ROUTLEDGE HANDBOOKS

The Routledge Handbook of Embodied Carbon in the Built Environment

Edited by Rahman Azari and Alice Moncaster

THE ROUTLEDGE HANDBOOK OF EMBODIED CARBON IN THE BUILT ENVIRONMENT

This handbook explores the critically important topic of embodied carbon, providing advanced insights that focus on measuring and reducing embodied carbon from across the built environment, including buildings, urban areas and cities, and construction materials and components.

Split into five distinct sections, international experts, researchers, and professionals present the recent developments in the field of embodied carbon from various perspectives and at different scales of material, building, and city. Following an introduction to the embodied carbon question, the chapters in Section 1 then cover the key debates around issues such as the politics of embodied carbon, links between embodied carbon and thermal mass, and the misuse of carbon offsets. Section 2 reviews the embodied carbon policies in a selected number of countries. Sections 3, 4, and 5 approach the topic of embodied carbon from urban-, building-, and material-scale perspectives, respectively, and use case studies to demonstrate estimation techniques and present opportunities and challenges in embodied carbon mitigation.

This will be important reading for upper-level students and researchers in Architecture, Urban Planning, Engineering, and Construction disciplines. Presenting case studies of embodied carbon assessment, this book will also help practicing architects, engineers, and urban planners understand embodied carbon estimation techniques and different mitigation strategies.

Rahman Azari, PhD., is an architect, Associate Professor of architecture, and Director of the Resource and Energy Efficiency [RE2] Lab at the Pennsylvania State University (USA). Azari is also affiliated with the Penn State Institute of Energy and the Environment (IEE), the Hamer Center for Community Design, and the Stuckeman Center for Design Computation (SCDC). Azari's research on carbon-neutral buildings and cities has been supported by research grants from the US Department of Energy (DOE), the Council on Tall Buildings and Urban Habitat (CTBUH), and the American Institute of Architects (AIA).

Alice Moncaster, PhD., is a civil and structural engineer by background, whose work in industry has strongly influenced her subsequent career in academia. She is Professor of Sustainable Construction at the University of the West of England, and retains visiting positions at her two previous institutions, the Open University, and the University of Cambridge. She has been one of the UK experts for the International Energy Agency Annexes 57, 72, and 89 working with colleagues from around the world on developing a better understanding of embodied and whole life carbon of buildings, and on its implementation into policy and industry practice.

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This book is dedicated to
Nasrin Davatgar, Hilda Azari, Shahnaz Mahmoodian,
and Hassanali Azari
Richard Bridgeman, and Poppy and Cicely Moncaster Bridgeman

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CONTRIBUTORS

Jane Anderson is an internationally recognized expert in LCA for the construction industry (UK).

Rahman Azari is Associate Professor in the Stuckeman School of Architecture and Landscape Architecture at the Pennsylvania State University (USA).

Lola Ben-Alon is Assistant Professor in the Graduate School of Architecture, Planning, and Preservation at Columbia University (USA), where she directs the Natural Materials Lab.

Harpa Birgisdóttir is Professor in the Department of the Built Environment at Aalborg University (Denmark).

Morten Birkved is Professor in the Department of Green Technology at the University of Southern Denmark.

William Braham is Professor of Architecture at the Weitzman School of Design at the University of Pennsylvania (USA).

Stefan Bringezu is Professor of Sustainable Resource Management at the Centre of Environmental Systems Research at the University of Kassel (Germany).

Giulia Celentano is a senior researcher at the Chair of Sustainable Construction at ETH Zurich (Switzerland).

Shaoqing Chen is Professor of Urban Environmental Management and Climate Change Mitigation at Sun Yat-sen University (China).

Bernardino D'Amico is Associate Professor in the School of Computing Engineering and the Built Environment at Edinburgh Napier University (UK).

Benjamin P. Goldstein is Assistant Professor of Environment and Sustainability at the School for Environment and Sustainability at the University of Michigan (USA).

Jonathan Grinham is Assistant Professor in Architecture at the Graduate School of Design at Harvard University (USA).

Srinivasa Raghavendra Bhuvan Gummidi is an Assistant Professor in the Department of Green Technology at the University of Southern Denmark.

Guillaume Habert is Full Professor at ETH Zurich (Switzerland) and head of the Chair of Sustainable Construction.

Tarja Häkkinen is Senior Research Scientist at the Finnish Ministry of the Environment (Finland).

Miaomiao Hou is a postdoctoral researcher in Net-Zero Carbon Building at the Harbin Institute of Technology (China).

Klaus Hubacek is Professor of Science, Technology, and Society at the University of Groningen (the Netherlands).

Borja Izaola is a PhD Candidate in the Life Cycle Thinking Research Group at the University of the Basque Country and a former LIFE Levels Project Coordinator at Green Building Council (Spain).

Ben James is a PhD student researcher at the Belfast School of Architecture and the Built Environment at Ulster University (UK).

Derek Jones is Senior Lecturer in Design at the School of Engineering and Innovation at the Open University (UK).

Thomas Jusselme is Associate Professor in low-carbon buildings at the University of Applied Science of Western Switzerland (Switzerland).

Bradley Kloostra is a professional with a Master of Applied Science degree from the Department of Civil & Mineral Engineering at the University of Toronto (Canada).

Matti Kuittinen is Senior Ministerial Advisor at the Finnish Ministry of the Environment and a Professor of Sustainable Construction at Aalto University (Finland).

Maud Lanau is Assistant Professor of Building Technology at Chalmers University of Technology (Sweden).

Gang Liu is Professor at the College of Urban and Environmental Sciences in Peking University (China).

Tove Malmqvist is Senior Researcher and docent in the Division for Sustainability Assessment and Management at the KTH Royal Institute of Technology (Sweden).

Matan Mayer is Associate Professor of Architecture at IE University (Spain).

Christoph Meinrenken is Associate Professor of Professional Practice in the School of Professional Studies at Columbia University (USA).

Alice Moncaster is Professor of Sustainable Construction at the University of the West of England (UK).

Clemens Mostert is Scientist at the Chair for Sustainable Resource Management at the University of Kassel (Germany) and a Professor for Environmental Engineering at the IU International University.

Esther Obonyo is Associate Professor of Engineering Design and Architectural Engineering at the Pennsylvania State University (USA).

Bruno Peuportier is Senior Scientist at Mines Paris, PSL University, and Professor at Ecole des Ponts ParisTech (France).

Francesco Pomponi is Visiting Professor at Edinburgh Napier University, Honorary Professor at the University of Cape Town, and a Senior Associate at Cambridge University.

Suryakiran Prabhakaran is Building Performance Researcher at KieranTimberlake (USA).

Yasmine Dominique Priore is Research Assistant at the Energy Institute of the University of Applied Science of Western Switzerland and a PhD candidate at the Chair of Sustainable Construction at ETH Zurich (Switzerland).

Freja Nygaard Rasmussen is Associate Professor in the Department of Civil and Environmental Engineering at the Norwegian University of Science and Technology (Norway).

Husam Sameer is a postdoctoral researcher in the Faculty of Civil and Environmental Engineering/Engineering Hydrology and Water Resources Management, Ruhr-Universität Bochum, Bochum (Germany).

Shoshanna Saxe is Associate Professor in the Department of Civil & Mineral Engineering at the University of Toronto (Canada).

Patrick Schalbart is Senior Scientist in the Centre for Energy Efficiency of Systems at Mines Paris, PSL University (France).

Yuli Shan is Associate Professor in Sustainable Transitions at the University of Birmingham (UK).

Joshua L. Sohn is an LCA expert at Nike in Oregon (USA).

David Tilley is Associate Professor in the Department of Environmental Science and Technology at the University of Maryland (USA).

Aoife Houlihan Wiberg is Associate Professor of Architecture in the Department of Architecture and Civil Engineering at the University of Bath (UK) and formerly, Professor of Architecture and Chair of Research in Architecture at the Belfast School of Architecture & the Built Environment (UK).

Lynnette Widder is Associate Professor of Professional Practice in Sustainability Management at Columbia University (USA).

Freya Wise is a postdoctoral researcher and visiting fellow in the School of Engineering and Innovation at The Open University (UK).

PREFACE

This book is launched in a period of unprecedented growth in awareness, when nations, industries, and individuals across the world are waking up to the devastating impacts of climate change and their own responsibilities. Designers of buildings have long seen themselves as embracing the future; it is now becoming clear that that future is being blighted, and that the built environment is a major contributor to that blight. Constructors of buildings have historically been far slower to change methods and materials, highly averse to what they see as risk; it is now becoming clear that the risks being avoided were far from those causing the greatest harm.

So what does climate change mean for the designers and constructors of our built environment, and for the financers and the policy makers? How should they, how should *we*, be responding? This book attempts to answer these questions. It is a resource for academics and students; for practitioners, including the many engineers and architects and developers who find themselves working in a world for which they have been ill-prepared by their education and professional training; and for all those working at a policy level trying to produce regulations and approaches that will rapidly reduce the impact of the built environment on the climate.

The papers on which the book is based were initially presented to an international audience at the 2022 Embodied Carbon Symposium (embodied-carbon.org). The symposium was supported and co-chaired by our excellent colleague Freja Nygaard Rasmussen, Associate Professor at the National Technical University of Norway in Trondheim, and author of chapter 8, who was instrumental in developing some of the first national regulations for reducing embodied greenhouse gas emissions from buildings. The two amazing keynote speakers were Luke Leung, Sustainability Engineering Studio Director of global design practice, Skidmore Owings & Merrill, and Stephen Richardson, European Director of the World Green Building Council and their representative on the EU Sustainable Finance Platform. Both speakers made the point that growth in awareness is not enough – what is needed is action. Their passion and belief that we can and will change, that the built environment can be redefined and reconstructed to provide shelter without destroying the planet, is both infectious, and utterly necessary.

Alice Moncaster and Rahman Azari

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ABSTRACTS

Chapter 1

Rahman Azari and Alice Moncaster

Introduction to Section 1

Chapter 2

Alice Moncaster

Embodied carbon (EC) has long been a thorny issue, for many years excluded from policy and regulation. Definitions of 'zero carbon' have been framed to include only operational impacts, encouraging improvements in energy efficiency but continuing to promote construction. With the embodied impacts of new buildings responsible for 9 to 10% of global carbon emissions each year, this chapter considers the reasons why it has taken so long for this issue to start to be regulated. Through a case study of the introduction of zero carbon in the UK, it reveals policy development as a contest over both what is important and who controls the narrative. It also shows how policy works through and sometimes against industry experts, and how percentages can be used to support arguments while obscuring their impact.

Many other chapters in this book will provide evidence of the extent of embodied impacts, and of the imperative to reduce them. This chapter instead considers the political history of what has happened and why, in order to understand what is needed to accelerate real transition. Rather than the politically attractive (and espoused) target of 'net zero' new buildings, the chapter proposes the radical reduction of construction, including that of both buildings and the infrastructure that supports them. This will need radical, not incremental, change, and must be measured in absolute reductions of greenhouse gas (GHG) emissions, not percentages. It is no longer enough for professionals and academics to understand how to calculate embodied impacts; we must also understand the role that politics has had, and continues to have, in order to be able to steer a new course.

Chapter 3

Guillaume Habert

International Panel for Climate Change (IPCC) recommends reaching carbon neutrality in the next 20 years. The challenge seems gigantic, and to be honest, out of reach. The built environment is under high pressure as it represents 40% of greenhouse gas (GHG) emissions and embodied emissions coming from building materials production are considered among the most difficult industrial sector to decarbonize. What should we do?

What if we choose to live with what we have rather than seek what we don't have? What if we decided that human activities had caused enough destruction to the Planet and agreed that we should not disturb it more? And more fundamentally, what if we stopped waiting for new technologies that will solve all our problems but unfortunately do not exist yet?

What if we just defined, right here, right now, with the technologies, the knowledge and the collective intelligence we have, pathways that will guide us towards a climate-neutral and circular built environment in a desirable way.

This is the overall objective of this chapter. We will first identify what is possible and can be directly implemented within existing standards. The chapter will focus on excavation materials, reinforced concrete, timber and insulation materials as main construction materials and show first that it is possible to build climate-neutral buildings with the appropriate combination of such materials; and secondly that we have enough resources. No time to wait for the silver bullet that will save us all. It doesn't exist… or if it does, it will arrive too late.

Chapter 4

Bernardino D'Amico and Francesco Pomponi

The climate change burden associated with buildings and construction is being increasingly recognised globally by the many stakeholders involved. For decades, there has been an unnecessary divide between the operational and embodied impacts of buildings, with the former attributed to the energy sector and the latter attributed to (yet mostly ignored by) the construction industry. This has shadowed the real size of the environmental impacts of buildings and construction but at last, there is an increasing trend to look at buildings in their entirety, which has revealed the enormous challenge that lies ahead to decarbonise our built environments.

Given the above, and the technicalities of the construction sector (which is the major user of hard-to-decarbonise materials such as steel and cement), there is an emerging consensus that net zero targets can only be realistically achieved through the inclusion of carbon offsets, as acknowledged by the World Green Building Council (WGBC) in its Net Zero Carbon Building Commitment. In short, these are carbon accounting mechanisms whereby the remaining emissions in a project or product that cannot be further lowered with optimization, efficiency, or technological gains, are offset by financing projects aimed at reducing greenhouse gas (GHG) emissions. These projects may include carbon capture and storage (CCS), biogenic uptake and sequestration (e.g. planting trees or preserving forests), development of renewable energy generation (wind, solar, etc.), or any other intervention project for which a reduction in GHG impacts can be credited.

Carbon offset schemes (and their trading markets) are booming. As instruments to tackle the climate crisis, their value depends on how the associated credit is measured and hence certified. Outcomes can range from effectively drawing down GHG concentration in the atmosphere, to the most common greenwashing and marketing mechanisms. Currently, both carbon removal and carbon avoidance offsets can be used for net zero reporting of buildings and construction projects. In this chapter we demonstrate, using causal reasoning and a simple thought experiment, that an offsetting project should be assigned a carbon credit only if a physical (empirically measurable) net reduction in atmospheric concentration occurs (carbon removal). Our argument hence dismisses carbon offsetting schemes which are based upon counterfactual baseline scenarios of avoided emissions; financing a carbon avoidance offset, rather than a carbon removal offset, results in emission reductions that are non-existent (best case), or in an increase in atmospheric GHG concentrations (worst case). We demonstrate that if every single carbon-emitting activity on this planet (including buildings and construction) is offset with a carbon avoidance scheme, we would achieve the paradoxical result of a *net zero* global society with rising GHG concentration levels.

Chapter 5

Matan Mayer and Jonathan Grinham

Globally, carbon-neutral design targets are transitioning from a focus on exclusively offsetting operational emissions to a focus on offsetting life cycle emissions more broadly. While this shift represents a relatively direct transformation for static systems like structure or cladding, it implies significant challenges for thermal regulation systems. In operating-centered low carbon design schemes like Passivhaus or LEED, thermal regulation insufficiencies are addressed through additional thermal resistance or additional mechanical systems. Both options are environmentally prohibitive when material-related carbon emissions are considered. This situation is even more severe in cold climates or in regions that experience large amplitudes between daytime and nighttime temperatures. In those instances, increased thermal mass is a vital component in any successful low-operational carbon strategy to maintain thermal comfort. Within this context, the chapter aims to examine and characterize the often-conflicting link between embodied carbon and thermal mass. An analysis workflow for exploring this link for a range of material groups is presented and the results are reviewed. The chapter concludes with a discussion regarding the applied implications of this work and future research trajectories.

Chapter 6

Alice Moncaster and Rahman Azari

Introduction to Section 2

Chapter 7

Rahman Azari

Environmental impacts of buildings, especially their embodied carbon, have been extensively documented and it is imperative that we take measures to quantify, mitigate, and even reverse them if we want to restrict global warming to below 1.5°C increase above the preindustrial levels. This chapter posits that embodied carbon is but one piece of the broader paradigm shift underway in all sectors, including the construction industry, which is moving towards net-zero emission status. This work then delves into the urgency of addressing embodied carbon, given the vast scale of the construction industry and its environmental footprint, both in North America and around the world. It also provides a review of the current regulations and policies in North America at the city, state, and national levels that aim to tackle this issue. The chapter then reports on the life cycle assessment of a case study, designed to meet a specific embodied carbon intensity target. Finally, this chapter concludes with an exploration of the barriers that must be overcome to achieve embodied decarbonization.

Chapter 8

Freja Nygaard Rasmussen, Harpa Birgisdóttir, Tove Malmqvist, Matti Kuittinen, and Tarja Häkkinen

Initiatives on operational carbon have been an integrated part of legislation in many countries for decades, but the issue of embodied carbon is just starting its breakthrough in a regulatory context. This chapter provides an account of how the introduction of LCA-based limit values for whole-life-carbon has been approached in Finland, Sweden and Denmark. The starting point for these whole-life-carbon declarations have been the policies outlined via national climate acts, and there has been extensive knowledge exchange between the three neighbouring countries. Still, the LCA-based assessment methods outlined for the regulation have taken significantly different paths. For instance, the Swedish approach focuses on the upfront carbon from production and construction processes, whereas the other two approaches include the use- and the end-of-life stages. The methodological variations reflect the different national weightings between the ease-of-application for users and the accuracy-to-scope of the building model and its real life-cycle impact. All three approaches have drawn up reference values for typical buildings, and have already, or are planning to, introduce politically defined limit values for new buildings. At the same time, distributions from a global carbon budget approach show large discrepancies between the emsissions 'allowed' for new constructions (<2 kg CO_2e/m^2/year) and the limit- and reference values in place for the countries (around 9–15 kg CO_2e/m^2/year). This makes it clear that additional giant leaps are needed for policies in the building industry to operate within the planetary boundaries.

Chapter 9

Yasmine Dominique Priore, Guillaume Habert, and Thomas Jusselme

Stringent limits and reduction strategies paths on greenhouse gas (GHG) emissions are being defined at different levels to limit global warming. Carbon budgets and impact reduction targets are the main instruments used today to set goals and follow progress across industrial sectors and countries (e.g.: IPCC, Paris Agreement, science-based targets, etc.). In this context, translating global goals to local realities implicates a set of different challenges. Standardized methodologies of allocation can support a target-cascading process. On the other hand, local strategies are not currently designed to directly respond to carbon budgets in a 2050 horizon. The life cycle analysis of buildings implicates an intricate cross-industry and cross-border carbon accounting. For these reasons, effective and aligned targets are needed to support and guide all actors in the construction sector. This chapter aims at addressing these challenges by identifying carbon reduction strategies compliant with a limited carbon budget in a dynamic approach using the Swiss built environment as a case study. This approach allows for the assessment of current best practices in regard to limited budgets and the determination of specific dynamic carbon targets for the building stock. Results show the misalignment of global goals with current practices and present the magnitude of effort that would be required to have a chance to limit global warming to 1.5°C or 2°C. An adequate, interconnected, and interdisciplinary carbon-targets definition is needed to align stringent global climate goals with local climate strategies. The proposed methodology allows for this definition at different scales and sectors in a specific context.

Chapter 10

Borja Izaola

European countries are committed to leading climate change mitigation action in all sectors, including the building sector. In recent years, limiting values to GHG emissions of building materials, techniques, and ultimately whole buildings, are pushing a new paradigm of low-carbon construction. To set policies, a whole array of research projects, standards, methodologies, and related market and regulatory innovation is needed.

This chapter introduces relevant initiatives focusing on reducing the embodied carbon of buildings: GHG emissions associated with the life cycle of a building, operated under CO2 metrics standardized in European Norms such as the EN15978. A common language and methodology have been adopted at the Level(s) Framework to include other sustainability indicators for European buildings. This has set in motion best practices and projects.

Carbon metrics are to be seen as the spearhead of other environmental metrics that help understand the multifaceted impact of buildings. Innovative and updated traditional solutions are needed to meet the challenges of climate change, biodiversity loss, and resource deployment. Every agent must engage responsibly in pursuing common goals. Some good practices can be seen here.

Chapter 11

Aoife Houlihan Wiberg, Ben James, Alice Moncaster, Freja Nygaard Rasmussen, Tove Malmqvist, and Harpa Birgisdottir

A climate emergency has been declared and government, policymakers, industries, researchers and architects have tremendous potential to shift the entire industry towards a (net) zero greenhouse gas (GHG) emissions-built environment. In particular, they all play a different but equally important role in the early design phase when there is the greatest opportunity to make design decisions that can directly lead to buildings that reduce their overall GHG emissions towards zero within their life cycle. This chapter is specifically aimed at the role of building designers.

Buildings account for 40% of total GHG emissions and are one of the main contributors to the climate crisis. Recent results show that as net zero emission buildings become more highly efficient, the contribution from EEG (embodied energy and greenhouse gases) increases, thus underlying its growing importance. Life Cycle Assessment (LCA) is used to assess embodied carbon and to provide early phase feedback in order to compare the environmental impact of different material, design and construction choices in buildings. However, it is still a relatively new method, and many designers often find it difficult to interpret the results in order to understand how a particular material, component and/or design proposal contributes to the overall GHG emissions in the built environment. This lack of fundamental knowledge and understanding presents a significant barrier to industry uptake and decarbonisation of the built environment.

This chapter reports results from the International Energy Agency (IEA) EBC Annex 57 (subtask 4) using data from 80 international case studies, which were collected and systematically analysed alongside supporting data from the literature. The research findings are communicated through simplified diagrams and concise text presented in tabular form where possible, in order to support designers and other non-expert decision makers in the early stage design process. The results presented in this chapter offer a simple and easy to understand visual communication to help develop industry knowledge of net zero and embodied carbon, to help improve participation from key decision makers and more easily integrate science-based knowledge on embodied carbon in industry and in the mainstream.

Chapter 12

Rahman Azari and Alice Moncaster

Introduction to Section 3

Chapter 13

Klaus Hubacek, Yuli Shan, and Shaoqing Chen

More than half of the global population now lives in cities, and the share of the urban population is projected to further increase to about two-thirds by 2050. The majority of human economic activities, 80% of global GDP, 60% to 80% of final energy consumption, and 75% of final-energy-use carbon emissions are related to urban activities. Therefore, cities are central to climate change mitigation. Given the fact that global supply chains play a significant role in urban activities, cities predominantly rely on their hinterlands to supply the resources they need. When accounting for emissions associated with the entire supply chain of products that enter the city for further processing or consumption, so-called consumption-based emissions (CBE), typically, more than half of emissions of cities are imported from outside their borders. Thus, it is important to distinguish between different scopes of urban emissions. Different accounting scopes, such as production-based emissions (PBE) and CBE, may lead to significant differences in emission patterns of cities and may greatly change the interpretation of the success of cities' carbon mitigation efforts. This chapter provides a brief summary of the relevant literature on urban carbon footprints with a specific focus on different system boundaries and embodied carbon emissions. We show how the choice of a footprint metric will influence the outcome of carbon accounting, mitigation policies, and policy evaluation.

Chapter 14

Srinivasa Raghavendra Bhuvan Gummidi, Benjamin P. Goldstein, Joshua L. Sohn, Maud Lanau, Morten Birkved, and Gang Liu

Constructing buildings and infrastructure in cities generates immense emissions of carbon dioxide. Understanding these emissions can aid in low-carbon urban planning and development. Current efforts to estimate these emissions use the *Carbon Replacement Value* method, which calculates the carbon cost of replacing the urban stock using current technologies. The CRV is useful for forecasting the carbon costs of near-term urban development. However, the perspective of historical emissions from technologies from the time of construction is missing. Quantifying historical emissions would improve our understanding of the embodied carbon spent to build the cities we live in today. This study proposes a methodology to estimate the *Sunk Carbon Cost* of urban material stocks. This method combines urban material cadastral maps with temporally dynamic life cycle assessment (LCA) of previous construction technologies to quantify and spatialize the historical carbon investment in the urban built form. We demonstrate the method by estimating the historical carbon emissions from concrete in all construction since 1961 (~105,000 individual buildings) in the city of Odense, Denmark. We estimate that 20.2 Mt of concrete was used in these buildings which released 3.0 Mt of carbon dioxide. We find that the sunk carbon cost for all construction since 1961 may be up to ~36% greater than estimates using carbon replacement value, but that these differences decrease for newer buildings. The spatial analysis identifies low-density settlement patterns as spatial hotspots of historical emissions, highlighting the material and carbon efficiencies of high-density neighborhoods. Applying this method to a city's entire material stock can identify hotspots of embodied emissions across the urban fabric and suggest how to best utilize spent carbon through the adaptive reuse of existing buildings and low-carbon urban design.

Chapter 15

Shoshanna Saxe and Bradley Kloostra

This chapter explores the embodied GHG in transportation infrastructure focusing on land-based passenger transportation. The chapter discusses the data needed to calculate embodied GHG emissions and the breakdown between A1 and A3 emissions and A4/A5, which are often a larger percentage of embodied GHG in transport infrastructure than in buildings. The chapter includes approximate examples of embodied GHG in road, rail, and active transport infrastructure using global average GHG impact factors for concrete, asphalt, granular material, and steel rebar and provides references to the literature where more detailed calculations are published. Finally, the chapter discusses the consequential embodied GHG impacts of transportation infrastructure choice on other aspects of the built environment.

Chapter 16

Rahman Azari and Alice Moncaster

Introduction to Section 4

Chapter 17

Bruno Peuportier and Patrick Schalbart

In France, the first applications of life cycle assessment (LCA) in the building sector began in the 1990s, according to a common framework sketched in a European project in collaboration with Swiss/German and Dutch partners. LCA is now included in the next French building regulation that will be implemented in January 2022. It was extended to the scale of urban projects in 2006. This chapter presents the modelling approaches, and example applications, and discusses limits leading to propose perspectives for further work. The long life span of buildings induces large uncertainties regarding the effect of climate change on heating and cooling loads, the long-term evolution of the electrical system, waste treatment processes, etc. Uncertainty evaluation and robust optimisation could increase the reliability of LCA, which would be useful for the wider dissemination of this method among decision makers, particularly in early design phases. LCA should not be limited to the simple application of meeting regulation requirements; the tool is also very useful as a design tool, based upon a methodology corresponding to this design-aid objective. Tools like BIM and parametric design could also facilitate the integration of LCA into the design process. In the upstream of the design phase, environmental performance targets should be integrated into clients' briefs.

Chapter 18

Husam Sameer, Clemens Mostert, and Stefan Bringezu

The construction industry is one of the leading industries responsible for the environmental impacts of the economy. Implementing ambitious climate protection and resource efficiency measures is a prime environmental policy target and becoming a top priority of many worldwide policies. This chapter describes the method, indicators, and a case study to reduce Greenhouse Gas (GHG) emissions in the built environment with regard to resource efficiency. An approach for the assessment of resource and climate footprints in building information modelling (BIM) is presented. Sustainable resource application (SURAP) is used for the footprint modelling in Autodesk Revit software. The material footprint is determined by the Product Material Footprint (PMF) using two indicators including Raw Material Input (RMI) and Total Material Requirement (TMR), and the water footprint is defined by the Available Water Remaining (AWARE) method. The climate footprint is quantified using the Global Warming Impact (GWI) indicator with the Global Warming Potential (GWP)-values according to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). The results of the case study show that the material footprint is dominated by the floors and foundation building elements. Concrete production has a relatively high material footprint while the production of cement screed and linoleum flooring has a relatively high climate and water footprint. The approach presented in this chapter is limited as it does not consider the use phase of the building and the land footprint has not been yet integrated into the assessment of the resource footprint.

Chapter 19

Giulia Celentano, Esther Obonyo, and Guillaume Habert

Our world and society are facing contingent challenges, these being the need of dignified housing for the present and raising population, and immediate solutions in response to the climate crises. The two are critically intertwined, with the construction sectoring significantly impacting on the environmental crises. This is done at the expenses of the most vulnerable, embracing the informal population of the Global South. A reflection on this topic of environmental injustice is required in order to identify responsibilities and put the pressure for immediate actions onto the relevant stakeholders and entities.

From a technical perspective, a diversity of options are available to accommodate a more safe, and sustainable building stock, with bio-based solutions and specifically fast-growing species being of tremendous interest due to their carbon storage capacity. While diversity within implementation strategies is key to achieve success at scale, bottlenecks still prevent reaching the rapid results needed to achieve the targeted transition towards a safe dignified habitat for all. The challenge is to be addressed with a systemic perspective, including enhanced normative frameworks and a trans-sectoral approach to facilitate engagement and benefits of all stakeholders.

In line with such transdisciplinary approach, reflections on the positive contribution of construction-related projects to the socio-technical system of the informal city is presented, based on learnings from Nairobi, Cape Town, and Bangkok. The approach is operationalized into a Regenerative Framework with reference to the SDG Goals, of support within the planning and implementation of housing construction projects in the informal cities.

Chapter 20

Freya Wise, Alice Moncaster, and Derek Jones

There is a critical need to reduce energy and associated carbon emissions from the existing built environment to help mitigate climate change. This requires significant upscaling of energy retrofitting. However, at present, retrofit assessments commonly consider only the operational impacts, neglecting the embodied carbon of measures. If retrofits are to make the greatest lifecycle savings, this embodied carbon should clearly be included.

This chapter assesses the embodied carbon of 40 retrofit measures, chosen as options to retrofit 13 residential heritage buildings in northern England. The assumptions and decisions made in the assessment process and the suitability of the international lifecycle assessment (LCA) standard EN 15978 – designed primarily for new construction – for heritage retrofit are discussed. The contribution of the different lifecycle stages is assessed, and the total embodied carbon of the different measures is identified.

Embodied carbon costs varied significantly across the different measures and material options, while in many cases offering similar operational carbon savings. In some cases, lifecycle stages which are often deemed insignificant were found to have a substantial impact on total embodied carbon. The study also identified a lack of available LCA data for some measures and noted a number of areas where EN 15978 was challenging to apply for retrofit projects.

These findings emphasise the importance of assessing embodied carbon for energy retrofitting, including as many lifecycle stages in the assessment as possible, and increasing the availability of LCA data for retrofit measures. Greater attention to this issue is needed to maximise lifecycle savings from the retrofit of existing buildings and thus help to mitigate climate change.

Chapter 21

Alice Moncaster and Rahman Azari

Introduction to Section 5

Chapter 22

Jane Anderson and Derek Jones

Environmental Product Declarations (EPD) provide information on the environmental impacts associated with products over their lifetime. In the construction industry, they have been developed to provide environmental data for use in building level life cycle assessments, and the European Standard EN 15804 has been developed to ensure consistency and enable their straightforward use at building level using EN 15798 and for infrastructure using EN 17472.

The reported embodied carbon impacts of a construction product can vary significantly and many examples of variation can be found in even a cursory search of the academic literature, including that focused on EPD. However there is rarely an explanation of the causes of variation, and the literature often includes suggestions that EPD are not robust or credible, because the large variation in impact seen must be indicative of methodological problems.

This leads to two problems. Firstly, our understanding of variation in EPDs remains incomplete and inadequate. We have little specific understanding of the types and causes of variation, and their significance for different product groups.

Secondly, continually focusing on EPD variation without studying cause or effect, leads to repetition of general statements about the reliability and data quality of EPD, and this has potentially had an impact on the take-up and use of EPDs in practice and policy. It also seems to assume some future state that, once a perfect methodology has been decided on, it will then provide perfect EPD without variation, and only then can we be allowed to start to make decisions around carbon reduction using consistent methods and data. This approach does not seem to respond with the urgency required to address the climate emergency, nor 12% of global CO2 emissions caused by construction materials and construction processes.

By reviewing the significant number of EPDs for cement, steel, brick, sawn timber and concrete now available, this chapter explores whether technological and geographical differences could be responsible for the variations found.

A number of different factors were found to influence impacts in EPD, including technology (production methods, inputs and product design), geography (electricity and energy mix), time (e.g. changes in grid mix), methodology (e.g. choice of allocation approach and system boundary) and granularity (i.e. the specificity of the EPD). Of these, variations in impacts within EPD caused by differences in technology and geography were considered to be real (reflective of actual differences in impact between products) and were often very significant (>100%) and not normally distributed. Variations due to methodological differences did exist but were considered unlikely to be the major cause of the variations seen in the GWP impact of construction products.

Variation still remains an issue, which must be considered and addressed in product comparisons and building level assessments. However, the hypothesis, that EPD data are robust or credible because of the range of variation seen in their impacts, has been rebutted and methodological differences should not therefore be considered a reason to delay assessments of building level embodied carbon at building or infrastructure level.

Chapter 23

Lynnette Widder and Christoph Meinrenken

The growing mandate to decarbonize the built environment will of necessity include existing building stock; at present, however, much of the attention on embodied carbon accounting, whether for a building's raw materials or for its construction, has focused on new buildings. In the US, more than 90% of the building stock is estimated to be more than ten years old. Therefore, the carbon these buildings embody is not necessarily well reflected in most current databases that specify carbon emissions for raw material extraction, fabrication, or transportation processes associated with constructing a building. Instead, architectural and cultural history must be enlisted to evaluate the carbon embodied in older buildings. This is true especially if the intention is to evaluate carbon already embodied in an older building vis-à-vis the carbon associated with that building's future operation, for example, to evaluate the costs and benefits of retrofitting or demolishing a historic building.

Three tightly framed case studies demonstrate the sweep and complexity that quantifying the carbon embodied in historic building stock entails. Our case studies and the resulting carbon footprint calculations give a sense of the capacity and limitations of current emission factor databases for understanding the embodied carbon of building elements older than ten or more years. For example, changes in mechanization, timber husbandry, technology and construction practice may not be reflected in current databases. While our study is not intended as a decision-making tool when weighing embodied carbon against future operational energy improvement, it lays out considerations and approaches that could be tested and expanded to support a better understanding of carbon costs and benefits involved in replacing, upgrading or retaining existing building components.

Chapter 24

William W. Braham, Miaomiao Hou, Suryakiran Prabhakaran, and David Tilley

Buildings are a central tool of the fuel-powered civilization that has released carbon dioxide and other greenhouse gases into the atmosphere over the last century, dramatically exceeding the ability of the geobiosphere to process the waste and changing the climate as it accumulates. This chapter uses the method of emergy synthesis (with an "m") to consider the multiple natural and technological systems in which buildings are built and operated. At the largest scale, building construction and operation contributes to the massive disruption of the cycles of biologically active elements, such as carbon, nitrogen, sulfur, and phosphorous, inducing global climate change, disrupting ecosystems, and reducing biodiversity.

Like so many environmental challenges and processes, carbon emissions are a matter of finding lower-intensity means of production and more productive ways to manage waste products. Many strategies for reducing embodied carbon in building materials have been developed, but these too need to be evaluated in their full context. Current methods of assessment address the inputs and emissions from human production processes, discounting or neglecting the work of the biogeosphere to prepare and deliver materials and to absorb wastes. Emergy synthesis expands the boundaries of analysis, reinforcing the critical distinction between biogenic and earth materials revealed in the conventional analysis of global warming potential.

Chapter 25

Lola Ben-Alon

Imagine a building constructed of raw earth that was drawn directly from the building site mixed with fibrous by-products from locally grown food. By using natural and readily available building materials, embodied energy and carbon can be minimized due to savings in transportation, chemical and thermal processing, and intermediate storage. This chapter discusses the importance, challenges, and required steps to the broader implementation of using low-carbon and natural building materials in mainstream construction. The chapter first reviews the historical and contemporary use of earth- and bio-based admixtures such as rammed earth, cob, and light straw clay for environmentally sound and healthy buildings, while quantifying the environmental and addressing the social life cycle of both manually and digitally fabricated assemblies, showing that natural assemblies outperform conventional assemblies over a 50-year life span due to their initial embodied advantages. The embodied energy of the insulated natural assemblies is shown to be 55–72% lower than the conventional benchmark assemblies, resulting in 32–50% total energy reductions over both the embodied and operational phases of the building. The chapter considers possible practices and supply chain mechanisms for natural materials, termed *farm to building*. Lastly, given the enumerated advantages and identified field hurdles, recommendations are drawn for the next critical steps required for the integration of natural materials within mainstream construction, including the need to incentivize an embodied approach to mandatory energy codes.

SECTION 1

The embodied carbon questions and debates

This section will cover some of the key questions, debades and discussions around the topic of embodied carbon, from the politics of embodied carbon, to potential mitigatiation strategies, carbon offsetting schemes, and the question of thermal mass.

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INTRODUCTION TO SECTION 1 – THE QUESTION OF EMBODIED CARBON

Rahman Azari and Alice Moncaster

The need to accommodate the increasing housing and infrastructure demands of the growing global population has led to a significant rise in greenhouse gas (GHG) emissions of built environments worldwide. One of the critical dilemmas facing us in the 21st century is therefore how to meet the expanding construction demands of modern societies while simultaneously reducing the carbon footprint of the construction sector.

Regulations and practices aimed at building decarbonization are based on two distinct yet interconnected ways in which buildings contribute to GHG emissions. Energy is used and GHG emissions are released, both indirectly and indirectly, because of buildings' operations to provide heating, cooling, illumination, and power. The carbon dioxide equivalency of these emissions is referred to as ***operational carbon*** and is responsible for 27% of global emissions (IEA, 2022). Additionally, buildings consume construction materials, the production, transportation, installation, repair, and end-of-life processing of which release GHG emissions over the complete life cycle. These emissions, known as ***embodied carbon***, are responsible for part of the global warming potential of buildings and cities, caused by the way we construct them.

The focus of the present book on embodied carbon in the built environment is motivated by a complex multifaceted challenge and an exceptional opportunity. The challenge lies in minimizing embodied carbon, which accounts for a considerable 11% share of global GHG emissions (WGBC, 2019), while still constructing and renovating a substantial amount of building floor space and associated infrastructure to meet the demands of the global population in the years to come. The United Nations projections estimate 230 billion square meters (i.e., more than 2.4 trillion square feet) of new construction are needed globally by 2060, a large part of which will happen in Asia and Africa (UNEP, 2021). The World Bank calls for 300 million new homes to be built by 2030 to meet the housing demands of 3 billion people (World Bank, 2021). In the United States, a housing supply deficit of 3.8 million housing units is believed to exist that needs to be addressed (FreddieMac, 2021). At the same time, there is a huge imperative to reduce the operational GHG emissions from existing buildings. The European Union aims for the renovation of 35 million buildings by 2030 and 220 million buildings by 2050 (EU, 2020), with a total of 9.4 billion square meters (i.e., more

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than 100 billion square feet) of walls and roofs estimated to be renovated or built in Europe by 2050 (Göswein, Reichmann, Habert, & Pittau, 2021).

These enormous figures translate into massive amounts of material consumption and embodied carbon emissions. The opportunity for the construction industry is encapsulated in the transformative changes that must be made within the industry to facilitate the transition towards a more sustainable future. This book considers what must be done and how, and considers some of the key debates which are happening across multiple countries at the moment.

This book is structured into 5 Sections incorporating 25 Chapters. Section 1 presents the key questions and debates around embodied carbon in the built environment, and a short introduction is provided in the following part of this chapter. Section 2 reviews national policies and initiatives which are happening in some countries and global regions, and is introduced in Chapter 6. Sections 3, 4, and 5 present embodied carbon perspectives at different scales, covering the urban, building, and material scale; these sections are introduced in Chapters 12, 17, and 21 respectively.

Embodied carbon; some questions and key debates

In Section 1 of the present book, the authors highlight four critical issues including the politics involved in embodied carbon discussion, the possibility of achieving climate-neutral buildings using available materials and technologies, the use and misuse of carbon offsetting schemes, and the tradeoffs between embodied carbon and thermal mass.

In Chapter 2, 'Minimising embodied carbon: a question of politics, not percentages', Alice Moncaster considers the prolonged absence of embodied carbon from the national regulations and hypothesizes that this omission, offering the example of the United Kingdom, can be attributed to political motives (Moncaster, 2023). Moncaster argues that politics in one definition is about who controls the narrative of what is important and that politicians can exploit numerical data such as percentages and selectively use and interpret them to align with the interests of political parties. Moncaster puts this in the context of embodied carbon and points out to numerical data in the form of percentages, used to show the share of embodied carbon in relation to operational carbon in building carbon emissions. Moncaster highlights two problems with embodied carbon percentages: First, percentages have the inherent problem of not reflecting the actual values of the subject of measurement and can therefore be employed to distract attention where the actual values are inconvenient to communicate. Second, there is significant variation in embodied carbon percentages reported by the literature due to estimation inconsistencies, methodological assumptions, and system boundary issues.

In this chapter, Moncaster provides an example of the UK government's political approach to justifying housing provision schemes between 2003 and 2010. She demonstrates how the government excluded embodied carbon from the zero-carbon narratives, to create the illusion of reducing the carbon emissions associated with building more homes. Moncaster proceeds to describe the present status of embodied carbon regulations in the UK and shows that, although there is recognition now of embodied carbon significance, political parties still employ the percentage figures to demonstrate that more aggressive housing development plans do not adversely affect the nation's ability to adhere to carbon reduction targets by 2050.

In Chapter 3, entitled 'Climate neutral and circular built environment – right here, right now', Guillaume Habert of ETH Zurich acknowledges the gravity of the climate crisis and the need to address it (Habert, 2023). However, he also draws attention to human capacity throughout history to adapt to adverse conditions. By citing historical examples, Habert argues that humans have been able to overcome the challenges of their times through ingenuity and innovation. He contends that this same spirit of adaptation and innovation must be applied in the face of today's climate crisis.

Habert advocates for an approach that utilizes environmental flows rather than 'fighting' them. He calls for the closing of material cycles and argues that excavation materials, which constitute the majority of outgoing material flows in the built environment, should be redirected back into construction processes. He also suggests that carbon flows should be viewed as part of a broader system that encompasses human-made, biological, and geological carbon flows. By utilizing built environments, Habert proposes that carbon release from biological cycles can be slowed, while carbon capture in geological cycles can be accelerated, thus affording more time. Habert highlights various strategies for reducing carbon emissions associated with concrete through the use of available technologies. These methods include improving kiln efficiency, using low-carbon fuels in cement production, employing supplementary cementitious materials, reducing waste, optimizing structural design for efficient concrete use, and carbon capture and storage. Habert also emphasizes the potential of rapidly growing bio-based materials like straw and hemp, which have the potential to make climate-neutral buildings a reality in the short term by significantly reducing CO2 emissions from the atmosphere. In the conclusion of Chapter 3, Habert underscores the need for cultural shifts and a change in mindset to take advantage of the currently available solutions to solve the carbon emissions of built environments.

In Chapter 4 entitled 'net zero in buildings and construction: use and misuse of carbon offsets', Bernardino D'Amico and Francesco Pomponi from Edinburgh Napier University argue that carbon offsetting is a required component to achieve net-zero carbon buildings but highlight a problem in the available schemes and suggest that relying on carbon avoidance offsetting schemes is problematic when it comes to building decarbonization (D'Amico and Pomponi, 2023). They explain that there are two types of carbon offsetting schemes: carbon removal (such as tree-planting) and carbon avoidance (e.g., avoiding tree logging). While carbon removal offsets result in an actual reduction in GHG emissions, they argue that carbon avoidance schemes only maintain current levels of emissions. D'Amico and Pomponi suggest that the intended outcome of carbon avoidance schemes may also not be realized due to the presence of financial incentives for both adhering to and not adhering to such schemes. For example, while avoiding tree logging might be rewarded in an offsetting scheme, financial incentives exist for engaging in illegal logging and selling of trees. The authors conclude that it is crucial to minimize both operational and embodied carbon first, and then implement verified carbon removal offsetting schemes in order to achieve net-zero status in built environments.

In Chapter 5, entitled 'characterization of links between embodied carbon and performance of thermal mass', Matan Mayer of IE University and Jonathan Grinham of Harvard focus on thermal mass as a potential solution to meet the operational and embodied emission constraints and examine the embodied carbon performance of material properties of various thermal mass alternatives (Mayer and Grinham, 2023). The authors use simplified heat storage models and estimate the diurnal heat capacity of different thermal mass materials as a function of material properties (depth, density, conductivity, and specific heat), and spatial and climatic factors. They then estimate the operational carbon offsetting associated with different material alternatives and compare it with embodied carbon. The authors highlight the importance of tailoring the properties of thermal mass materials to achieve optimized thermal storage, operational carbon savings, and embodied carbon avoidance in these materials and examine the effects of the grid's energy mix and data uncertainty on operational and embodied carbon.

The book chapters in Section 1 acknowledge the significance of embodied carbon and draw attention to some of the key technical and political considerations to minimize embodied carbon.

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MINIMISING EMBODIED CARBON
A question of politics, not percentages

Alice Moncaster

Introduction

The major cause of anthropogenic GHG emissions is the burning of fossil fuel for energy; however, energy is considered fundamental to development. This issue is at the crux of the concept of sustainable development, a term now in such common use that we generally accept it as something that is not just desirable but also clearly attainable.

Within the context of the built environment, 'development' is synonymous with 'building', while 'sustainable' in this narrative is increasingly focused on the mitigation of climate change through the reduction of GHG emissions (Moncaster, 2012). The World Commission on Economic Development (WCED) in 1987 suggested that two approaches were needed to achieve sustainable development: first, 'energy efficiency should be the cutting edge of national energy policies' (Brundtland, 1987, p. 195), and second, renewable energy should 'form the foundation of the global energy structure during the 21st century' (p. 196). Since then the subsequent decarbonisation of national energy grids through increased use of renewable energy sources has made a significant shift in many countries to reducing GHG emissions. For individual buildings, adding in situ 'renewables', such as roof-mounted solar PV and ground- or air-source heat pumps, has been encouraged. Meanwhile, national regulations across much of the globe require progressive improvements of the energy efficiency of new buildings; in Europe for example this has been governed by the Energy Performance of Buildings Directive since 2006. However this focus on in situ renewables and energy 'efficiency' has led us to consider and reduce the emission of greenhouse gases only once the building is complete – in other words, operational emissions only. The concept of embodied carbon, the emissions from the construction materials and processes which create the building, has long been omitted from national building regulations across Europe and elsewhere.

Despite its omission from regulation, for decades academic research has focused on calculating the embodied impacts of buildings (Azari & Abbasabadi, 2018). Hundreds of individual case studies have now been published (see for example Fnais et al., 2022), methods have expanded and formalised (Anand & Amor, 2017; Satola et al., 2021), data on the environmental impacts of materials has improved (Waldman et al., 2020), and tools

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have multiplied (Potrč Obrecht et al., 2020). Industry interest is growing exponentially, with professional bodies publishing guidance (for example RICS, 2023) and professional networks springing up around the world, such as the Carbon Leadership Forum (CLF, 2023) in the US and the London Energy Transformation Initiative (LETI, 2023) in the UK. The requirement to measure, and even to limit, embodied carbon is starting to appear in some city plans (for example GLA, 2021) and some national regulations (Skillington et al., 2022; Nygaard Rasmussen et al., 2023). The latest data from the United Nations Global ABC report suggests that, while operational energy from all existing buildings is responsible for 28% of global GHG emissions, embodied impacts from the materials for new construction each year are responsible for another 9% of global emissions (UNEP, 2022).

This chapter considers whether this omission is accidental, stemming from a limited understanding of the WCED report and others, or whether it has come about due to political, rather than technical arguments. If the latter is true then politics has had, and most importantly continues to have, a defining role in the interpretation and knowledge of embodied carbon, and this is a critical issue to understand for anyone hoping to make real reductions.

The following section provides a brief exploration of how political narratives use numbers in support of their arguments. This is followed by examples of the use of numbers, and in particular percentages, in texts on embodied carbon. Political narratives are then linked to embodied carbon and the use of numbers, through a case study of the development of policies for ‘zero carbon’ in the UK. The final section offers a discussion and conclusion.

Numbers in politics

In her article ‘What is Politics?’, Professor Christina Boswell, Professor of Politics at Edinburgh, offers three increasingly developed definitions. The first, classic, definition is that politics is a power struggle, about who gets what, when and how – a contest over the distribution of material goods. She proposes that there are two challenges to this definition. The ‘post ideological’ approach suggests that politics is also a contest around values and lifestyles, culture and identity – for example, the environment; in this case, it isn’t just about who gets what, but also about what is important. The second challenge, the ‘ideational turn’, takes this further by considering politics to also be about how these issues are then framed, and who gets to control the narrative. This, then, sees politics as being as much a contest about *who gets to decide what is important* and who controls the narrative, as it is about who gets what share of material goods (Boswell, 2020).

Different sides in political contests often use numbers to support their arguments. In his book ‘Trust in Numbers’, Porter (1995) suggests that States use numbers to support their political goals. This stems, he proposes, from a desire to impose control through the encouragement of trust, which in turn is won through quantification. He also proposes that numbers are most likely to be used in political areas where there is obvious public interest.

One example of this is offered by the late David MacKay, Professor of Physics at Cambridge, in Sustainable Energy Without the Hot Air (MacKay, 2008). MacKay also suggested that numbers can be used by politicians to persuade, but also potentially to mislead:

'Here's an example from the Conservative Party's otherwise straight-talking Blueprint for a Green Economy:

> The mobile phone charger averages around … 1W consumption, but if every one of the country's 25 million mobile phones chargers were left plugged in and switched on they would consume enough electricity (219GWh) to power 66 000 homes for one year.'
>
> *(MacKay, 2008, p. 113)*

There are a lot of numbers in this one sentence for a political report; Porter might see in this a suggestion that the State, in this case, the Conservative Party, are looking to invoke trust in the electorate over an issue that is clearly of public interest, energy reduction. Here they are suggesting, as MacKay goes on to point out, that if everyone makes just a tiny difference the result will be a huge difference. Instead, the reality is that this is still, in fact, only a tiny difference: as MacKay says, 'while the statement quoted above is true, I think a calmer way to put it is: … If everyone leaves their mobile phone charger plugged in, those chargers will use one-quarter of one percent of their homes' electricity.' (MacKay, 2008, p. 114).

However, and despite the premise of his book which claims to focus on the numbers and not the politics, Toke (2011) suggests that MacKay's own use of numbers could be seen as equally misleading. Toke shows that in MacKay's calculation of the total energy needed in the UK, he multiplies the number of UK inhabitants by 'average Western' (as opposed to average UK) energy consumption. This produces a figure 64% *higher* than the actual energy used in the UK that year. This inflated figure is then used by MacKay to demonstrate that there is not enough potential renewable energy capacity to power the country and that therefore the UK needs more nuclear power in its future energy mix.

Porter (1995) also suggests that the State often relies on public trust in professional experts (and their numbers) to strengthen support for the State's political message, suggesting an alliance between expertise and politics. Foucault had earlier questioned 'the political status of science and the ideological functions it could serve', and 'the interweaving of effects of power and knowledge', seeing this as particularly relevant to the more empirical sciences which are 'profoundly enmeshed in social structures' (Foucault, 1976). In 2001 Scott too, writing about social power and how it operates, suggests that state authorities might use experts in this way: 'The apparent neutrality of expertise obscures its character as power and can help to legitimate contentious policies and decisions.' (Scott, 2001, p. 108).

Soon after his book was published, MacKay was appointed Chief Scientific Advisor to the Department for Energy and Climate Change, who had long advocated for the increased use of nuclear power. Following the theoretical framings of Foucault (1976), Porter (1995) and Scott (2001), we might well consider this to be an example of the State's use of professional experts, and their numbers, to add legitimacy to a contentious policy where there is considerable public interest. While MacKay didn't argue the need for nuclear power because of his political interest but because of a genuine belief in its technical necessity, nevertheless this made him a useful expert to be adopted by a political department that had the same goal.

There are other examples that are specific to the built environment. Galvin (2011) for example describes a calculation, developed by building physicists, which the German Government used to calculate the economic viability of energy retrofit works for homes; if the viability was 'proved' (that is, if *the calculation showed that* the cost of the energy saved was greater than the cost of the retrofit works), then the retrofit was in effect imposed on the homeowner. However, Galvin revealed that the reality was quite different. The assumptions built into the initial calculations meant that often the energy saved was considerably *less* than modelled, and the cost of the works was therefore never recuperated in energy savings. Nevertheless, on paper the Government retrofitting programme was a success, as the calculation used suggested it had saved considerable energy from homes. Again this wasn't a deliberate ploy to deceive homeowners, but numbers based on assumptions that did not reflect reality were used to persuade and impose an action that would not otherwise have happened. After several years in which owners became increasingly disillusioned, the policy was dropped.

Flyvbjerg (1998) highlights a further aspect use of the political use of numbers in his seminal study of the redevelopment of the bus terminal in Aalborg. During the project, numbers were used on all sides of the political debate, but as Flyvbjerg points out it was the numbers used by *the side with greater pre-existing power* that 'won' the argument (Flyvbjerg, 1998, p. 132). He suggests that this was not because these winning numbers were any more rational, or truthful; instead it was their use by the more powerful team that allowed them to be defined as such. *What* is defined as rational, therefore, depends on *who* is doing the defining:

'Defining reality by defining rationality is a principal means by which power exerts itself. …power defines what counts as rationality and knowledge and thereby what counts as reality' (Flyvbjerg, 1998, p. 227).

In each of the cases described by MacKay, Toke, Galvin and Flyvbjerg, numbers can be seen as a political tool, with experts helping 'to legitimate contentious policies and decisions' as Scott (2001) had suggested. Where the numbers were validated by the experts used to produce them, they served to reinforce the political message. Conversely, where the political message was that of the more powerful side, the numbers used were taken to be rational.

Perhaps the most famous example of the political use of numbers in the UK recently is the 'Brexit bus'. This stated, 'We send the EU £350 million a week – let's fund our NHS instead.' (Vote Leave, 2016). This (false) claim is credited with having persuaded enough voters to swing the outcome of the vote for the UK to exit the EU (Duffy, 2018). In 2023, there is little evidence that the 'decade of underfunding' experienced by the NHS (Alderwick, 2023) has changed for the better following Brexit – but the political power of the number is uncontested.

Numbers and percentages in embodied carbon

So it is clear that numbers can be, and often are, used to support political arguments, particularly in cases where there is obvious public interest as Porter (1995) suggests. Within the field of whole-life impacts of buildings, the importance or otherwise of embodied impacts is often argued in terms of percentages rather than absolute numbers. Sartori and Hestnes (2007) provide one of the highest-cited papers in this area, reviewing previous research which suggested that embodied impacts were equivalent to between 2 and 46% of total life cycle energy. A later review by Ibn-Mohammed et al. (2013) found the variation to be between 2% and 68%. More recently still, Röck et al. (2020) found that while for buildings built to current energy performance standards this share is around 20–25%, this increases to 45–50% for energy-efficient buildings, and can even exceed 90%.

This may suggest that embodied impacts are increasing as operational impacts are decreasing, as Röck et al. suggest, or it may be to do with what is included in the calculations. It is now well known that calculation boundaries and methodological approaches to