Retrofitting the Built Environment

Retrofitting the Built Environment:

An Economic and Environmental Analysis of Energy Systems

By

Taofeeq Ibn-Mohammed

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To my late dad, Hon. Yusuf Ibn-Mohammed, the man that I admire the most, whom I consider the special gift in my life and who in the 19 years that I had with him gave me unconditional love, a sense of duty, and reasons to keep working hard and be selfless.

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ABSTRACT

Whether based on current emissions data or future projections of further growth, the building sector currently represents the largest and most-important contributor to greenhouse gas (GHG) emissions globally. This notion is also supported by the Intergovernmental Panel on Climate Change based on projection scenarios for 2030 that emissions from buildings will be responsible for about one-third of total global emissions. As such, improving the energy efficiency of buildings has become a top priority worldwide. A significant majority of buildings that exist now will still exist in 2030 and beyond; therefore, the greatest energy savings and carbon footprint reductions can be made through the retrofit of existing buildings. A wide range of retrofit options are readily available, but methods to identify optimal solutions for a particular abatement project still constitute a major technical challenge. Investments in building energy retrofit technologies usually involve decision-making processes targeted at reducing operational energy consumption and maintenance bills. For this reason, retrofit decisions by building stakeholders are typically driven by financial considerations. However, recent trends towards environmentally conscious and resource-efficient design and retrofit have focused on the environmental merits of these options, emphasising a lifecycle approach to emissions reduction. Retrofit options available for energy savings have different performance characteristics, and building stakeholders are required to establish an optimal solution, where competing objectives such as financial costs, energy consumption, and environmental performance are taken into account. These key performance parameters cannot be easily quantified and compared by building stakeholders since they lack the resources to perform an effective decision analysis. In part, this is due to the inadequacy of existing methods to assess and compare performance indicators. Current methods to quantify these parameters are considered in isolation when making decisions about energy conservation in buildings. To effectively manage the reduction of lifecycle environmental impacts, it is necessary to link financial cost with both operational and embodied emissions. This book presents a novel deterministic decision support system (DSS) for the evaluation of the economically and environmentally optimal retrofit of non-domestic buildings. The DSS integrates the key variables of economic and net environmental benefits to produce optimal

decisions. These variables are used within an optimisation scheme that consists of integrated modules for data input and sensitivity analysis, and takes into account the use of a set of retrofit options that satisfies a range of criteria (environmental, demand, cost and resource constraints), a hierarchical course of action, and the evaluations of a "best" case scenario based on marginal abatement cost methods and Pareto optimisation. The steps involved in the system development are presented and their usefulness is evaluated using case study applications. The results of the applications are analysed and presented, verifying the feasibility of the DSS whilst encouraging further improvements and extensions. The usefulness of the DSS as a tool for policy formulation and developments that can trigger innovations in retrofit product development processes and sustainable business models are also discussed.

The methodology developed provides stakeholders with an efficient and reliable decision process that is informed by both environmental and financial considerations. Overall, the development of the DSS, which takes a whole-life CO_2 emission accounting framework and an economic assessment viewpoint, successfully demonstrates how value is delivered across different parts of the techno-economic system, especially as it pertains to financial gains and embodied and operational emissions reduction potential.

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Melody Beattie (1987), the author of *Codependent No More* wrote:

> Gratitude unlocks the fullness of life. It turns what we have into enough, and more. It turns denial into acceptance, chaos to order, confusion to clarity. It can turn a meal into a feast, a house into a home and a stranger into a friend.

It is on the premise of the above quote, a favourite of mine that, I would like to express my glowing admiration and heartfelt appreciation to a number of people, especially my excellent advisory and supervision team who have made my PhD journey enchantingly magical. Right before I commenced my PhD, a sparkle of fear beclouded my heart—not from self-doubt, but from the uncertainties associated with the dreadful mileage of the doctoral research. As my heart faltered, the gracefulness radiated by both Dr Simon Taylor and Dr Leticia Ozawa-Meida, my respective (former) first and second supervisors, buoyed my confidence and strengthened my determination during my interview for the research position. Now that the journey is complete, I am wholly grateful for what you have both been to me. Your styles of supervision, persistent encouragement, and outstanding support have inspired me to think more, dream more, and explore my intellectual prowess more. Thank you!

The news of Dr Taylor's move to Loughborough University was received by me with mixed feelings. I was thrilled at the career advancement the move will bring him, but the thought of losing a supervisor with whom I have struck a chord was disappointingly sad. However, he handed me over into the safe and competent hands of Dr Rick Greenough, who then effectively became my new first supervisor. Rick was profoundly knowledgeable and astute as a supervisor. His constant encouragement, psychological reassurance, constructive instructions, and useful guidance during the course of the research have been essential motivators in completing this task. Every comment during monthly meetings was the law! Rick's aura of tolerance, his subtle approach to difficult research issues, and his high level patience and professionalism are a few of the qualities I have found exceedingly motivating in the course of this research journey. Accordingly, I say a big thank you!

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As the island of knowledge grows, the surface that makes contact with mystery expands. When major theories are overturned, what we thought was certain knowledge gives way, and knowledge touches upon mystery differently. This newly uncovered mystery may be humbling and unsettling, but it is the cost of truth. Creative scientists, philosophers, and poets thrive at this shoreline.

~ W. Mark Richardson, "A Skeptic's Sense of Wonder," (1998)

LIST OF ABBREVIATIONS AND ACRONYMS

ASHP: Air Source Heat Pump
ASHRAE: American Society of Heating, Refrigeration and Air-conditioning Engineers
BEMS: Building Energy Management System
BP: British Petroleum
BRE: Building Research Establishment
BREDEM: BRE Domestic Energy Model
BREEAM: Building Research Establishment Environmental Assessment Method
CASBEE: Comprehensive Assessment System for Building Environmental Efficiency
CCC: Committee for Climate Change
CHP: Combined Heat and Power
CO_2: Carbon dioxide
CO_2e: Carbon dioxide equivalent
CoP: Coefficient of Performance
DECC: Department of Energy and Climate Change
DEFRA: Department for the Environment, Food and Rural Affairs
DSS: Decision Support System
DTI: Department of Trade and Industry
EIA: Energy Information Association
EPC: Energy Performance Certificate
FIT: Feed-in Tariff
FP: Fuel Poverty
GHG: Greenhouse Gas
GSHP: Ground Source Heat Pump
GWP: Global Warming Potential
HEQ: High Quality Environmental standard
HM's Government: Her Majesty's Government
IEA: International Energy Agency
IPCC: Intergovernmental Panel on Climate Change
KPI: Key Performance Indicator
KWh: Kilowatt hour
LCC: Life Cycle Costing
LCEA: Life Cycle Energy Analysis

LCTP: Low Carbon Transition Plan
LEDs: Light Emitting Diodes
LEED: Leadership in Energy and Environmental Design
MACC: Marginal Abatement Cost Curve
MRIO: Multi Region Input Output
NPV: Net Present Value
OECD: Organisation for Economic Cooperation and Development
PO: Pareto Optimisation
PIR: Passive Infrared
PV: Photovoltaic
RES: Renewable Energy Supply
RHI: Renewable Heat Incentives
RHO: Renewable Heat Obligation
SBCI: Sustainable Buildings and Climate Initiative
SIC: Standard Industrial Classification of economic activities
SPC: Shadow Price of Carbon
TFA: Total Floor Area
TRV: Thermostatic Radiator Valve
UK: United Kingdom
UNEP: United Nations Environmental Programme
UNFCCC: United Nations Framework Convention on Climate Change
USGBC: United State Green Building Council
VAT: Value Added Tax

GLOSSARY OF KEY TERMS AND DEFINITIONS

S/N	Term	Definition
1.	**Building Energy Management System (BEMS)**	This is a powerful tool for energy management in buildings and not a substitute. It involves the installation of a system that is computer-controlled and integrates the energy-using services and facilities in a building. It allows the facilities to be centrally managed by controlling the energy-consuming equipment to reduce energy use while maintaining a comfortable environment
2.	**Carbon footprint (CF)**	This is a measure of the total amount of greenhouse gas (GHG) emissions that are directly and indirectly caused through the activities of an individual, organisation, event, or product, or accumulated over the life stages of a product. It is expressed as a carbon dioxide equivalent
3.	**CO_2-eq**	This is the concentration of CO_2 that would cause the same level of radiative forcing as a given type and concentration of GHG
4.	**Direct emissions**	These are emissions accruing from sources that are owned or controlled by an organisation. They are also called on-site or scope 1 emissions
5.	**Direct Requirement Coefficient Matrix**	This is also called the Technology Matrix in input-output analysis and represents the matrix of direct deliveries required to produce a product per unit of the total output

6.	**Downstream emissions**	These relate to the emissions that accrue in the lifecycle of goods and services subsequent to sale by the reporting organisation. These include the emissions by customers enabled through the purchase of these goods and services. Downstream emissions are part of scope 3 emissions as defined by the GHG Protocol.
7.	**Embodied CO_2-eq**	This is the equivalent carbon dioxide discharged into the atmosphere due to the energy embodied in a particular product
8.	**Embodied CO_2-eq Intensity**	This is the embodied CO_2-eq of a product per unit output, measured in terms of £, m^2, kg etc.
9.	**Embodied Energy**	This is the measure of all energy input that goes into the production of any given product. It includes energy used in the extraction of raw materials, processing, manufacture, transportation, delivery to the site, construction, renovation and maintenance, final knocking down as well as all the activities and processes along the supply chain
10.	**Emission factors**	This is the average emission rate of a given pollutant from a given source relative to the intensity of a specific process or activity
11.	**Energy and emission policies**	These are policy instruments developed to encourage the reduction of energy consumption, promote energy efficiency and conversion processes, renewable energy supplies, etc., and the reduction of discharge of emissions into the environment

12.	**Epistemology**	This refers to the extent to which reality can be known (i.e. the assumptions that are made regarding the nature of the knowledge of the human and how such knowledge is obtained and understood)
13.	**Feed-in-Tariff (FiT)**	This is a grant scheme that was introduced in April 2010 by the UK Government. It is part of a range of measures acting as drivers for a more rapid deployment and uptake of renewable energy generation technologies with a view to reducing demand
14.	**Greenhouse Gases**	These are gases in the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. They are responsible for the heating of the earth in what is known as the greenhouse effect. The most common GHGs include carbon dioxide (CO_2), methane (CH4), nitrous oxide (N_2O), hydro fluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6)
15.	**Hybrid Embodied Energy Analysis**	The systematic integration of the specificity of process analysis with the completeness of input-output analysis. By combining the benefits of both process and input-output analysis, fundamental errors and limitations associated with each method can be eliminated, improving both accuracy and precision
16.	**Indirect emissions**	These are emissions that are a consequence of the operations of an organisation, but occur at sources not owned or controlled by them. These include scope 2 and 3 emissions as defined by the GHG Protocol

17.	**Input-Output analysis**	The input-output approach to lifecycle assessment operates through the tracking of all economic transactions between different sectors within an economy and the consumers. It is an economic modelling method that facilitates the understanding of the interactions between economic sectors of a country, the producers, and the final consumers
18.	**Input-Output tables**	These are tables in the form of matrix, which provides a complete picture of the flows of products and services in an economy for a given year, illustrating the relationship between producers and consumers and the interdependencies of industries. The tables are usually compiled by the national government
19.	**Interactions**	This is a phenomenon that arises when the GHG emission savings potential of a measure is reduced due to the fact that another measure has been previously implemented. It usually arises between different types of abatement measures that act on the same end user
20.	**Leontief Inverse Matrix**	This is the matrix of cumulative (direct and indirect) deliveries required to produce a product per unit of total output, and it can be approximated by the power series approximation of the matrix of direct requirement coefficient
21.	**Life Cycle Assessment**	This is a well-established systematic approach used for the identification, quantification, and assessment of environmental impacts throughout the lifecycle of an activity, product, or process

22.	**Marginal Abatement Cost Curve**	In simple terms, MAC, expressed in cost per ton of GHG emissions saved, is the additional cost of abating an additional ton of GHG above what would be achieved in a “business as usual” context. Therefore, a MACC is a graphical device that combines the MACs of available abatement projects to facilitate decision making. MACCs are a useful tool to identify options that deliver the most economically efficient reductions in GHG and prioritise mitigation options based on certain criteria
23.	**Midstream emissions**	These are indirect (scope 3) emissions associated with the activities of an organisation but not caused by suppliers (upstream) or customers (downstream). E.g. an employee commuting to and from the workplace
24.	**MRIO framework**	A Multi Region Input-Output (MRIO) framework allows for the estimation of the environmental loads (embodied emissions) and implications of consumption associated with international trade flows regarding GHG emissions associated with the options. The framework allows for the tracking of the production of a given product in a given economic sector, quantifying the contributions to the value of the product from different economic sectors in various countries or regions captured in the model
25.	**On-site emissions**	These forms of emissions are those from sources that are owned or controlled by a company or an organisation. They are also known as direct or Scope 1 emissions
26.	**Ontology**	This phenomenon relates to the nature of reality regardless of human attempts to understand it

27.	**Overlap**	This is a form of interaction that comes into play when "like for like" abatement measures are used to actualise the same result under different circumstances. Overlap also arises when a measure cannot be implemented because another measure that is deemed to have a better cost-effectiveness has already been implemented
28.	**Pareto optimisation**	This is also called Pareto efficiency or Pareto optimality and is named after Vilfredo Pareto. The concept is a state of allocation of resources in which it is impossible to make any one individual better off without making at least one individual worse off. It is employed when a solution is required in the midst of conflicting objectives where there are reasonable trade-offs among them. With the Pareto Optimisation scheme, rather than generating a single optimal solution, a myriad of solutions are generated that satisfy the Pareto Optimality criterion. The criterion is such that a solution point P is accepted only if there are no solutions better than P with respect to all the objectives
29.	**Performance validation**	This involves the assessment of the performance aspects of a system with the view to ascertain how effective its mode of operation is, how well it performs its functions, and the extent to which the knowledge base of the system is accurate and complete
30.	**Process Analysis**	The measurement in physical terms of all the energy and material flow that goes into the manufacturing of a product to produce a unit output undertaken at an industrial level