CLIMATE CHANGE RISKS FROM A BUILDING OWNER'S PERSPECTIVE: ASSESSING FUTURE CLIMATE AND ENERGY PRICE SCENARIOS

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ABSTRACT

This paper presents a new building analysis method that incorporates climate change temperature impacts and climate-policy energy price scenarios in order to help building owners to financially compare energy retrofitting measures. The method is based on morphed 'future' weather files and energy pricing scenarios from current climate models. Operational energy use of an example office building in Boston is predicted using EnergyPlus. The analysis is repeated for a range of different climate change and price scenarios allowing owners to 1) understand how their building might perform under a spectrum of possible futures, and 2) determine the associate risk ranges present when choosing between design solutions. For the example 'Minimum' retrofit design, it is shown that cumulative energy cost savings range between 0.2 and 0.8 million 2010 $US and the financial paybacks range from 14 to 15 years.

INTRODUCTION

Global circulation models have been under development since the 1980's to help scientists understand current, and project future, climate. According to the 2007 IPCC 4th Assessment Report (AR4), climate change is already upon us and observed temperatures have thus far been tracking the high-end temperature range from the 2nd and 3rd IPCC assessment reports (Figure 1) (Solomon et al 2007). The AR4 models project an average global annual temperature increase of up to 6.4°C through this century; the minimum change is +1.1°C even with intense emissions mitigation.

As a political response to climate change, there has recently been an increased effort to mitigate GHG emissions through various measures such as the 'cap & trade' policies implemented in Europe and the U.S. northeast. One direct result of these policies is a projected change to energy prices, as emissions costs are expected to increase over the coming decades. Figure 2 illustrates the change to electric and gas prices as modelled under the proposed 2009 'U.S. Clean Energy & Security Act, HR 2454 (Pew 2010). Other models from the US Energy Information Administration (EIA) and the Energy Modelling Forum (EMF) also indicate energy price increases in tandem with GHG mitigation (EIA 2010, Clarke et al 2009).

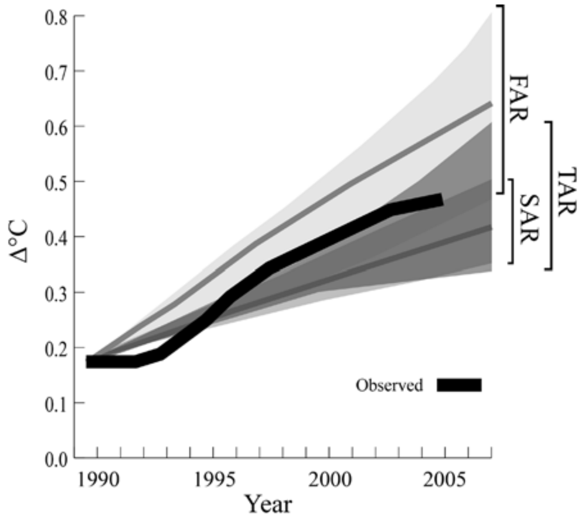

Figure 1. Climate modelling temperature comparison

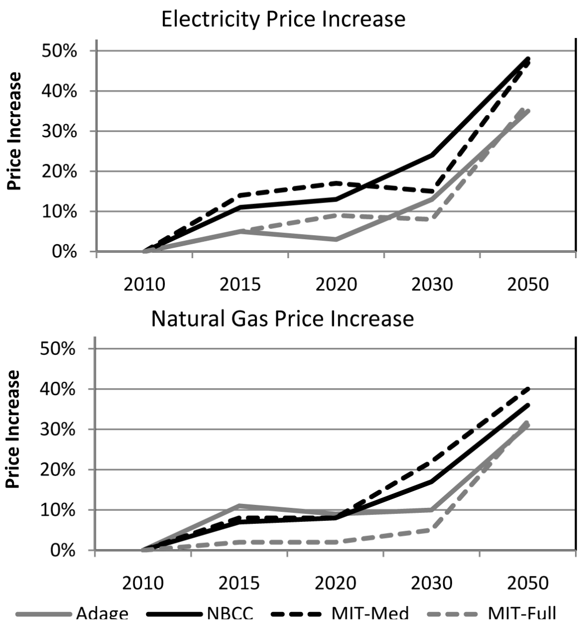

Figure 2. Energy Price Projections under HR2454

Both of these climate change related variables, temperature and energy price increases, will directly affect the cost of long-term building operations. Various energy modelling studies previously examined the effect of climate change on building energy performance; predictably, these studies concluded that as the earth's average temperature changes, annual heating energy requirements will decrease while cooling energy use will increase in buildings with traditional HVAC systems (Hacker et al 2005, Crawley 2008, and de Wilde & Tian 2010). However, these studies did not incorporate future energy price predictions associated with climate change modelling and/or emissions policies currently being considered by policymakers and economists (Clarke et al 2009, Fawcett 2009). This limitation somewhat minimizes the direct usefulness of previous studies for building owners and investors since the decision to invest in energy efficient technologies today is typically driven by medium and long-term return on investment projections, which are intimately linked to future energy prices.

The objective of this paper is to overcome this limitation by developing an analysis method and tool that introduces climate change and energy price predictions to the financial analysis of new construction or retrofitting projects. The basic approach is described in the methodology section followed by a case study for an office building in Boston.

METHODOLOGY

The method presented is based on three steps that are described in more detail in the following sections. Initially, a building energy model of a new construction or retrofitting project under consideration has to be generated. Whole building energy models mimic all heat flows in a building and predict building energy use and interior comfort conditions. For projects that aim for certification under a green building rating system such as LEED or BREEAM, such models are already part of the design team's scope of work. The next step is to generate future climate files and to rerun the energy model for various points in the future and for various storylines. Then the resulting energy use totals are combined with predicted energy prices under the different storylines so that an owner can estimate future operational energy costs under a variety of climate change scenarios.

Future hourly weather files

A time series adjustment, or 'morphing', technique is used to generate future hourly weather data for building simulations. The process combines "an observed high resolution time series with projections for average changes from a climate model" (Hacker et al 2009). For this study, a morphing tool called the 'Climate change world weather generator' was selected to generate future weather files using a TMY baseline file and downloaded climate change data from the HadCM3 global circulation model (Jentsch et al 2010). The HadCM3 model forms part of the models that were used in the 2001 IPCC 3rd Assessment Report (TAR). Though there are more up-to-date global circulation models and data available, to the authors' knowledge, this tool is the most efficient means of generating hourly weather files that include climate change driven weather predictions. The weather generator creates an hourly weather file based on one of the four primary socio-economic scenarios, or storylines, utilized to predict global GHG emissions over the next century. Socio-economic scenarios are "plausible and often simplified descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions" (Solomon et al 2007).

The four primary scenarios, A1, A2, B1, & B2, were created in the 'Special Report on Emissions Scenarios (SRES)' to represent possible socio-economic futures based on historical patterns of development (Nakicenovic 2000); these scenarios are used in both the TAR and AR4 assessment reports. Each scenario has a separate development focus (global, regional, technological, environmental) and is generated using unique driving forces such as population, economy, technology, energy, land use and agriculture. Resulting GHG emissions and atmospheric radiative forcing vary significantly between scenarios due to these driving force imputs. Additionally, the A1 subgroup known as A1FI represents a 'fossil intensive' energy path scenario. Though the SRES report considers no one scenario to be more likely to occur than another; it is widely recognized that the A1FI scenario best illustrates a 'business as usual' scenario. Similar to other climate change studies, this paper utilizes the A1FI, A2, B1, and B2 scenarios for its analysis; Figure 3 indicates the TAR projected temperature impacts and GHG emissions for these 4 scenarios (Cubasch 2001). This paper's analysis includes emissions based energy pricing, therefore the temperature impacts for all four scenarios are required due to their various emissions projections.

The weather generator tool specifically uses the HadCM3 weather data files for the A2 scenario. To generate hourly weather data for the other three scenarios, the A1FI, B1, and B2 data files are also downloaded from the HadCM3 model data website and renamed to 'A2' prior to morphing with the weather generator tool. This is possible because the weather data files for each scenario have identical formats. Preferably, a TMY2 hourly weather file should be used with the weather generator as the baseline file because its input ranges from 1961-1990, which is close to the range utilized in the HadCM3 model. The result from the weather generator process is the creation of future hourly weather files for each scenario for the years 2020, 2050, and 2080.

Emissions related energy price projections

The SRES scenarios do include energy price projections; however, the pricing data available are

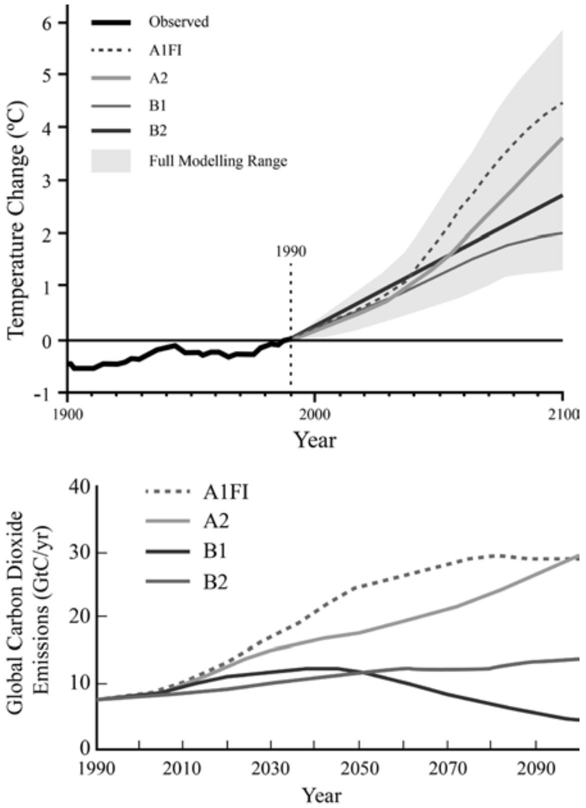

Figure 3. SRES temperature (top) and GHG emissiosn projections (bottom) from the IPCC 3rd Assesment Report

primary energy figures and cannot be analyzed for end-use functions such as building thermal comfort energy. Additionally, these prices are policy neutral and do not reflect future efforts to mitigate greenhouse gas (GHG) emissions (Nakicenovic 2000). Consequently, this paper's research uses more current energy price projections from the 2009 Energy Modelling Forum (EMF-22) study, which is associated with current efforts to create new emissions scenarios for the ongoing IPCC 5th assessment report (Kriegler et al 2010). The EMF-22 study analyzes a number of international and U.S. 'transition scenarios' to reflect various degrees of future GHG emissions mitigation efforts through the year 2100 (Clarke 2009). Three earlier versions of models used in the EMF-22 study were also used in the creation of the SRES scenarios; however, data required to generate hourly weather files from the EMF-22 study is not readily available. The U.S. portion of the EMF-22 study utilizes six primary models, some of which have two or more iterations for a total of 13 models that predict energy price development in the U.S. Each model analyzes three separate 'transition scenarios' through the year 2050 and one baseline 'reference', or business-as-usual, scenario which excludes GHG mitigation efforts (Fawcett 2009). The three U.S. transition scenarios modelled have GHG emissions targets of 287, 203, & 167 GtCO2/year by 2050; these targets directly associate with the EMF-22 international study's CO2 equivalent atmospheric concentration goals and associated radiative forcing targets through the year 2100 (Clarke 2009 & Fawcett 2009).

In order to evaluate heating and cooling energy independently, the simulation and pricing analyses assume natural gas use for all heating requirements and electricity for all cooling requirements. In the U.S., 98% of commercial buildings use electricity for cooling energy, while natural gas use for heating is steadily on the rise (EIA 2006).

For this study, seven of the EMF-22 U.S. models were selected because they all project electricity and natural gas prices for the year 2010 and model all three transition scenarios. The EMF-22 models included are: ADAGE, EPPA, IGEM-NDO, IGEM-UDO, MiniCAM-Base, MiniCAM LoTech, MRM-NEEM. The energy prices are given in ten-year increments; Table 1 illustrates the 2010 and 2050 prices from one of the models. The EMF-22 energy prices are national in scope, therefore a factor is assumed for each model to convert 2010 prices to match existing 2010 energy prices for the case study's location (EIA 2011); each subsequent decade is then multiplied by each model's calculated regional factor in order to normalize the resulting energy prices across all 7 models. Prices for intermediate years are linearly interpolated.

Linking Temperature and Pricing Models

Current energy projection methods for buildings do not include both future temperature and price projection data; therefore, this data needs to be directly associated in order to simulate their impact on building operational costs accurately. In this study, this link between the SRES and EMF-22 scenarios is established using radiative forcing projections from each scenario. Radiative forcing is one of the primary metrics in climate change modelling and is defined as the change in the net vertical irradiance at the tropopause (expressed in Watts/square metre) (Cubasch 2001). Changes to radiative forcing levels can occur from a variety of events including increased GHG or aerosol emissions, as well as increased solar gain from solar flares. The IPCC measures radiative forcing relative to preindustrial conditions defined for

Electricity - $/kWh (2005 U.S. $)

Model	Scenario	2010	2050	% of 2010 prices
ADAGE	167	0.0913	0.1650	**181%**
ADAGE	203	0.0913	0.1810	**198%**
ADAGE	287	0.0915	0.1050	**115%**
ADAGE	Reference	0.0914	0.0938	**103%**

Natural Gas - $/GJ (2005 U.S. $)

Model	Scenario	2010	2050	% of 2010 prices
ADAGE	167	8.8401	10.8329	**123%**
ADAGE	203	8.8725	9.5865	**108%**
ADAGE	287	8.8629	9.2104	**104%**
ADAGE	Reference	9.0130	9.7284	**108%**

Table 1. Example EMF-22 prices (Clarke 2009)

1750. Radiative forcing is often directly linked with atmospheric Carbon Dioxide levels in climate change modelling techniques or analyses, such as the EMF-22 study.

Each of the SRES and EMF scenarios has a calculated radiative forcing projection for the year 2100. The three EMF-22 international transition scenarios have long-term emissions and radiative forcing targets of: (1) 450 ppmv CO2-e [2.6W/m2], (2) 550 ppmv CO2-e [3.7W/m2], and (3) 650 ppmv CO2-e [4.5W/m2] (Clarke et al 2009); subsequently, the ranges of model outcomes for the three U.S. transitions scenarios are associated with these targets (Fawcett 2009). Table 2 illustrates how this research associated the SRES and EMF scenarios. The A2, B1, and B2 SRES scenarios have similar radiative forcing levels to the EMF-22 transition scenarios (203, 287 and Reference respectively) However, the most aggressive transitions scenario (167) is well below the least forceful of the SRES scenarios (B1), while the most forceful SRES scenario (A1FI) is higher than the EMF-22 reference scenarios.

The linking process described above results in the following combinations of temperature and energy price scenarios [SRES/EMF-22]: B1/203, B2/287 and A2/Reference. Additionally, the comparison analysis includes a worst-case scenario combination using both high temperature impacts and energy prices (A1FI/167). This scenario assumes that the U.S. will administer aggressive GHG reductions through 2100, but that the rest of the world is unsuccessful at curbing their emissions due to growing emissions in developing countries such as China and India. The combined scenarios are here forth referred to as 'Temperature+Price' scenarios. The combination of the simulated annual energy use under different Temperature+Price scenarios can be carried out

Radiative Forcing Level	SRES / TAR (2001)	EMF-22 Inernational (2009)	EMF-22 U.S.A. (2009)
2.5		450	167
3.0			
3.5		550	203
4.0	B1		
4.5		650	287
5.0	B2		
5.5			
6.0			Reference Range
6.5			
7.0			
7.5			
8.0	A2		
8.5			
9.0	A1FI		

Table 2. Scenario radiative forcing association (worst case scenario in white text)

using a new Microsoft Excel 2007 based design tool developed for this research; this tool is available upon request to the authors.

Case Study

In this section the above described method is demonstrated for a generic 1980's era office building located in Boston, MA, USA. The building corresponds to the U.S. Department of Energy's 'Post-1980, Medium Office' reference building (former benchmark building) version 1-3-5.0 for which detailed EnergyPlus models are available (DOE 2010). The building is three stories tall, has a floor area of 5,000 m2 (54,000 ft2) and contains a variable air volume (VAV) heating and cooling system. These building models are downloadable from the US department of Energy and are designed to represent typical US buildings (Deru et al 2011). For this case study, it is assumed that the building requires a new HVAC system and the owner and design team consider four retrofitting options, which are:

- 'baseline': A simple replacement of the existing, broken HVAC system with an identical one.
- 'minimum upgrade': so that the building meets ASHREA 90.1-2004 (more efficient HVAC and windows (inoperable)
- 'medium upgrade': Same as previous but add mixed-mode ventilation & solar shading.
- 'advanced upgrade': Same as previous but double all insulation levels.

For all four options, the VAV system uses gas fired reheat terminals so that all heating elements use natural gas; all cooling is achieved through electricity. Additionally, the two 'mixed-mode' design options modify the DOE's 'New-2004' reference model (upgrade to Post-1980 model) to include a hybrid ventilation controller, operable windows, external solar static shading, and an increase of insulation levels as previously indicated. The hybrid ventilation system directs all windows to open 50%, allowing natural ventilation to achieve heating and cooling setpoints. The hybrid system operates if the outdoor air temperature is between 15 & 32°C (59 & 89°F); otherwise, the standard HVAC system provides thermal comfort. Heating and cooling set points are identical for all three building models. All simulations were run using the DOE's software EnergyPlus, v 6.0.

The associated costs for the design options were calculated using R.S. Means construction data (Balboni 2010). The resulting construction costs for each retrofitting option are listed in Table 3.

For the case study, future hourly weather files were initially generated with the 'World Weather Generator' for the years 2020, 2050, & 2080 based on the 1990 Boston TMY2 weather file. Using these files heating and cooling energy use was determined for the different retrofitting options resulting in 16 EnegyPlus simulations (4 designs x 4 temperature scenarios). Consumption figures for the intervening years were determined by linear interpolation.

The calculated energy consumption data for the years 2010-2050 was multiplied by the calculated energy prices from the associated EMF-22 transition and reference scenarios for each temperature scenario. The process was repeated for all seven selected EMF-22 models resulting in a wide range of price projections. From these seven models, a median price for each year was selected to simplify the final cost analysis; however, the full range of the seven models is still illustrated in the final analysis tool. Additionally, because EMF-22 prices projections end in 2050, the years 2051-2080 use the associated 2050 prices from each model, which effectively represents flat prices from 2050.

The final step in the analysis incorporated the building construction costs to determine a payback period and internal rate of return for each design. The payback period illustrates how long it takes the building design investment to pay for itself. The IRR expresses the estimated rate of return, or profitability, on the investment over a specific timeframe; in other words, it measures the return on invested cost compared to the positive cash flow achieved due to that investment over time (Geltner et al 2001). For this analysis, positive cash flow is equal to the energy cost savings achieved by each upgrade design. These investment metrics were calculated for each Temperature+Price scenario using both the construction cost differences between baseline and upgrade designs, as well as each design's energy costs through 2080. These calculations further assumed a 3% inflation rate under each scenario. However, future maintenance and replacement costs were not included in the calculation.

RESULTS

The case study generated a multitude of results in various stages including energy consumption projections, energy cost projections, and investment comparisons. Prior to including costs, the energy consumption projections indicate a rise in cooling energy with a decline in heating, to various degrees, for each temperature scenario; overall, total thermal energy use declines slightly in each model under all scenarios, as illustrated for the A1FI/167 'Temperature+Price' scenario in Figure 4. However, as indicated previously in Table 1, most of the EMF-22 models project high electricity price increases with modest increases to natural gas prices; therefore building energy cost results increase over time, even when discounting inflation as shown in Figure 5.

	Construction Cost	Δ from Baseline
Baseline	**$1,251,522.36**	n/a
Mimimum Upgrade	**$1,340,860.91**	$89,338.55
Medium Upgrade	**$1,435,029.37**	$183,507.01
Advanced Upgrade	**$1,506,906.03**	$255,383.67

Table 3. Case Study Construction Costs

In the following, the case study simulation results for the different scenarios are presented in two different ways. The first compares cumulative energy costs using three different cost calculation techniques for each design upgrade individually. The purpose of this comparison is to show in how far the method presented in this paper yields different results as opposed to conventional cost prediction methods. The second comparison investigates the investment results independently for each 'Temperature+Price' scenario in order to visually compare the different outcomes that one might get for different futures. This analysis corresponds to an overall risk analysis for the investment; it also mimics a perspective that an owner or lending institution might take when analyzing the financial viability of various design retrofits.

Comparison of Cost Prediction Techniques

A first set of results calculates cumulative energy costs for each design option regarding cost projection techniques. This process includes each design simulated from 2010-2080 for A) both the baseline TMY2 temperature and baseline prices, B) the TAR based weather files and the 2010 baseline prices, and C) the 'Temperature+Price' scenarios. Method A ignores rising temperatures and prices and corresponds to the analysis that an investor would carry out today; method B considers rising temperatures but ignores energy price developments; and method C corresponds to the method developed and promoted in this paper. Figure 5 illustrates these results for cumulative energy costs for each design option. The error bars attached to each projection correspond to the range that one gets for the various scenarios. The projected value is the mean of the different scenarios. For the all four designs, the 'Temperature+Price' scenarios predict cumulative cost increases of 15% to 68% compared to the conventional method (static climate and price). As one would expect, taking climate change into account, but ignoring price developments, leads to significantly

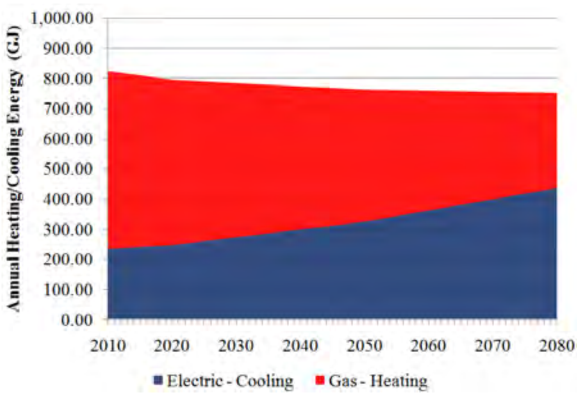

Figure 4. Thermal energy consumption results - Minimum Design under A1FI Scenario

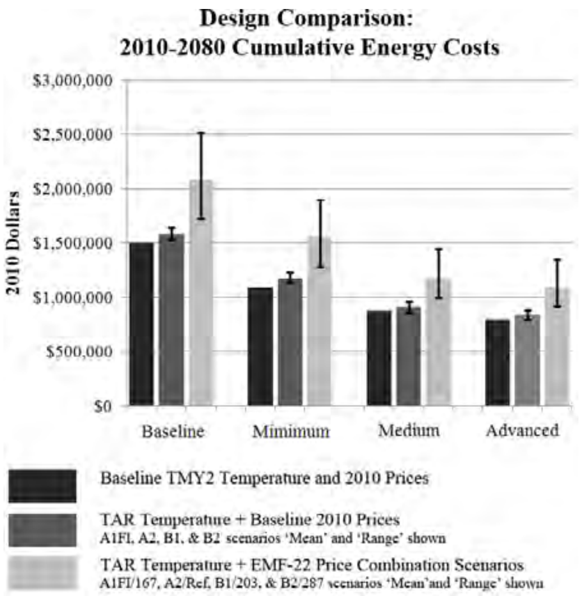

Figure 5. Cost calculation comparison

lower cumulative energy costs changes between -1% and 12% for all design upgrades.

Financial Analysis Tool

The investment analysis compares the building designs for each 'Temperature+Price' scenario independently. The baseline models are generated using the baseline building and the annual variables from the corresponding 'Temperature+Price' scenario. This technique allows each design to calculate the payback period and IRR in comparison to a baseline that reflects the same temperature and energy price variables. Figure 6 indicates the average payback period and IRR for each model as well as the range for the four 'Temperature+Price' scenarios; the IRR calculations use the full 70 year timeframe and include the inflation variable as described above. Payback periods for the three upgrade models range from 12 to 18 years, while the IRRs range from 7.0% to 10.5%.

An Excel based tool, developed for this research, displays the four case study design options in a side-by-side fashion to illustrate the result data. Tool outputs are shown in Figure 7. These graphs help illustrate the operational life-cycle cost changes for each design under various scenarios. Since an owner cannot know which scenario will become reality, the gray area in Figure 7 shows the range of likely futures for the building based on the range of the seven EMF-22 scenarios; this range can be interpreted as a visual risk assessment. Users of the tool may toggle between the four 'Temperature+Price' scenarios to compare the resulting energy cost impacts (in 2010 dollars), payback periods and the IRR for each design option under the selected scenario. The full range and four specific medians for each 'Temperature+Price' scenario can also be compared simultaneously to illustrate the entire scope of the study, as illustrated in Figure 7.

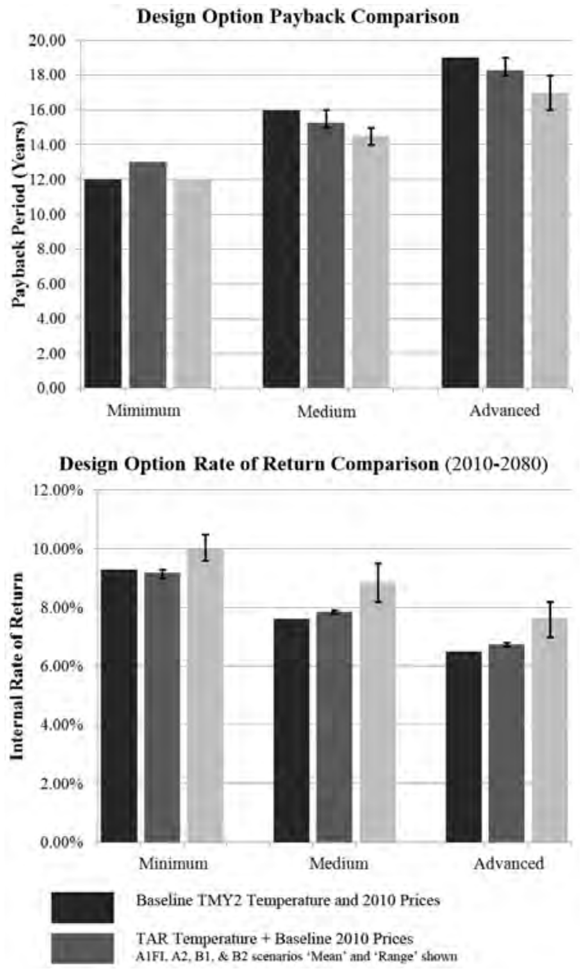

Figure 6. Investment calculation results

DISCUSSION

The case study results primarily illustrate the differences between cost projection methods that consider climate and energy price changes vis-a-vis traditional methods, which ignore one or both of these variables. Figure 5 suggests that long-term energy costs are significantly higher for the 'Temperature+Price' scenario analysis than for a traditional 'static' analysis or one that only considers temperature changes. This shows that an owner is well advised to use the more advanced method when it comes to long-term building operations planning.

In general, the results illustrate in how far efficient building designs reduce energy costs in the long term. As expected, all analyses conclude that more energy efficient designs save the most in cumulative and annual costs when compared to the 'baseline' building (Figure 5). The results also show that more efficient designs produce less variation across the 'Temperature+Price' scenarios when compared to a traditional energy cost calculation for the same design. One possible conclusion is that more efficient designs help reduce the risk of wide ranging energy costs in the future.

The investment analysis indicates that the paybacks for upgrade designs are consistently shorter

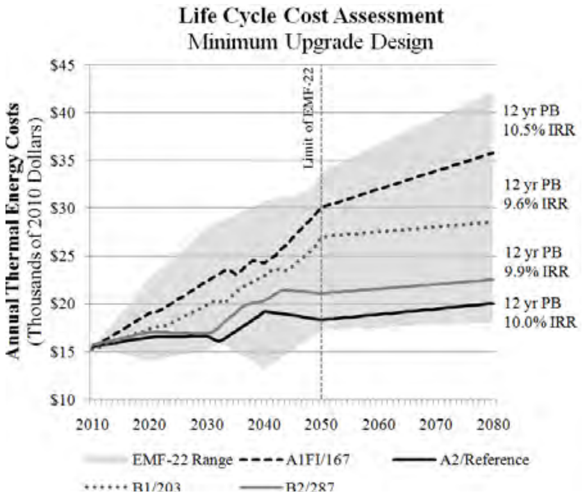

Figure 7. Scenario comparison chart example

when considering climate and price variables (Figure 6); this result produces favourable opportunities for 'green' design and technology deployment. However, for the Boston based case study, the 'medium' and 'advanced' designs do not provide as great a payback or IRR as the standard 'minimum' design. Even though these designs save more in energy costs, their initial construction costs outweigh the cost savings. Additionally, payback periods greater than 10 years may not be considered adequate depending on the building owner; institutional owners may consider this sufficient whereas real estate developers may not. However, for long term owners, the IRR analysis indicates adequate return on investment (7-10.5%) for all design options for the duration of the study; again, the 'minimum' building provides the greatest return on investment.

These findings are meaningful and contribute to building simulation research in a number of ways. First, this research found that it is possible to link climate change based temperature projections and energy price projections in order to economically evaluate building design choices. By using this analysis strategy, building owners may make better-informed investment decisions as well as minimize risk to increased operations costs. More specifically, this analysis can pinpoint the design options most sensitive to climate change temperatures and GHG mitigation efforts; for instance, a building owner may consider a different energy source for cooling needs due to the increases in electricity prices.

As previously indicated, this research builds on other researchers efforts to determine how buildings perform under the climate change temperature scenarios. Similar to their conclusions, this research's results find that heating loads decrease while cooling increases to the point that total thermal energy is less in a heating dominated climate such as Boston (Crawley 2008). Furthermore, this research could help building code developers and high performance standards (LEED, BREAM, etc) to evaluate their metrics more broadly when considering long-term implications. The case study also represents a validation to the suggested use of mixed mode design techniques for reducing cooling energy and better adapting to climate change, as described by previous authors (Hacker et al 2005, Nicol et al 2006, and de Wilde & Tian 2010).

This research contains various limitations. The primary limitation is the use of outdated climate change weather data; the 2001 TAR data is easily adapted for generating hourly weather files, but is almost a decade older than the energy price models utilized. Additionally, since the US energy price data is formulated at a national scale, regional price variations are not precisely accounted for. Also, for the case study, a single climate (Boston) was investigated; one can expect the observed effects to be considerably larger in more cooling dominated climates. Construction costs are of course also regionally dependant. Finally, the study does not take peak loads and overheating into account, i.e. as temperature changes HVAC systems might become insufficient to deal with increased loads. Furthermore, the simulation technique does not specify design for robustness; i.e. whether all parts of the building and HVAC equipment will even last for 70 years.

This research represents only the 'tip of the iceberg' in terms of how energy price projections due to GHG mitigation can be combined with climate change weather in building performance simulations. All the limitations previously listed provide opportunities to expand this research in order to evaluate multiple regions, climates, and energy price scenarios. Additionally, other energy efficiency efforts should be evaluated from behavioural (modified setpoints, clothing, and occupancy) to envelope improvements (window to wall ratio, materials, and orientation). Finally, the methods used can be refined to generate a standard for accommodating future inputs from both energy price scenario and climate change weather scenario models. Ideally, one climate and economic model should provide both the weather and energy price inputs for future climate change based building simulations and life-cycle cost analyses.

CONCLUSION

This research primarily illustrates how long-term energy cost projections for building operations are more robust when simulations account for climate change temperature and energy price impacts. This research shows how energy price projections due to GHG mitigation policies generally increase life-cycle operations cost of buildings under various climate change scenarios. More energy efficient buildings generally show less variability under the range of climate scenarios. Overall, this research generates a larger question: Where is the 'sweet spot' in designing and implementing a building efficiency upgrade that provides an acceptable return on investment while considering climate change and GHG mitigation policies? This research currently shows the range of investments opportunities that exist, but it does not yet indicate what solutions are best for the specific region and case study analyzed.

ACKNOWLEDGEMENTS

We want to thank the following people for their advice and assistance in this work: John D. Macomber, Dr. Leon Clarke, Drury Crawley, Joyce Rosenthal, Martin Bechtold, Tapio Schneider, Richard N. Cooper, Matt Elley, Karthik Dondeti, Azadeh Odmidfar, Diego Ibarra, Holly W. Samuelson, Rashida Mogri, Julia Africa, Ryan Dings and Andrea Doratan.

NOMENCLATURE

A1, A1FI, A2, B1, B2 – SRES emissions scenarios

AR4 – IPCC 4th Assessment Report, 2007

EMF-22 – Energy Modelling Forum report, 2009

GHG – Greenhouse Gases

IPCC – Intergovernmental Panel on Climate Change

IRR – Internal rate of return

SRES – IPCC Special Report on Emissions Scenarios

TAR – IPCC 3rd Assessment Report, 2001

TMY2 – Typical Meteorological Year 2

REFERENCES

Balboni, B (ed.) (2010). *2011 R.S. Means Square Foot Costs: 32nd Annual Edition*. Construction Publishers & Consultants, Norwell, MA.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., & Tavoni, M. (2009). *International climate* policy architectures: *Overview of the EMF 22 international scenarios*. Energy Economics, 31, S64-S81.

Clarke, L (2009). *EMF Briefing on Climate Policy Scenarios: U.S. Domestic and International Policy Architectures*; DataUS Updated. Retrieved on MArch 1, 2011 from: http://emf.stanford.edu/events/emf_briefing_on_climate_policy_scenarios_us_domestic_and_international_policy_architectures.

Crawley, D. (2008). *Building Performance Simulation: A Tool for Policymaking*. Doctoral Dissertation, University of Strathclyde, Glascow, UK.

Cubasch, U., Meehl, G.A. (2001) C*limate Change 2001, IPCC Working Group I: The Scientific Basis; Chapter 9, Projections of Future Climate Change*. Cambridge, UK. Cambridge University Press.

Deru, M., Field, K., Studer, D., Benne, K., Griffeth, B., & Torcellini, P. (2011). *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock*. US DOE Technical Report NREL/TP-5500-46861

DOE (U.S. Department of Energy) (2010). *Commercial Building Initiative; Commercial Reference Buildings, Version 1_3_5.0*. Retrieved on February 1, 2011 from: http://www1.eere.energy.gov/buildings/commercial_initiative/reference_buildings.html

EIA (U.S. Energy Information Adminstration) (2006) *2003 Commercial Building Energy Consumption Survey: Table B30*. Cooling Energy Sources, Number of Buildings and Floorspace for Non-Mall Buildings.

EIA (2010) *Annual Energy Outlook 2011; Early Release Overview*. Report Number: DOE/EIA-0383ER(2011).

EIA (2011). *Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State & Massachusetts, Natural Gas Prices*. Retrieved on March 1, 2011 from http://www. eia.gov.

Fawcett, A. A., Calvin, K. V., de la Chesnaye, F. C., Reilly, J. M., & Weyant, J. P. (2009). *Overview of EMF 22 U.S. transition scenarios*. Energy Economics, 31(Supplement 2), S198-S211.

Geltner, D.M. & Miller, M.G. (2001). *Commercial Real Estate Analysis and Investments*. South-western Publishing, Mason, OH, U.S.

Hacker, J., Holmes, M., Belcher, S., & Davies, G. (2005). *Climate change and the indoor environment: Impacts and Adaptation*. CIBSE, London, UK. TM36: 2005.

Hacker, J., Capon, R., Mylona, A. (2009). *Use of climate change scenarios for building simulation: the CIBSE future weather years*. CIBSE, London, UK. CIBSE TM48: 2009.

Jentsch, M.F., Bahaj, A.S., James, P.A.B. (2010). *Manual: Climate change world weather file generator, Version 1.5*. University of Southampton, Sustainable Energy Research Group. UK.

Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R., Moss, R.H., Wilbanks, T.J. (2010). *Socio-economic Scenario Development for Climate Change Analysis*. CIRED Working Pap No. 2010-23.

Nakicenovic, N., & Swart, R. (eds.). (2000). *IPCC Special Report on Emissions Scenarios.* Cambridge University Press, Cambridge, UK.

Nicol, F., Rudge, J., & Kovats, S. (2006). *Safe and Warm: Effect of Climate Change on Thermal Comfort and Health; Chapter 5 in Adapting buildings and cities for climate change: A 21st century survival guide* (2nd ed.). Oxford: Elsevier.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (eds.) (2007) *Climate Change 2007, IPCC Working Group I: The Physical Science Basis.* Cambridge; UK: Cambridge University Press.

de Wilde, P. & Tian, W. (2010) *The role of adaptive thermal comfort in the prediction of the thermal performance of a modern mixed-mode office building in the UK under climate change*. Journal of Building Performance Simulation, 3:2, 87—101.