year (AMY) weather data from the Philadelphia International Airport, located a few miles from the building site. A detailed summary of building instrumentation and calibration are available in the literature [21,29].

The model is calibrated to 10-month hourly sub-metered energy data for heating, cooling, service hot water, fan, lighting, total building electric, and total building gas energy use. Plug load and miscellaneous electric use, including water systems pumps and elevators use, is assumed equal to the total building electrical energy use less all other metered electrical loads – cooling, fans, and lighting. January 2012 data are not available, as sub-meter data was not installed until late January. Furthermore, HVAC sub-meter data in December 2012 are not comparable, as the building underwent a major controls upgrade. The lack of data for these periods increases the uncertainty in heating energy use for model calibration, as nearly a fourth of annual heating degree days occurred in January. The calibration disregards anomalous service hot water use data in April and May, when water use spiked, coinciding with a construction period on the second floor. Table 1 shows coefficient of variation of the root square mean error (CVRSME) and normalized mean bias error (NMBE) calibration statistics for each end use following ASHRAE Guideline 14 [18]. The final model calibration adjusted solely building temperature setpoints to 71.5 ± 1 °F (21.9 ± 0.6 °C) for heating and 72.5 ± 1.5 °F (22.5 ± 0.8 °C) for cooling, to match observed variation in the deadband range for VAV temperature control. This calibration method based on end-uses was possible with the availability of sub-meter data. Typically, most of the existing case studies calibrate energy models with monthly energy use by fuel type due to the lack of sub-meter data.

3.2. Select energy efficiency measures

The baseline building energy end-uses and the component contribution to peak heating and cooling load are helpful indicators to determine promising EEMs. Fig. 4 shows the contribution of each energy end use to total building energy use. Heating loads, and then internal equipment and lighting loads, dominate the energy use of the building. Fig. 4 shows that infiltration and conduction through exterior walls and windows are the contributors to peak heating loads, and are offset partially by lighting and internal equipment. Solar heat gain, interior lighting, and equipment are the major contributors to the peak cooling load. EEMs that reduce these peak load contributions enable HVAC equipment downsizing upon replacement (Fig. 3).

This study considers seven energy efficiency measures, shown in Table 2. Several of these measures, including measure “a”, “b”, and “c”, were commonly recommended by energy audits for the cases study building [30], and other measures were included to reduce peak heating and cooling loads. Cost assumptions come from RSMeans [31] using standard union rates in Philadelphia that are summarized in Table 3. Energy efficiency measures were implemented as BCL measure scripts modifying the OpenStudio model of the building.

3.3. Scenario parameters

Life-cycle costs for different retrofit scenarios are compared to life-cycle cost for a baseline scenario. The baseline scenario assumes that the expected lifespan of the outdoor air-cooled condensing units is 20 years, meaning a replacement in 5 years, and that the expected lifespan of the boiler is 25 years, meaning a replacement

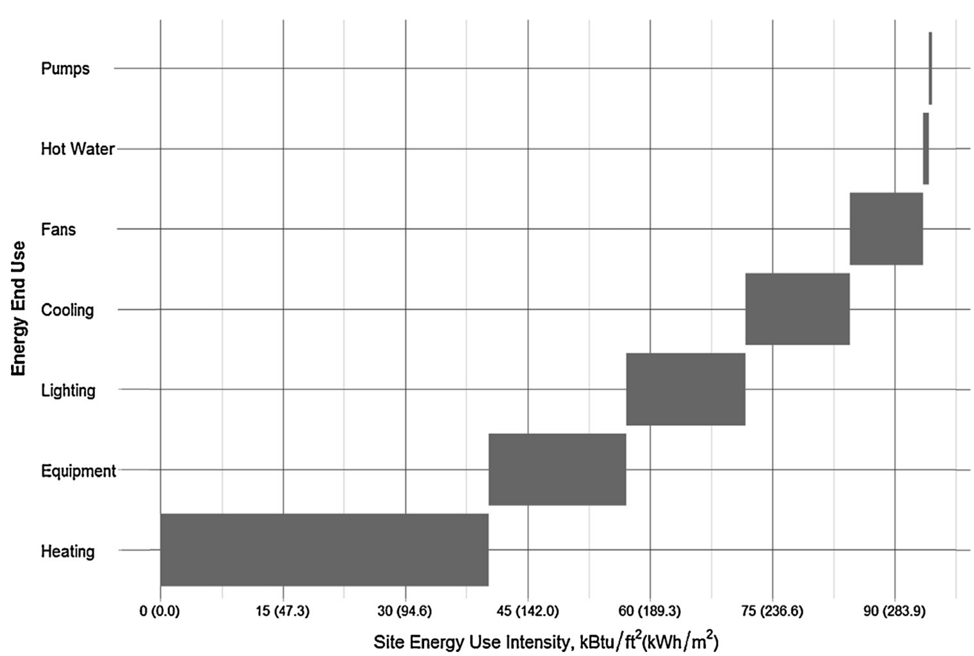

Fig. 3. Breakout of building energy end use.

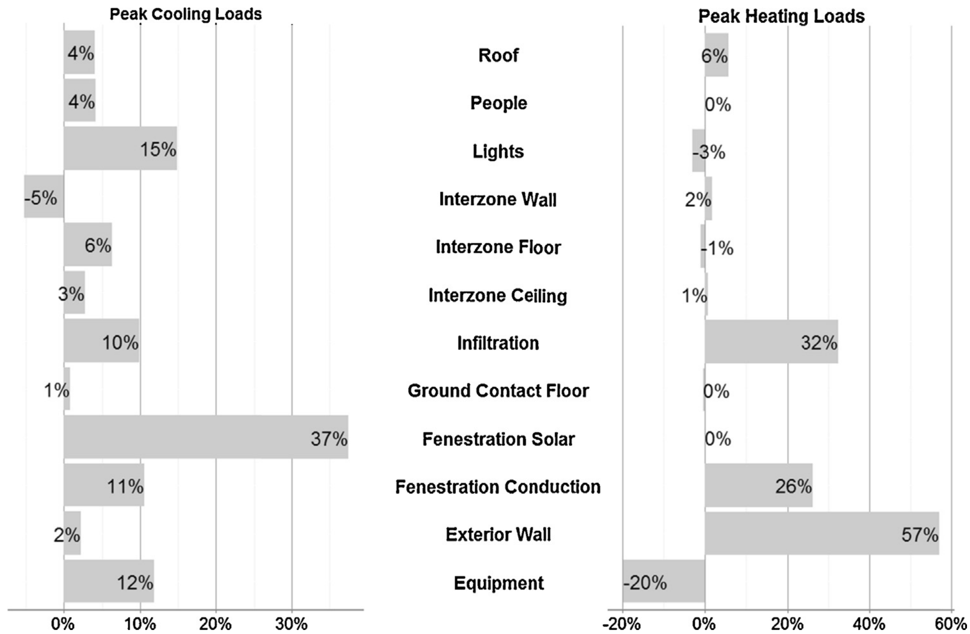

Fig. 4. Percent contributions of component loads to thermal zones' peak heating and cooling.

Table 2
Energy efficiency measure descriptions.

Letter	Energy efficiency measure	Description	Source
a	Wall insulation	Add an exterior insulation and finish system, with 4 in. (0.1 m) EPS board, R-16, reduce infiltration by 30%	[32]
b	Light power density reduction	Reduce conference and office lighting power density from 1.15 to 0.9 W/ft^2 (12.38–9.69 W/m^2)	[33]
c	Occupancy sensors	Reduce lighting fraction from 0.2 to 0.05 during unoccupied hours on weekdays, and 0.15–0.05 on weekends	Engineering judgment
d	Infiltration reduction	Reduce outdoor air infiltration by 15%	Engineering judgment
e	Window film	Reduce Solar Heat Gain Coefficient (SHGC) from 0.764 to 0.38	[8]
f	Condensing boiler	Replace boiler with 90% efficient condensing boiler, auto-size capacity and flow rates for loop, lower supply temperature to 140 °F (60 °C)	[34]
g	Condensing unit replacement	Replace condensing units with auto-sized unit with high speed Energy Efficiency Ratio (EER) 11.5 and low speed EER 16.2	[35]

Table 3
Energy efficiency measure costs.

Energy efficiency measure	Cost/unit	Cost	Yr-1 savings	Simple payback (years)	Source
Wall insulation	\$4.78/ft^2 (51.45/m^2) wall area	\$927,930	\$6301	147	RSMeans, "4 in (0.1 m). EPS insulation, Commercial renovation Exterior Insulation and Finish System", 25% mark-up for Multiple Stories
Light power density reduction	\$4.78/ft^2(51.45/m^2)	\$202,886	\$6323	32	RSMeans, "Fluorescent high-bay 4 lamp fixture, 1 W/ft^2 (10.76 W/m^2), 59FC, 4 fixtures per 1000 ft^2 (92.9 m^2)"
Occupancy sensors	\$1.06/ft^2 (11.41/m^2)	\$44,991	\$2384	19	RSMeans, "5 fixtures per 1000 ft^2 (92.9 m^2), including occupancy and time switching"
Infiltration reduction	\$150,000	\$150,000	\$1749	86	Engineering judgment
Window film	\$18.93/ft^2 (203.76/m^2) glazing	\$182,311	\$4259	43	RSMeans, "Solar Films on Glass" average of min/max value
Condensing boiler	\$20,706 + \$13.82/MBH (\$20,706 + \$4.05/kW)	\$42,176	\$3960	11	RSMeans, commercial gas boilers
Condensing Unit replacement	\$7909 + \$766/ton (\$7909 + \$2693.91/kW)	\$116,631	\$4864	24	RSMeans, packaged air-cooled refrigerant compressor and condenser

in 10 years [36]. The resulting energy costs, capital costs, and greenhouse gas emissions costs over the building lifetime, are combined into a cash flow that is then discounted to calculate the net present value (NPV) of the scenario. The scenarios assume a lifetime of 20 years with a real discount rate of 3%. Natural gas and electricity prices are adjusted according to the NIST energy price escalation rates for census region 1 [37]. In addition, four greenhouse gas emissions prices are considered: no cost for emissions, and the default, low, and high greenhouse gas price scenarios from NIST. Lastly, measure costs are considered at full price and half-price, reflecting the possibility of measure cost reductions and significant additional efficiency incentives that are not accounted for in the greenhouse gas price. Each scenario for ordering retrofit measures is considered under five capital availability scenarios: $1/ft^2 ($10.76/m^2), $2/ft^2 ($21.53/m^2), $3/ft^2 ($32.29/m^2), $5/ft^2 ($53.82/m^2), $100/ft^2 ($1076.39/m^2), reflecting different annual capital allotments available to fund energy efficiency measures. The $100/ft^2 ($1076.39/m^2) scenario is an intentionally high value that practically imposes no financial limitation to implementing measures, meaning all measures for a given retrofit scenario are able to be implemented in the first year. In the other scenarios, the capital limitation causes a delay in implementation for an energy efficiency measures.

4. Results

The NPV of the baseline case where the equipment is replaced ranges from −$35.58/ft^2 (−$382.98/m^2) to −$42.63/ft^2 (−$458.87/m^2), depending on the greenhouse gas price scenario and the cost modifier for the measures. This includes the cost of replacing the central HVAC equipment and the energy costs over the project lifetime. The equipment will need to be replaced at the end of its service life, so the relative financial performance of a retrofit path is measured in reference to this baseline with equipment replacements and no other measures. For example, in the default NIST GHG price scenario, and measures at full costs meaning a cost modifier of 1, the net present value of the baseline case is −$38.50/ft^2 (−$414.41/m^2). If a retrofit path were to have a net present value of −$39.50/ft^2 (−$425.17/m^2), it would mean that it is $1/ft^2 more expensive than the baseline case.

Fig. 5 shows the comprehensive range of all possible retrofit paths relative to this baseline case for different financial scenarios, including the cost modifier, greenhouse gas price, and capital availability. Retrofit paths are shown based on the average annual site energy use of the building over the 20 year financial lifetime, and the net present value compared to the baseline case for the same financial scenario. The majority of the retrofit paths show negative net present value relative to baseline, with the greatest differences between retrofit paths determined by whether they include the wall insulation measure, which greatly reduces the net present value of retrofit paths that include it. Another source of major variation is the cost modifier that adjusts the measure costs. Fig. 5(a) shows the retrofit paths for measure costs at full price (cost modifier of 1, gray) and measure costs at half price (cost modifier of 0.5, black). Each cost modifier scenario shows two distinct clusters of retrofit measures; the retrofit paths that include the wall insulation measure comprise the cluster with lower net present value. The box (b) in Fig. 5(a) is the domain in Fig. 5(b), expanded to show the influence of the greenhouse gas price scenario. For most retrofit paths, there is a difference of less than $0.75/ft^2 ($8.07/m^2) between the high and no greenhouse gas price scenarios for most retrofit paths. Within a given greenhouse gas price scenario, there is a further difference in retrofit path financial performance depending on the capital availability. In general, the capital availability yields a more significant difference than does the choice of greenhouse gas price scenario.

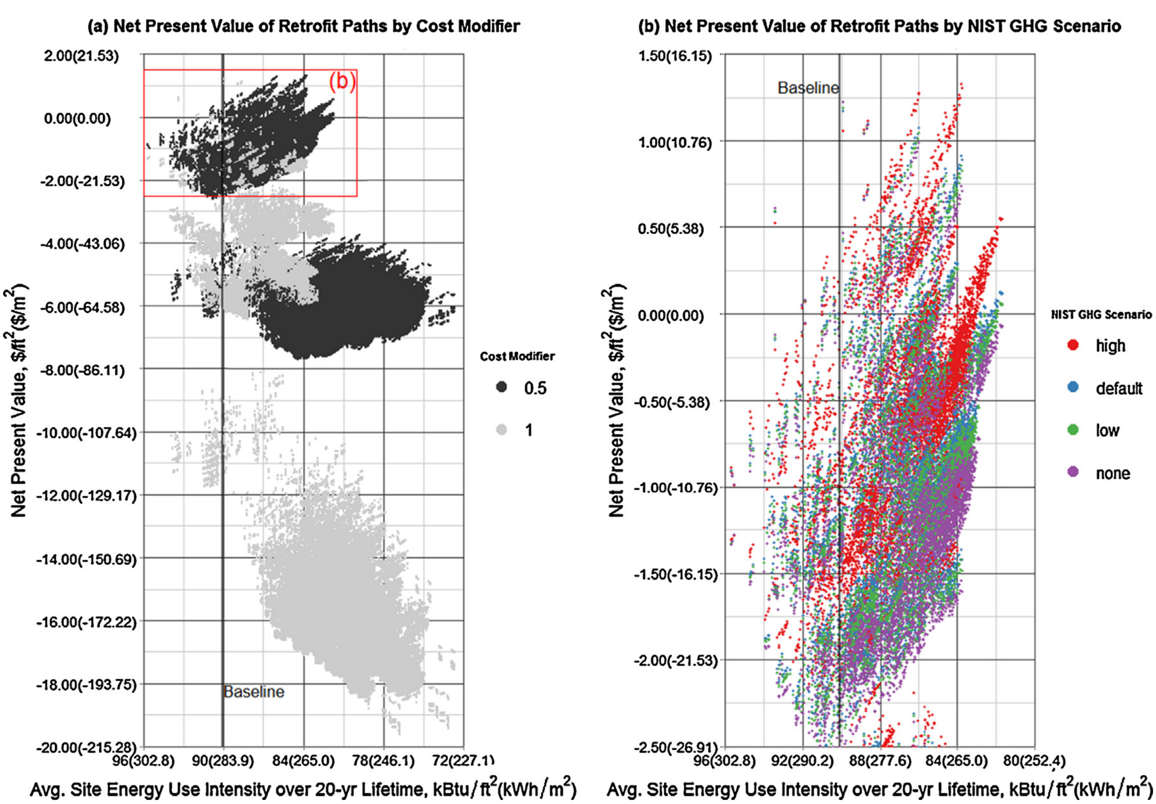

Fig. 5. (a) Net present value of retrofit paths relative to the net present value of the baseline case. The retrofit paths are colored by whether they are part of the financial scenario when measure costs are at full price (cost modifier of 1, black), or at half price (cost modifier of 0.5, gray). (b) Net present value of retrofit paths relative to the net present value of the baseline case. The retrofit paths are colored by their NIST GHG price scenario.

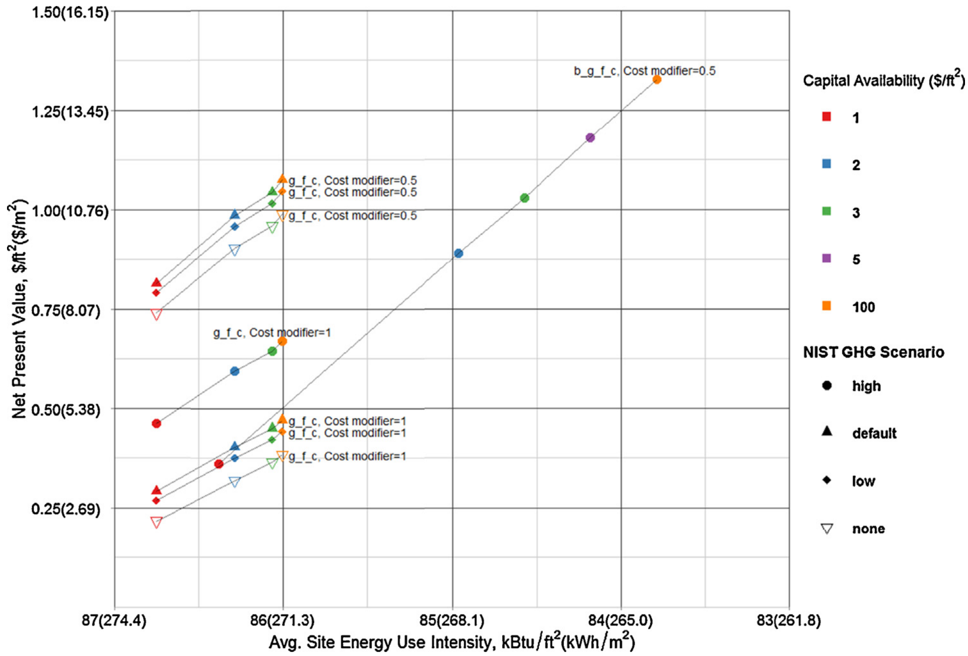

Fig. 6. Optimal path options depending on the financial scenario.

Fig. 6 shows the optimal paths relative to the baseline case for a range of financial scenarios. Optimal paths are those that have the most positive net present value relative to the baseline case, and include equipment replacements before the end of the service life of the equipment. The optimal paths include a combination of the measures reducing lighting intensity (measure "b"), occupancy sensors (measure "c"), replacing the boiler (measure "f"), and replacing condensing units (measure "g"). In the scenario with measure costs at full price, only permutations of path g_f_c, implementing the equipment replacements and then the occupancy sensors, show a positive net present value. Furthermore, when measure costs are at half price to model the hypothetical case where efficiency measures are much cheaper than they are at present, the g_f_c path remains the optimal option for all but the highest greenhouse gas price scenario. In the highest greenhouse gas price scenario, the optimal path includes reducing the lighting intensity before the other three measures. In Fig. 6, each retrofit path is presented by a line, with the points showing a specific financial scenario. The shape of the point indicates the NIST GHG Scenario, and the color of the point indicates the capital availability. For each retrofit path, reducing the capital availability reduces the net present value of that option, and increases the average annual site energy use of the building over the 20-year financial lifetime. This makes intuitive sense: as the amount of available annual capital increases, measures are able to be implemented sooner, which means a longer time over which energy cost savings can accrue. In this case study, not having enough money to implement the optimal path at once greatly reduces the achievable financial benefits from that retrofit option.

Another consideration is how the financial performance depends on the order of measure instillation. Fig. 7 shows the influence of changing the measure order for the b_g_f_c path for all financial scenarios. The maximum difference is the difference between the optimal ordering of measures and the worst ordering of measures within a given financial scenario. For this measure path, the largest difference between the optimal and worst ordering occurs in the lowest capital availability scenario. In this scenario, the size of the difference is comparable in magnitude to the net present value of the retrofit path. This means that when capital is not available to install measures, choosing which measures to install first can be as important as choosing which measures to install. The influence of measure order is less important in higher capital availability scenarios. In the case of no capital restrictions, the $100/ft^2 ($1076.39/m^2) scenario, the maximum difference in measure ordering is around $0.05/ft^2 ($0.54/m^2), which is much smaller than the variation in financial scenarios shown in Figs. 5 and 6. This finding suggests that for this case study, the importance of installing measures with the optimal financial return is much more important than making sure they are ordered correctly to get the downsizing benefit, and that difference in financial performance under capital restriction is mostly explained by not implementing the measures with the optimal energy savings sooner. Overall, Fig. 7 shows that for the optimal retrofit path, the difference in net present value between the optimal and the worst ordering of measures depends on the amount of capital avialiable to implement energy efficiency measures. Furthermore, Fig. 8 shows that for retrofit paths with a positive net present value relative to the baseline case, the maximum relative greenhouse gas emissions reductions possible over 20 years is 85% of the emissions of the baseline case. With measures at full price, fewer paths are available, and only a 5% emission reduction is possible.

5. Discussion

The aim of selecting the considered energy efficiency measures in this study is to reduce overall energy use and reduce peak demand served by the central heating and cooling equipment. However, none of the measures has a simple payback under the typical 7 year requirement of institutional investors, shown in Table 3. A life-cycle cost approach opens up further options, especially assuming an existing planned replacement cost of the HVAC systems. The load reduction benefits are minimal, and other factors dominate the financial performance of the retrofit options.

5.1. Minimal impact of load reduction benefits

While the selected measures reduce peak load considerably, this is reflected only in the replacement costs for the HVAC equipment and does not extend to significantly reduced energy use, and

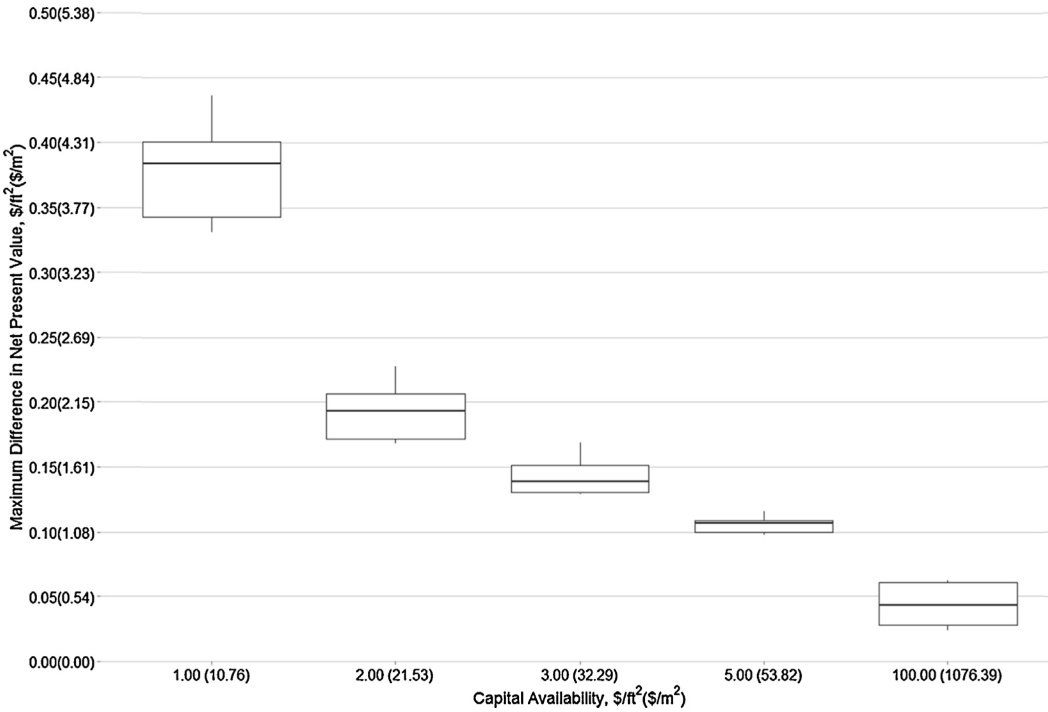

Fig. 7. Net present values with changing capital availability resulting in different implementation order from the optimal retrofit path, worst retrofit path, which changes depending on the financial scenario.

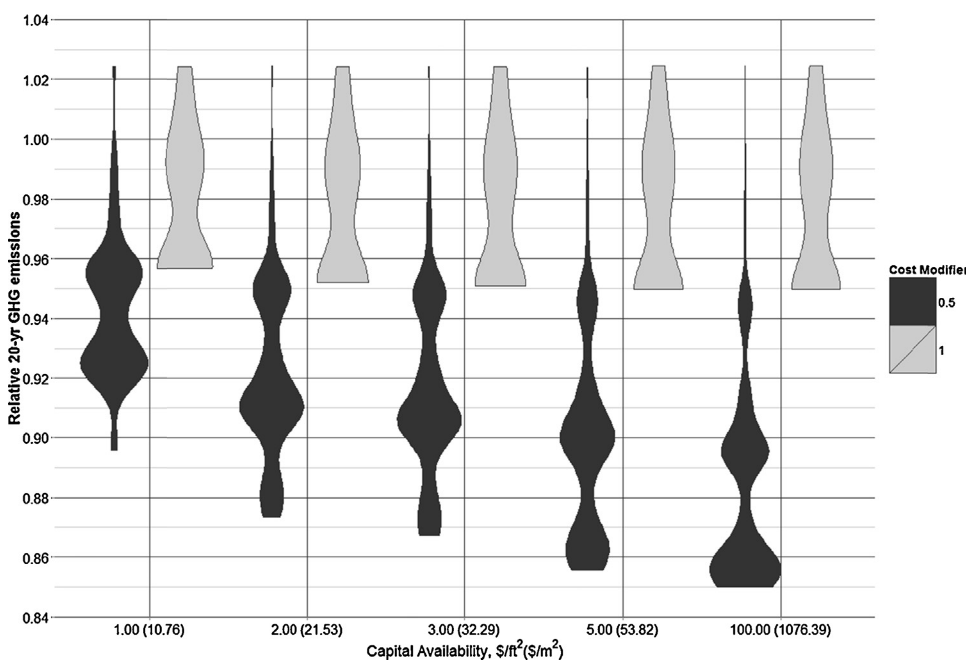

Fig. 8. Relative 20-year greenhouse gas emissions dependent on the capital availability and measure costs for retrofit paths with positive net present value relative to the net present value for the baseline case.

therefore cost, over the year. Furthermore, some measures have counteracting effects that negate the load reduction savings. For example, the window film measure reduces cooling loads, and thus annual electricity use by 8%, but this is offset by an increase in heating requirements for the building, raising annual gas use by 13%. The net result is a 1% increase in annual site energy use, but a 4% decrease in annual source energy use, a 3% decrease in annual energy cost, and 5% decrease in greenhouse gas emissions. The wall insulation measure behaves similarly. When wall insulation is added, the annual natural gas use reduces by 35% and the annual electricity use increases by 7%, for a net 11% energy savings, but is neutral for annual energy cost and greenhouse gas emissions. The reason for the electric use increase is that there was a modest cooling effect in the shoulder seasons for the building with lower insulation that offset the cooling requirements. This countering effect could be mitigated by reducing plug load consumption, or including natural ventilation or other free-cooling option. In addition, the natural gas rate per unit energy is cheaper than the electricity rate in this study, so electricity use is more significant for marginal energy cost savings.

For all measures, the improvement in financial performance from the demand reduction is of secondary importance to the aggregate savings of an energy efficiency measures, and often smaller than the marginal increase in heating that some of the cooling measures provided or vice versa. This does not negate demand reduction as a consideration for choosing energy efficiency measures, but suggests that this impact is only significant in cases where downsizing opens up further technology options to meet building loads instead of simply replacing equipment with a more efficient model, or if there are other significant demand response financial incentives that were not considered here.

5.2. Important parameters for financial performance

For a given measure selection, the most significant determination in retrofit path financial performance comes from variations in measure cost. This matches a similar case study that considered uncertainty in measure performance and financial scenarios, which found measure cost and energy price to be the most significant determinants of measure package performance [12]. The case study presented here found less energy and greenhouse gas emissions savings opportunity, with only 10% emissions mitigated over the 20 year lifetime compared to the baseline that includes equipment replacement, and only 14% emissions mitigated compared to the baseline scenario that does not include equipment replacement. Part of the explanation for this difference is the case study present in this paper did not consider a micro combined heat and power (CHP) system, which would offset the emissions from the relatively coal-intensive energy supply where the case study is located. The savings estimates in this case study are less than what was found in prior energy audits [30,38], with discrepancies from the difference in weather assumptions and increased occupancy in the building after the audits. The later study considered more EEMs, and found a retrofit package including daylight dimming, upgraded lighting, and weatherization reduces site energy use by 23% and source energy use by 24%, with simple payback of 7.6 years assuming no incentives. The difference in recommendations is attributed to the different types and technical performance of EEMs considered, and the inclusion of a daylight dimming measure.

Uncertainty associated with measure costs and future measure costs are a significant part of financial performance uncertainty within this study and between studies. For example, newer LED technology could replace the fluorescent tube lighting common to most commercial buildings, but it is unclear how quickly it will achieve significant market penetration. This study assumed measures at full price and half price to represent potential reduced measure costs from cheaper technology or market scaling. As measure prices and financial scenarios are likely to change frequently, this study provides the developed code so others can test different financial scenarios and measures [17].

Lowering the capital availability reduces the financial benefit from implementing measures, as the energy cost savings accrue over a smaller portion of the project lifetime, and later implementation is more heavily discounted. For a given retrofit path, the impact of the capital availability was as significant as the difference in greenhouse gas pricing scenarios, meaning that limited capital for energy retrofit projects imposed a similar barrier to achieving a given energy savings or emission reduction level. This is significant, because it suggests that funding retrofits through an annual budget or a revolving loan fund whereby the accrued energy cost savings is used to fund further retrofits may limit the extent of energy savings and emission reductions.

For a given selection of measures, measure order matters more with limited capital ability. However, the difference in load reduction is small compared to the difference in energy cost savings from implementing more cost-saving measures sooner. This effect is smaller than the uncertainty estimated for measure performance in the existing literature [12], suggesting that measure analysis should include measure uncertainty and interaction, but the impact of marginal load reduction is not as necessary for consideration. Furthermore, this study benefited from sub-meter calibration to help determine load reduction opportunity. This level of meter detail is rarely available in most buildings undergoing a retrofit, and imposes significant risk from the uncertainty of meeting buildings loads with demand reduction, given that building energy models can be prone to over-specification and mischaracterization of the source of buildings loads.

6. Conclusion

Building energy retrofit projects often use a single-measure ranking based on simple payback to analyze the financial performance of retrofit options. Such a ranking does not include the potential financial savings from load reduction measures that also reduce the cost of replacement heating and cooling equipment. This study considered the life-cycle cost of several Energy Efficiency Measures (EEMs) over an exhaustive list of measure combinations based on the building cooling and heating loads as well as financial scenarios with different capital availability. The selected EEMs are (1) wall insulation, (2) lighting power density reduction, (3) occupancy sensors, (4) infiltration reduction, (5) window film, (6) condensing boiler, (7) condensing unit replacement. The scenarios include consideration of NIST greenhouse gas pricing projections, full and half-price measure costs, and capital availability ranging from \$1/ft^2-yr, a minimum value for the capital constrains, to \$100/ft^2-yr, a representative of no capital constraint. In the most pessimistic scenario where measure costs are full-price, a capital constraint of \$1/ft^2-yr (\$10.76/m^2), and no greenhouse gas emissions price, the net present value is \$0.22/ft^2 (\$2.37/m^2). For the most optimistic scenario, where the measure costs are half-price, no capital constraint, and the highest greenhouse gas emissions price, the net present value is \$1.33/ft^2 (\$14.32/m^2).

Measure costs were the most significant source of variation in financial performance, followed by the capital availability and greenhouse gas pricing scenario. The difference in measure ordering, and the importance of load reduction were relatively insignificant compared to the importance of the financial scenario, and are smaller than typical uncertainty measure performance and model calibration. Therefore, until model calibration of building loads and uncertainty of measure performance is more reliable, it is not useful to consider marginal capital cost savings on equipment from demand reduction or difference in measure installation order. Larger energy savings targets, for this building in excess of around 40% site energy savings or under 60 kBtu/ft^2-yr (189.3 kWh/m^2-yr), will require more substantial building component and heating and cooling equipment changes than the marginal improvements considered in this case study, and will likely entail behavioral change and internal equipment load reductions as well. While low energy savings potential depends on the particular building and range of measures considered, this methodology suggests that the nonlinear dependence of energy and greenhouse gas savings potential on capital availability, and the relative lack of significance of the greenhouse gas price on financial performance implies that measures cost reduction and increasing capital availability are key concerns for emissions reductions. Therefore, increasing investment in energy retrofits is key to reducing greenhouse gas emissions.

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