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Assessing the Value of Commercial Building Low-carbon Retrofit in Edinburgh City in Scotland

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Key Words

- Low carbon building, low carbon building retrofit readiness, option value, low carbon retrofit, LCB Readiness.

Abstract

The purpose of current work is to assess the economics in the retrofit of non-domestic buildings in the UK, and recommend policy mechanisms to bridge the gap. This paper gives an overview of evaluation methodologies, incl. the technology assessment mechanism, financial cash flow valuation method, and the novel real option approach for assessing the value of new buildings designed in a low carbon retrofit readiness status. Detailed analysis of potential benefits from retrofitting existing commercial buildings in Edinburgh City is carried out. Resultshows substantial financial value in retrofitting a buildingover a lifetime through assessing the option value.The economic viability of retrofitting a commercialbuilding to low carbon design in Edinburgh is proven to be very high. Thus, new buildings are proposed to design in a 'Low Carbon Building Retrofit Readiness' status ('LCB Readiness') and it would be beneficial to develop a standard orbest practice for low carbon design for commercialbuildings.

Chapter One Introduction

1.1 Energy Consumption in the Building Sector

The rapid growth of the world economy requires substantial demand and consumption for energy, resulting in exhaustion of energy resources and adverse environmental impacts. During the last two decades, the world's total final energy consumption increased by 48% to 9,321 Mtoe while CO_2 emissions increased by 56%, reaching 32,190 Mt in 2013, with an average annual increase of 2.1% and 2.4% respectively (Fig.

1). The European Union (EU) countries endeavoured to tackle energy and environment issues after the agreement of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. Although the energy consumption and CO_2 emissions seemed subsequently to be under control (Fig. 2), final energy consumption and CO_2 emissions in the EU contributed 12% and 10% of the world's total numbers respectively (IEA, 2015).

Final energy consumption is usually dominated by the industry sector, followed by others including agriculture, commercial and public services, residential and non-specified, the rest being composed of the transport sector and non-energy use. However, the building sector in developed countries accounts for 20-40% of the total final energy consumption and has exceeded the other major sectors (Perez-Lombard, et al., 2008). In 2004, energy consumption in building sector in the EU was 37% of final energy, bigger than industry (28%) and transport (32%). In 2010, it increased to 40% of total energy consumption in the EU (EU Commission, 2010). In the UK, up to 42% of the energy consumption is spentin heating and cooling the buildings (DECC, 2010) and 43% of all the UK's carbon emissions are caused by the building sector (DCLG, 2015). This is slightly above the European figure and partly due to the shift away from heavy industry towards service sector activities (Perez-Lombard, et al., 2008).

Furthermore, the building sector is expanding. The energy used by domestic and non-domestic buildings accounts for approximately 25% and 18% of UK carbon emissions (DECC, 2015), and it is expected that non-domestic floor area in the UK will increase by 35% by 2050, while 60% of existing buildings will still be in use (LCICG, 2012). Public sector buildings in Scotland emitted 1.2 $MtCO_2e$, which represented 2.3% of Scottish GHG emissions in 2013. Buildings and other developments can also be environmentally hazardous through poor waste management or inefficient use of resources (DCLG, 2015). Therefore, reducing energy use, and in particular emissions of greenhouse gases (GHGs) in the building sector are essential for tackling climate change issue and retrofitting existing buildings offers a significant opportunity to help improve energy efficiency and reduce greenhouse emissions in the UK.
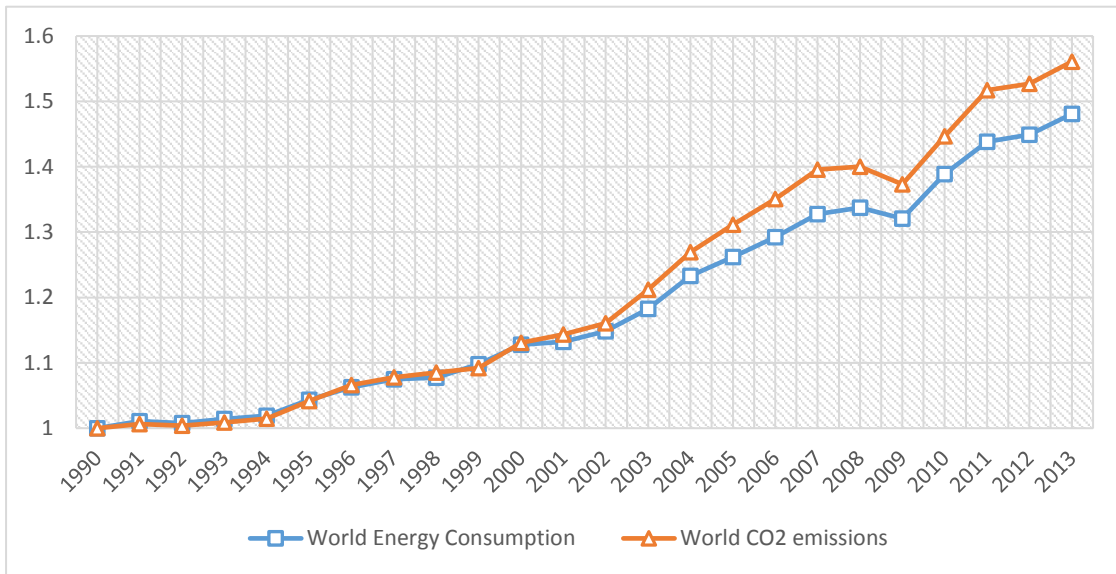
Figure 1. World's total final energy consumption and CO_2 emissions since 1990.

Source: International Energy Agency (IEA).
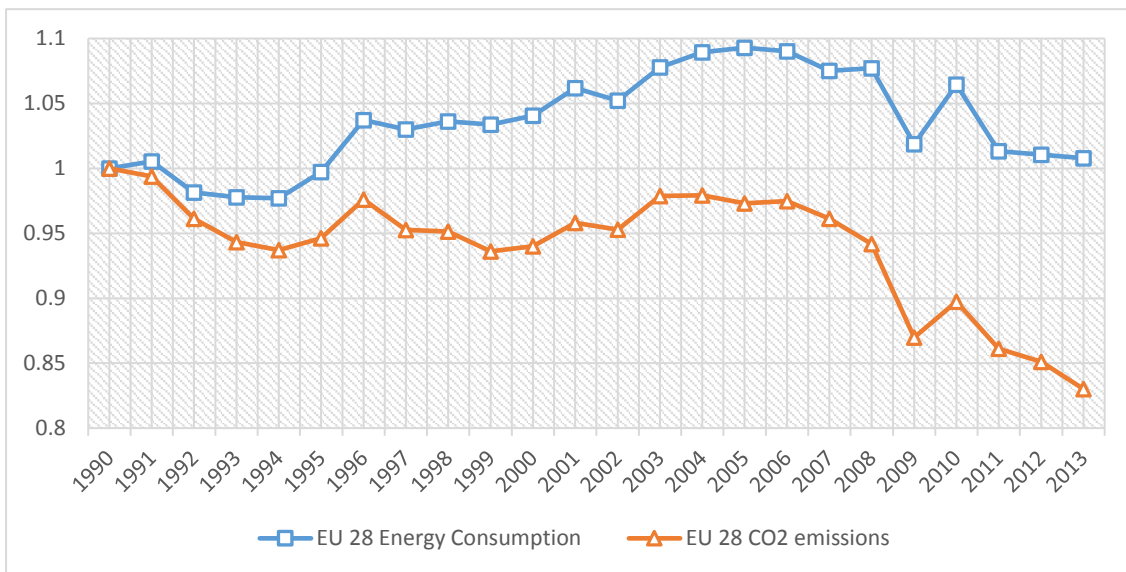
Figure. 2. EU 28 countries' total final energy consumption and CO_2 emissions since 1990. Source: International Energy Agency (IEA).

1.2 BuildingEnergy Policy in Scotland

The Scottish Government has declared a strong commitment to achieve the 2050 target defined as 80% lower net Scottish emissions than the 1990 baseline. The interim target, which is set for year 2020, is at least 42% lower net Scottish emissions than the baseline. Moreover, for each year in the period 2011-2019, the annual carbon

emission target must be set at an amount that is consistent with a reduction over that period of net Scottish emissions amounts which would allow the interim and the 2050 target to be met. For each year in the period 2020-2050, the target must be set at an amount that is at least 3% less than the target for the preceding year (Climate Change Bill, 2009).

The bill for the Building (Scotland) Act was passed by the parliament on 20th February 2003, including provisions with respect to buildings, building standards, verification and certification, building warrants etc. In 2007, the Sullivan Report proposed a route map for delivery of very low carbon buildings, setting aspirations for carbon abatement and energy efficiency within building standards. The report also suggested that all owners of non-domestic buildings should conduct a carbon and energy assessment and produce a programme for upgrading.

The Sullivan Report (2007) also considered ways in which carbon and energy performance of existing buildings can be improved. Introduction of legislation to require all owners of non-domestic buildings to conduct assessments of carbon and energy and produce a programme for upgrading were recommended.Such assessment is listed as Section 50 "Non-domestic buildings: assessment of energy performance and emissions" in the Climate Change (Scotland) Bill.

Therefore, energy performance of non-domestic buildings, and promotion of energy efficiency and renewable heat were emphasized in the 2009 Climate Change (Scotland) Act. In the same year, the Scottish Government issued the Renewable Energy Framework to advocate the EU target of 20% renewable energy by 2020, and play its role in meeting the contribution proposed for the UK for 15% renewable energy and aim to go further than that (to 20%).

Almost all of the recommendations from the original Sullivan Report in 2007 have now been taken forward. In the most recently Sullivan Report in 2013: A Low Carbon Building Standards Strategy for Scotland: to support a more successful implementation of low carbon building standards, and subject to the previous recommendation,

subsequent reviews of energy standards were suggested to be programmed to align with the EU Directive requirement for 'nearly zero energy' new buildings from 2019.

The Scottish Government is also using building standards and the planning system to help achieve low carbon buildings. The Scottish Government, Building Standards Division (BSD) has published new guidance regarding Building Standards compliance from 1 October 2015, including new Technical Handbooks with major revisions to Section 6 (Energy) Domestic & Non-domestic. The standard now applies to extensions to non-domestic buildings that increase the total area by more than 100 m^2 or 25%. Figure 3 shows the timeline of policy regarding building energy in Scotland over 12 years.
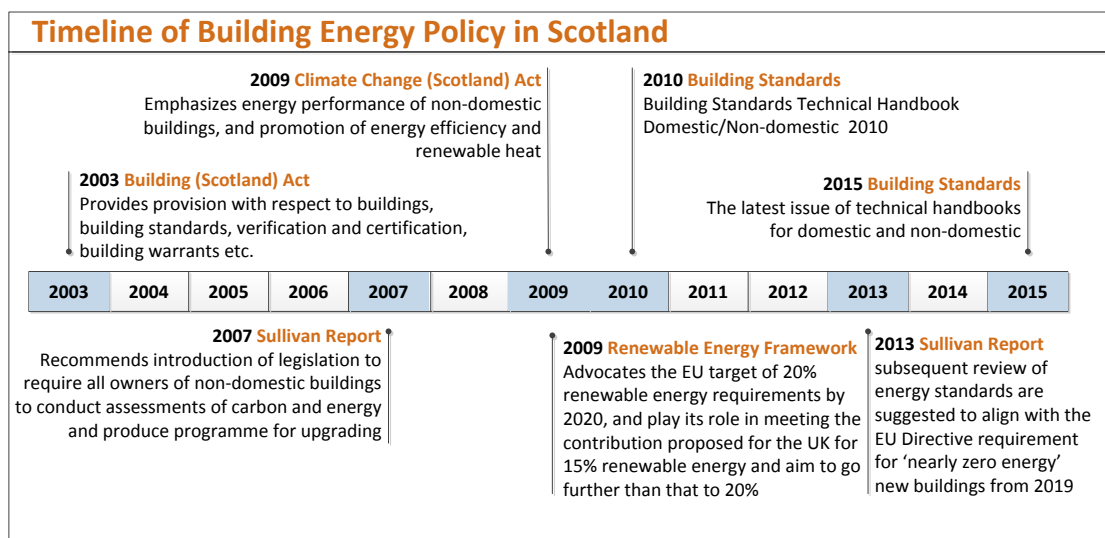
Timeline of Building Energy Policy in Scotland

2009 Climate Change (Scotland) Act
Emphasizes energy performance of non-domestic buildings, and promotion of energy efficiency and renewable heat

2003 Building (Scotland) Act
Provides provision with respect to buildings, building standards, verification and certification, building warrants etc.

2010 Building Standards
Building Standards Technical Handbook Domestic/Non-domestic 2010

2015 Building Standards
The latest issue of technical handbooks for domestic and non-domestic

| 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |

2007 Sullivan Report
Recommends introduction of legislation to require all owners of non-domestic buildings to conduct assessments of carbon and energy and produce programme for upgrading

2009 Renewable Energy Framework
Advocates the EU target of 20% renewable energy requirements by 2020, and play its role in meeting the contribution proposed for the UK for 15% renewable energy and aim to go further than that to 20%

2013 Sullivan Report
subsequent review of energy standards are suggested to align with the EU Directive requirement for 'nearly zero energy' new buildings from 2019

Figure. 3. Timeline of Building Energy Policy in Scotland

1.3 Literature on Retrofitting of Non-domestic Buildings

The main proposal for retrofitting is to extend the beneficial use of an existing building by taking a cost-effective alternative to redevelopment (Markus, 1979). Retrofitting may be initiated suddenly due to profound damage, or driven by depreciation and the loss of a property's investment value (Aikivouri, 1996). However, since the conventional economic performance analysis has been extended with more consideration of the social and environmental impacts of a business, Mansfield (2009) suggested that sustainability policies with respect to the corporate social responsibility

(CSR) and socially responsible investment (SRI) may bring forward the timing of retrofitting, thus making an effort to address energy efficiency, CO_2 emissions and other sustainability issues.

Ma et al. (2012) identified five steps in the process of a building retrofit: project set up and pre-retrofit survey, energy audit and performance assessment, identification of retrofit options, implementation and commissioning and the last one validation and verification of energy saving. A successful retrofit programme depends on many factors including policy and regulation, retrofit technologies, building specific information and other uncertainties. Since there are a wide range of retrofit technologies readily available, reliable estimation of the most cost-effective retrofit options for particular projects on existing buildings is essential for sustainable building retrofit. Performance of different options is commonly evaluated using energy simulation and modelling.

Furthermore, economic feasibility analysis that facilitated the comparison among the retrofit alternatives can provide an indication of whether the alternatives are cost-effective, and the selection of retrofit alternatives is a trade-off between capital investment and benefits (Ma et al., 2012). Blackhurst et al. (2011) examined costs and benefits of existing local residential and commercial building retrofits aiming to reduce GHGs by conducting two case studies: Pittsburgh, PA and Austin, TX. They analysed the capital and labour costs as well as net benefits of consumer savings from retrofits, and evaluated the trade-offs between capital constraints, social savings, and GHGs reductions. Net present value (NPV) was employed to measure the net saving. Their results suggested that uncertainty in local stocks, demands, and efficiency significantly impact anticipated outcomes.

Rysanek and Choudhary (2013) augmented the above study by employing a combined engineering-economic assessment model of a building energy system. They modified the standard approach to building energy modelling by using TRNSYS[1] in order to

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[1] Transient System Simulation Program, used in renewable energy engineering and building simulation for solar design

improve the speed at which accurate performance estimations of numerous retrofit options are made. Meanwhile, Bull et al. (2014) assessed energy efficient retrofit options for schools in the UK by conducting dynamic energy simulations of a range of energy retrofit measures using EnergyPlus v.7.2[2] and jEPlus v. 1.4. They introduced life cycle effects on costs and carbon emissions since these retrofits will last for many years. They found that carbon payback is shorter than financial payback and all options and combination of options repaid the carbon invested in them.

One of the case studies in McArthur and Jofeh's research (2015) involved a large global tenant with 40 properties in their UK portfolio, and their retrofitting goal is to reduce portfolio carbon emissions by 50% between 2007 and 2017. McArthur and Jofeh identified the best opportunities in the portfolio to achieve the goal by assessing and sorting portfolios using historic energy use data. Aste et al. (2016) also presented economic analysis referring to local energy efficiency programs for retrofitting existing building and for promoting new low emissions buildings.

1.4 Report Structure

Whilst energy saving and emission reduction might have been the 'top priority' in the previous decade, the global economy recession and the following public debt crisis made 'energy efficiency cost saving' as the popular rationale for retrofitting existing buildings (Rysanek and Choudhary, 2013). Different types of building exhibit unique architectural, geographical and operational characteristics, therefore retrofit options must be rationally analysed for every individual building in a building stock, and computational building energy models must be employed to investigate the cost and benefit of these options.

Meanwhile, progress in retrofitting the UK's commercial properties continues to be slow and fragmented. New research from the UK and USA suggests that radical changes are needed to drive large-scale retrofitting, and that new and innovative models of financing can create new opportunities (Dixon, 2014). Moreover, despite a

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[2]updated version in 2012 of EnergyPlus simulationsoftware for modeling heating, cooling, lighting,ventilating, and other building energy flows

number of studies on carbon reduction in residential buildings and new buildings, there is limited research into the disaggregated potential for energy and carbon by retrofitting the existing non-domestic buildings with more efficient and low-carbon designs. Also, most studies on energy and environmental performance of the retrofit of existing commercial office buildings were carried out based on numerical simulations, more studies with practical case studies on non-domestic building retrofits are essentially needed.

Therefore, this report evaluates the potential benefits from retrofitting existing commercial buildings in Edinburgh City through assessing the option value of retrofitting. The purpose of this paper is to assess the economics in the retrofit in non-domestic buildings in UK, and provide policy mechanisms to bridge the gap. The generic assumption of the model is based on analysing the technical and financial performance of a commercial building retrofit case in Edinburgh City. The report also proposes that new buildings should be designed in a 'Low Carbon Building Retrofit Readiness' status or 'LCB Readiness'.

The report is structured as follows: Chapter Two gives an overview of evaluation methodologies, incl. the technology assessment mechanism, financial cash flow valuation method, and the novel real option approach for assessing the value of making new buildings designed in a low carbon retrofit readiness status. Chapter Three presents the technical case studies. Chapter Four presents the model results and outlines the potential implications.

Chapter Two Methodology

The traditional financial option pricing methodology, the Real Option Approach (ROA), has been applied to value real assets which are either uncertain or flexible since the 1970s (Myers, 1977). This is because that alternative, deterministic net present value method fails to capture the option value involved in the sequential decision-making at each decision node[3]. This study applied ROA to investigate the economics of retrofitting a building to low carbon building status.

The existing ROA studies in the energy sector could be classified into three clusters: (1) analysis of the private investment decisions under market uncertainty, e.g. electricity, fossil fuel, and/or carbon markets (Rothwell, 2006; Fortin et al, 2008; Szolgayova et al, 2008; Yang et al, 2008); (2) optimisation of R&D , commercialisation and diffusion of energy technologies of a firm (Kumbaroglu et al, 2005; Tan et al, 2007; Siddiqui et al, 2007); (3) investigation of public energy policy decision-making in an uncertain or flexible energy system (Lee and Shih, 2005; Marreco and Carpio, 2006; Lin et al, 2007; Fuss and Szolgayova, 2010; Zhu and Fan, 2011).

The methodology of this study was builton the knowledge and understanding gained from the existing ROA studies described above. We took the perspective of a project investor (e.g. commercial building investor) investigating the value of exercising a retrofit option in a commercial building. Uncertainty is the driver of the option value. A number of uncertainties may potentially affect this investment decision, including the technology progress ratio (or learning rate), global installed capacity of low carbon building, gas and electricity prices and carbon price. High learning rate would drive down the economic of scales, which helps to increase attraction of retrofitting option. The globalinstalled capacity should be examined to provide constraint of low carbon building worldwide. Gas and electricity prices and carbon price are both positively correlated to building retrofitting.

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[3] As a part of a real option model, the investment decision is made at each decision node.

Because there weresignificant policy uncertainties in modelling the carbon price, the regulatory motives other than existing carbon markets were, in reality, more likely to be a possible driver for low carbon building retrofit. In this study, we simplified the assumption and assumed the investment wasdriven solely by market factors. To identify the probability of retrofitting a low-carbon building, a stochastic free cash flow model was built to estimate each year's net present value of future cash flows generated by low carbon retrofit. The net present value of the future cash flow at year T is given by:

$$PV_T(S_t, I_t, O_t, F_t) = \sum_{n=T}^{L} \frac{(S_t - I_t - O_t - F_t)}{(1+q)^t} \qquad (2\text{-}1)$$

t   year   Present life of the commercial building at a decision node

L   year   Lifetime of building

PV_T $ Present value of the future cash flow at year T

S_t $ Revenue from rental at year t

I_t $ Investing cash flow at year t

O_t $ Non-fuel and non-carbon operating cash flow at year t

F_t $ Payment for electricity, gas and carbon at year t

q   %   Private Discount Rate (required internal rate of return)

The main driver for retrofitting a building to low carbon building was assumed to be an increase in revenue driven by increasing rent and a reduction of carbon and energy bill. The value of a future retrofit was inherently uncertain and a robust exploration with probabilistic Monte-Carlo analysis was conducted to take this into consideration.

In theory, increasing the number of time-steps would result in higher option values, but actual investment decisions are more likely to be made on an annual basis, because the process to evaluate an upgrade investment decision would incur sunk costs (e.g. detailed engineering and economic assessment, special board assemblies). Therefore, this study wasconducted with discrete time intervals to approximate the real decision-making process (Plantinga, 1998). It was assumed that the decision is

only made at the end of each year. In other words, if one retrofit takes place in year t, a further upgrade could also be made at year t + N. For a 50 year economic lifetime there are therefore 24 time-steps, or decision nodes.

At each decision node, the decision to retrofit a commercial building depends upon the balance between the cost of a one-off capital investment to retrofit and the sum of future cost savings and revenue increase.

Technology learning rates, assumed to be translated into a reduction of the retrofit cost with new low carbon technologies entering the marketin this study, were therefore critical to determine the value of the option considered for retrofitting. These learning rates focused on the total capital cost of retrofitting the building. The RCOST is here modelled by a one-factor learning curve model (Alberth, 2008; Junginger et al, 2010), given by:

$$RCOST_n = RCOST_0 (\frac{Cap_n}{Cap_0})^{\log(1-m)} \qquad (2\text{-}2)$$

$RCOST_n$	GBP	Retrofit cost at year n
Cap_n	m^2	Global capacity of low carbon commercial building at year n
m	-	Learning rate

For simplicity, it was assumed that the technology learning rate and the global deployment capacity rate were not affected by other assumptions or the model specification, so that they were exogenous, independent values. There is a lack of study estimating the learning rate for low carbon retrofit. This study assumed a learning rate of 5%.

In addition, it was assumed that a stochastic process applies to the technology learning rate, m, and the rate of global installed generation capacity with low carbon retrofit (this follows findings from McDonald and Schrattenholzer (2001) who showed that the historical energy technology learning rates is not constant and varies stochastically). However, there is a lack of literatures to justify the stochastic process of learning rates and deployment rates for low carbon building. Based on our best knowledge with a

reference of past learning and deployment process, the hypothetical learning rate was assumed to follow a mean reverting process and tends to drift towards its long term mean assumption at a hypothetical reversion rate of 0.5; similarly, the hypothetical deployment rate of installed capacity varies stochastically and drifts towards its mean value with a mean hypothetical reversion rate of 0.25.

The process of technology learning rate and deployment rate of low carbon building capacity can be written as:

$$Q_t = Q_{t-1} + \omega_m(Q_L - Q_{t-1}) + Z_m \qquad \text{(2-3)}$$

ω_m	-	Mean reverting rate
Q_t	$	Rate at year t
Q_L	$	Long run equilibrium Rate
Z	-	Random variable following a standard Wiener process

The main barrier to the retrofit is thus the cost of the upfront capital investment necessary to make a building in low carbon status. To represent the uncertainty for electricity price, gas price and carbon price, a stochastic process is modelled by a mean reverting process, as in Equation 2-4.

$$P_t = P_{t-1}(1 + \alpha) + \omega_g(P_L - P_{t-1}) + Z_g \qquad \text{(2-4)}$$

α	-	Drift factor (growth)
ω_m	-	Mean reverting rate
P_t	$	Price at year t
P_L	$	Long run equilibrium price
Z_g	-	Random variable following a standard Wiener process

To complement with uncertainties in the model assumptions for this study, a sensitivity analysis was conducted to investigate the value of retrofit options for different electricity, gas and carbon price growth scenarios as well as different learning rates and required capital for upgrade. The boundary for exercising the option to

retrofit the building aims to estimate the probability of exercising the option at each decision node. Thus the ROA decision-making framework is a complex model with the following characteristics:

- It is an American style claim option, i.e. options could be exercised anytime from now to any expiry date;

- Because of the sunk cost in exercising the option, only one decision node per year is considered;

- In the baseline scenario, it is assumed that both the electricity price and the gas price are not growing, thus in that case, the drift (i.e. growth) of electricity and coal price is low; and

- A backward looking algorithm is used to estimate the optimal exercise boundary.

In evaluating a retrofit option (i.e. the net benefit of retrofit), a heuristic approach in four steps was applied to evaluate options to upgrade a building:

(a) Identify the sample paths for each variable undergoing a stochastic process;

(b) Use a least square regression method with Monte-Carlo simulation to estimate the probability of upgrade and the value of the retrofit option at each option decision node, based on the current retrofit cost and the current information of stochastic variables (i.e. retrofit cost, fuel price, electricity price, carbon, deployment rate, and learning rate);

(c) Estimate the initial value of the retrofit option exercised through a backward deduction approach;

(d) Calculate the mean value of the retrofit options at year 0.

The estimated building rental level at the beginning of period t is x_t . It is clear that x_t depends on the realizations of the rental level in the previous periods, i.e., $x_t \in$

$\{x_0, ..., x_{t-1}\}$. Suppose that the current rental level for low-carbon building at the market I denoted e_t. If an retrofit decision is made, then the rental level (x_t) becomes the current low carbon building market rental level e_t and the beginning low carbon building market rental level of next period is e_t, i.e., $x_{t+1} = e_t$. If no retrofit decision is made, then the market rental level remains at x_t and $x_{t+1} = x_t$. The value of retrofit options can be evaluated by the following Bellman equation (2-5).

$$V_t(x_t, e_t, Q_t, P_t) = max \begin{cases} \frac{1}{1+r} \, b_{t+1}(e_t, Q_t, P_t) - k_t + \frac{1}{1+r} E[V_{t+1}(e_t, e_{t+1}Q_t, P_t)], \\ \frac{1}{1+r} E[V_{t+1}(x_t, e_{t+1}, Q_{t+1}, P_{t+1})] \end{cases}$$

(2-5)

where the expectation is taken with respect to the market retrofit cost level of next period and the terminal value $V_T(x_T, e_T) = 0$.

t	year	Present economic life of the building at a decision node
T	years	Lifetime of the building
V_t	$	Stochastic value of the retrofit option(s) at year t
$E[V_{t+1}]$	$	Estimated value of the retrofit option at year t+1
b_{t+1}	$ Estimated marginal benefit in the present value of operating cashflow at	
		year t+1 with a retrofit option exercised at year t
x_t	$	Building rental level at year t
e_t (estimated)	$	Estimated market rental level for low carbon building at year t
r	%	Risk-free real discount rate
k_t	$	One-off capital cost investment to retrofit the building at year t

The decision to make an additional investment at year 0 to future-proof **low carbon readiness** depends on the present value of the additional investment required, S₀, and the mean value of the option to be able to retrofit the building. In other words, an additional investment to future-proof a building with **low carbon readiness status** would be justified if the present value of the investment (I₀) is lower than the

anticipated value of the option (2-6).

$$\text{Invest, if } V_0 \geq S_0 \qquad \text{Do Not Invest, if } V_0 < S_0 \qquad (2\text{-}6)$$

S_0 \$ Additional investment at year 0 to future-proof the commercial building

V_0 \$ Value of the option to be able to retrofit the building to a low carbo

status

It should be noted that the investment required to future-proof the building, I_0, is site specific, and would, in practice, require a detailed design study. The scope of this analysis was limited to introducing a methodology applied to an illustrative case study, which could also be used to assist decision-making in real projects. Also, the initial investment I_0 was not added directly to the cash flow model. The outcome of the model was the value V_0, in \$, of the option of being able to retrofit the building under the different assumptions for gas price, electricity selling price, carbon price technology learning rate and deployment rate. The decision to invest or not in a commercial building is out of the scope of this study.

Chapter Three Case Study

Figure. 4. Edinburgh Centre for Carbon Innovation. Source: edinburgharchitecture.

The study reviews Edinburgh Centre for Carbon Innovation, a commercial building case studies at Edinburgh City, Scotland.

Edinburgh Centre for Carbon Innovation, Edinburgh

Background

The Edinburgh Centre for Carbon Innovation (ECCI) is a hub for the knowledge, innovation and skills required to create a low carbon economy. Hosted by the University of Edinburgh, in partnership with Heriot-Watt University and Edinburgh Napier University, the ECCI supports Government policy implementation, enhances

business enterprise and innovation and delivers professional skills training.

Work began on the construction of ECCI's new premises in February 2012. This case study covers the refurbishment and remodelling of space in the University of Edinburgh's Old High School in High School Yards to create an innovation suite, lecture theatres, seminar rooms, exhibition and social space.

The building refurbishment complies with the University of Edinburgh Estates & Building Sustainability Strategy, which includes commitments to social responsibility and sustainability and requires environmental standards higher than legal requirements.

The objective was to create a low energy and highly efficient building targeting a minimum BREEAM rating of 'Excellent' and an aspirational rating of 'Outstanding'. The ECCI would be the first listed or refurbished building to be awarded 'Outstanding' if it is achieved.

Building Description, Design & Construction

Fabric

The ECCI refurbishment project involved a major alteration and extension of the Grade B listed, Old High School. Where a pair of historic 18th century buildings had been lost, next to the rear ECCI building, a new café building has been created, with meeting/office spaces above. A generous opening within the lecture and teaching space reinforces a new connection to the adjacent courtyard.

The main structure, inserted within the atrium and all new construction areas, is a Cross Laminated Timber frame (CLT) and CLT floor panels system. CLT is said to lock in around 4-5 times more carbon than it takes to produce. The Structural Engineer assessed steel structural beams removed from the existing building; many could be reused as supports within the construction.

The existing Cullaloe and Blaxter stonework has been carefully and conservatively repaired. The 'base' course to the new construction areas is also constructed in Cullaloe stone from Fife. Locally sourced stone is durable and repairable.The upper levels of the new construction are covered in bronze cladding (80% copper and 20% tin). This is lightweight reducing demand on the structure. It is a durable and a recyclable material.The existing sash windows have been retained and repaired with additional draft proofing and the installation of slim line double glazed units in some areas.Deep composite timber studs support the external wall construction. The internal partitions are also timber stud.

Insulation is a combination of flexible wood fibre batts and rigid fibreboard with an airtight layer internally. The wall construction is vapour open, allowing moisture to move from both inside the building, and from within the wall construction, to the outside. This improves the internal environment and also the health of the construction.

Internal finishes use timber for floors, ceilings and many wall linings. Other floors use linoleum (from natural sources) and carpets. Paint finishes are water based and have high breathability to work in conjunction with the vapour open external wall construction.

Ventilation
The ventilation strategy is primarily passive natural ventilation. An air source heat exchanger also supplies limited chilled beam cooling to some rooms. Cooling and displacement air are only in high occupancy rooms (e.g. lecture theatres).

Lighting
Internal and external lighting is low energy (including LEDs) throughout, with zoned control and use of sensors to limit usage. Daylight studies were carried out at design

stage to maximise natural light and reduce areas of summer overheating.

Water

All sanitary appliances are low water usage. Rainwater harvesting was intended to be installed, until 14th Century archaeology discovered on site inhibited the location of storage tanks. Permeable landscaping and an increase of soft landscaping are also used to control and divert surface water.

CHP

A district CHP system is installed to provide heating and power. Photovoltaic panels (covering 30m²) were also installed on the south facing roof surfaces of the rear building.

Chapter Four Modelling Results and Financing Mechanisms

4.1 Key Assumption

As illustrated in the Chapter Three, the design of low carbon buildings are site specific. According to research from Qiu (2007), the energy consumption in these buildings are 70-300kWh/m^2 per annum. The study develops a generic model for assessing the economic value of keeping the low carbon retrofit option open by using data from Edinburgh Centre for Carbon Innovation. Basic assumptions (e.g. building life, rental cost, discount factor and additional costs)and data calculated from ECCI reports are shown in Table 4-1 and Table 4-2. The total cost is GBP 6.1 million for 20 months of contract duration and the total area is 4790 m^2. The economic life assumption is 50 years. The baseline gas consumption is 127.4 kWh thermal per m^2 per year and the baseline electricity consumption is 56 kWh per m^2 per year[4]. The baseline carbon emission is calculated as 0.05 tCO$_2$ per year using conversion factors given by DEFRA[5].Carbon emission reduced to 0.04 tCO$_2$ per year after retrofitting. The baseline local rental cost at Edinburgh is GBP 100/m^2 in 2016. The retrofit cost is calculated from information above as GBP 764/m^{2}annually.

Table 4-1 Static Assumptions for Economic Assessment

Static Assumptions	Unit	Value
Building Life	Years	50
Baseline Gas Consumption	kWh/m^2 per year	127.4
LCB Gas Consumption	kWh/m^2 per year	98
Baseline Electricity Consumption	kWh/m^2 per year	56
LCB Electricity Consumption	kWh/m^2 per year	43
Baseline Carbon Emissions	tCO$_2$/m^2 per year	0.05
Baseline Rental Cost	GBP/m^2 per year	100

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[4]Calculation based on *Edinburgh Centre on Climate Change Stage C Summary*available at http://www.docs.csg.ed.ac.uk/EstatesBuildings/Development/ECCCFurtherInfoDoc4.pdf
[5] Carbon emission conversion factors for gas and electricity are 0.18445 Kg CO2e per kWh and 0.46219 Kg CO2-e per kWh respectively. For more details: http://www.ukconversionfactorscarbonsmart.co.uk/

Baseline Retrofit Cost	GBP / m^2		764
Discount Factor			6%
Additional Building O&M Cost (retrofit)	GBP/m^2 per year		0

The low carbon retrofit cost is GBP 764 / m^2 in 2016 with assumed learning rate of 20%, i.e. assuming 20% cost reduction per doubling of global capacity in low carbon building. The initial global low carbon building capacity is assumed as 1.2 million m^2. The initial market rent (GBP 100/m^2 per year) is assumed to grow at 3% with a mean reverting rate of 20% and a standard deviation of 5%.The rental cost is calculated using 80% occupancy rate of six different types of rooms and facilities in ECCI. Thus rental revenue is calculated as GBP 145/m^2 per year[6]. We also assume the gas, electricity and carbon prices based on the local market environment.

Table 4-2 Stochastic Assumptions for Economic Assessment

Stochastic Assumptions	Unit	Base Value	Learning Rate	Drift	Mean Reverting Rate	Standard Deviation
LCB Retrofit Cost	GBP / m^2	764	20%			
Global LCB Capacity	m^2	1200000		3%	5%	3%
Market Rent	GBP/m^2 per year	100		3%	20%	5%
LCB Market Rent	GBP/m^2 per year	145		5%	20%	5%
Gas Price	GBP/MWh	20		1%	50%	10%
Electricity Price	GBP/MWh	60		1%	50%	10%
Carbon Price	GBP/tCO2	10		5%	20%	20%

4.2 Result

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[6]Calculation based on room and facility rates at http://edinburghcentre.org/Facilities.html

The estimated option value of low carbon retrofit (Figure 4-1) is GBP 413.8per m². In other word, a new building if designed in low carbon retrofit readiness, could increase the economic value by GBP 413.8 per m². The estimated present value of option payoff ranges from negative GBP 103.5 to positive GBP 944.7. Approximately 75% chance, low carbon building retrofit will provide a higher than GBP 500 payoff.
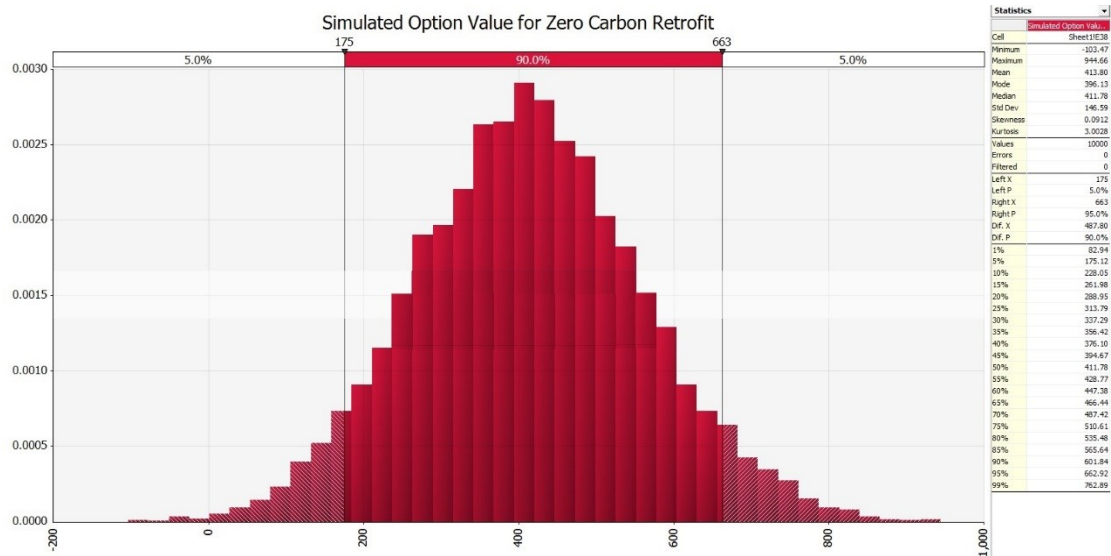

Figure 4-1 Simulated Option Value for Low Carbon Retrofit (10000 trials)

4.3 Scenario Analysis

The study tests a number of scenarios. If there is no rent increase benefit (i.e. only driven by carbon and fuel cost saving), the option value is dramatically reduced to GBP 19.9/m² (Table 4-3). If there is no fuel saving benefit, the option value is reduced to GBP 378.92 /m². The initial cost assumption for retrofit influences the option value.When the initial retrofit capital cost is increased to GBP1000/m², the option value is reduced to GBP 177.44/m². If the initial retrofitting cost increase to GBP 1100 / m², the option value is further decreased toGBP 77.78/m².

Table 4-3 Option Values of Scenario Analysis (10,000 trials) unit: per m²

No Rent Increase after LCB Retrofit	GBP 19.9
No Fuel, Electricity and Carbon Saving	GBP 378.92

Benefit	
Increase from GBP 764 to GBP 1000 /m² *initial retrofit cost*	GBP 177.44
Increase from GBP 764 to GBP 1100 /m² *initial retrofit cost*	GBP 77.78

4.4 Key Implications

The generic analyses provide the following preliminary implications for future studies and policy makers:

- There is substantial financial value of retrofitting a building in Edinburgh to low carbon design captured over the lifetime

- The economic viable chance of retrofitting a commercial building to low carbon design in Edinburgh is very high

- Rent increase benefit is currently the main driver for low carbon retrofit

- It is critical to enable a policy to mandate new commercial building to keep low carbon retrofit options open and avoid the carbon lock-in effect

- It would be beneficial to develop a standard or a best practice for low carbon readiness design for commercial buildings.

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