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RESEARCH

Integrating life-cycle GHG emissions into a building's economic evaluation

Monique Schmidt¹, Robert H. Crawford² and Georgia Warren-Myers³

Abstract

Buildings contribute to greenhouse gas (GHG) emissions throughout their life—from material extraction and production to building demolition and disposal. Current GHG emission reduction efforts largely focus on building operation, typically ignoring embodied emissions. One of the main barriers affecting the uptake of embodied GHG emissions considerations is the uncertainty related to the economic value of a building with reduced life-cycle GHG emissions. A conceptual approach is presented for integrating the life-cycle GHG emissions of a building into an economic evaluation. A case study detached residential dwelling located in Melbourne, Australia, is used to demonstrate the approach using a range of economic valuation approaches. One approach, using a carbon tax, shows that the effective cost for a single household would be over A\$2000 for the first year, rising to almost A\$5000 in 10 years. Across the range of evaluation approaches considered, the total cost to the householder is found to be between A\$4600 and A\$7860. With the embodied GHG emissions accounting for over 66% of the case study's life-cycle GHG emissions, the majority of the economic liability for the householder relates to the initial construction and ongoing material replacement of the building.

Policy relevance

This research provides a comprehensive and integrated approach to GHG emissions and economic assessment of residential buildings. This could be used to drive better decisions in building construction and operation through policy improvement, generating greater understanding of the GHG emissions of buildings and the economic value of GHG emissions. By quantifying the total GHG emissions over a building's life-cycle and examining ecological and financial implications, new data can provide the basis for policy measures that transform the value of GHG emissions in property. The total life-cycle approach to GHG emissions can be used by developers or builders, for example, to demonstrate the potential financial implications of their choices. However, given its current format, there is a need to improve policy measures such as improved carbon tax strategies and the generation of an annual tax for the economic value implications to be realised.

Keywords: buildings; carbon metrics; economic value; greenhouse gas emissions; life-cycle analysis; valuation

1. Introduction

There is growing concern about the poor environmental performance of buildings. For example, buildings account for nearly 36% of global energy use and 39% of energy-related global greenhouse gas (GHG) emissions (IEA 2019). The rising threat of emissions is further compounded by the fact that the world is currently undergoing the largest wave of urban growth in human history, with an expected 230 billion m² of new floor area (the equivalent of adding an entire New York City every month for 40 years) to be added to the global building stock by 2060 (*Architecture 2030* 2019). Buildings provide a key opportunity for mitigating GHG emissions by delivering greater efficiencies, alongside energy-efficient refurbishment and net zero-emission construction (UNEP 2018; Falk, Simpkins, & Gaffney 2019).

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Building-related GHG emission mitigation strategies thus far has been largely focused on reducing operational GHG emissions (De Wolf, Pomponi, & Moncaster 2017). Even though the operation of buildings accounts for a large proportion of annual building GHG emissions, their embodied GHG emissions (those emissions associated with the extraction, processing and manufacture of materials, and construction of the building) have been shown to represent a significant proportion of a building's total life-cycle GHG emissions. Globally embodied GHG emissions have been estimated to be between 20% and 25% of annual anthropogenic GHG emissions (Röcka *et al.* 2020). Chastas & Theodosiou (2016) have shown that these embodied GHG emissions can range from 10% to 97% of a building's life-cycle GHG emissions (depending on building location, function, material use, and assumptions about service life and energy supply) and Adams, Burrows, & Richardson (2019) have stated that embodied GHG emissions account for one-third of all building-related emissions. It has become critical to consider building GHG emissions from a life-cycle perspective. However, several barriers hinder the uptake of this holistic approach, *e.g.* lack of policy and mandatory measures; lack of comparable data; and lack of a consistent assessment method. These barriers have been well documented in the literature (Menzies, Banfill, & Turan 2007; Dixit *et al.* 2012; Farhan *et al.* 2014; Ariyarante & Moncaster 2014).

One barrier that has not yet been as widely explored is the uncertainty associated with the economic implications of life-cycle GHG emission-reduction strategies (UKGBC 2014; Fouche & Crawford 2015). Current approaches fail to proactively engage consumers to make better decisions, particularly when it comes to selecting materials that effectively decrease the life-cycle GHG emissions of a building.

This study provides a conceptual approach for the integration of the life-cycle GHG emissions of buildings into a building's economic evaluation, with the aim of forming a monetary-based understanding of building-related life-cycle GHG emissions for consumers. It brings together existing platforms of both operational and embodied GHG emission assessment with economic valuation techniques and approaches to create a monetised consideration of a building's life-cycle GHG emissions. This conceptual approach aims to provide a much-needed economic mechanism for valuing and incentivising building-related GHG emission-reduction strategies and approaches. It is hoped this will not only provide the basis for future policy but also foster better-informed decision-making in building design and construction.

The paper is structured as follows. The next section provides further background detail on the current efforts employed to decrease building-related GHG emissions and their inherent limitations, followed by an overview of the role of consumer decision-making and GHG emission initiatives. Next, the proposed conceptual approach is presented and demonstrated with the use of a residential building case study. The key findings of this application are discussed and opportunities for future research and development highlighted.

2. Existing efforts to decrease building-related GHG emissions

As a response to escalating GHG emissions, decision-makers and public authorities have increasingly developed and adopted policies and tools to reduce building-related GHG emissions. The following section provides a brief overview of these policies and tools, including standards, regulatory measures, rating tools and incentives.

2.1 Standards

To help consolidate and standardise the assessment of environmental effects across the life-cycle of a good or service, the International Organisation for Standardisation (ISO) published the first life-cycle assessment (LCA) standard in 1997. There have been subsequent updates to the standard, with the latest being released in 2006 with ISO 14040:2006 Environmental Management—Life Cycle Assessment: Principles and Framework; and ISO 14044:2006 Environmental Management—Life Cycle Assessment: Requirements and Guidelines (ISO 2006a, 2006b). The European Standards Technical Committee CEN TC350 (Sustainability of Construction Works) defines a calculation method for the assessment of environmental performance of buildings in EN 15978 and environmental product declarations (EPDs) in EN 15804 (CEN n.d.). Another standard includes the British Standards PAS 2050:2011 Specification for the Assessment of Life Cycle GHG Emissions of Goods and Services; and PAS 2060:2010 Specification for the Demonstration of Carbon Neutrality (BSI 2011a, 2011b). However, the use of these standards in industry is generally not mandatory, and there is still debate as to the overall consensus on the correct approach for quantifying building-related GHG emissions (Reap *et al.* 2008). Shortcomings include, for example, ill-defined system boundaries, unfairly justified inputs and outputs, data quality, problems with selecting appropriate impact categories, and the inherent subjective approach dependent on the assessor (Dixit *et al.* 2012; Crawford 2011; Reap *et al.* 2008).

2.2 Regulatory measures

Several countries have mandatory regulatory measures in place to help reduce building-related GHG emissions. For example, in the UK, the Building Regulations include a section titled Part L—The Conservation of Fuel and Power. This sets out energy and thermal requirements for new buildings and requires, amongst other things, a simulation using the Standard Assessment Procedure (SAP) to ascertain conformity with the requirements (HM Government 2018). The European Union (EU) has established a legislative framework in 2002 that includes the Energy Performance of Buildings Directive and the Energy Efficiency Directive, which together promote policies that help to decarbonise the building stock by 2050 (European Commission 2020). The Australian National Construction Code (NCC), developed by the Australian

Building Codes Board (ABCB), has a set of mandatory measures for building operational energy-efficiency targets. Since 2002, all new residential buildings have had to meet minimum thermal performance requirements, which is commonly certified using a star rating scheme. At present, one of the ways to achieve this minimum thermal performance under the NCC is through the achievement of 6 stars under the National House Energy Rating Scheme (NatHERS) (with 10 stars being the highest rating). Most countries' mandatory regulations tend to focus only on operational energy and GHG emissions, leaving the embodied GHG emissions largely ignored (Zizzo, Kyriazis, & Goodland 2017). A building's life-cycle includes several stages (**Figure 1**, based on EN 15978:2011 and EN 15643-5:2017). A building's embodied GHG emissions result from various life-cycle stages from pre-construction (A0) all the way through to the end-of-life stage (C1–C4). The operational GHG emissions occur during the use stage (B6 in particular).

Examples of countries that have included mandatory embodied GHG emissions measures in their building regulations include Germany and Switzerland (whole-building life-cycle analysis is required for new federal and government buildings), the Netherlands (embodied GHG emissions reporting and meeting of a benchmark are required at the building permit application stage for new residential and office buildings over 100 m²) and Sweden (large transportation infrastructure projects are required to calculate and report embodied GHG emissions) (Zizzo *et al.* 2017).

2.3 Rating tools

There is a plethora of voluntary rating schemes and tools available to help assess building-related GHG emissions. These include the UK's Building Research Establishment Environmental Assessment Methodology (BREEAM) (BRE 2019); the United States' Leadership in Energy and Environmental Design (LEED) (USGBC 2019); Germany's Deutsche Gesellschaft für nachhaltiges Bauen (DGNB) (2020); and the Green Building Council of Australia's (GBCA) Green Star rating scheme (GBCA 2019). These offer a framework for assessing several environmental categories (*e.g.* energy to water) for commercial buildings. Several studies have discussed these tools in detail, such as Ng *et al.* (2013), Schwartz & Raslan (2013), Wong *et al.* (2015) and Doan *et al.* (2017), and have critiqued their exclusion of embodied GHG emission and the variability in their accuracy and reliability. Recent efforts have commenced to include life-cycle analysis as part of these rating schemes, although the benchmarking of these targets is still in its infancy (De Wolf *et al.* 2017). Examples include BREEAM, which introduced a 'Life Cycle Impacts Criterion' in 2014 (however, no specific credit awarding rule is provided and points are based on the relative improvement of hypothetical building types), and Germany's DGNB, which has since 2008 included two LCA-related credits called 'Life Cycle Impact Assessment' and 'Life Cycle Impact Assessment—Primary Energy' (where points are awarded to the building in relation to its performance when compared with a reference building) (Hamedani & Huber 2012; Oviir 2016).

2.4 Incentives

The provision of financial incentive has often been cited as an important method in promoting the uptake of energy-efficient building strategies (Olubunmi, Xia, & Skitmore 2017). Financial incentives have been shown to accelerate the implementation of green building technologies (GBCA 2006; Olubunmi *et al.* 2017). Financial incentives include examples such as direct grants, tax incentives and rebates. An example of a tax incentive can be seen in the United States where commercial buildings pay less tax under the 'Energy Efficient Commercial Building Tax Deduction' scheme. San Francisco also provides a property tax deduction based on the installation of solar energy systems (DSIRE 2019). An Australian example of another financial incentive was the Home Insulation Program implemented in 2009, which reimbursed homeowners and landlords for the installation of ceiling insulation. However, the programme was terminated in 2010 due to issues surrounding poor safety standards and installation practices (Crawford & Stephan 2014).

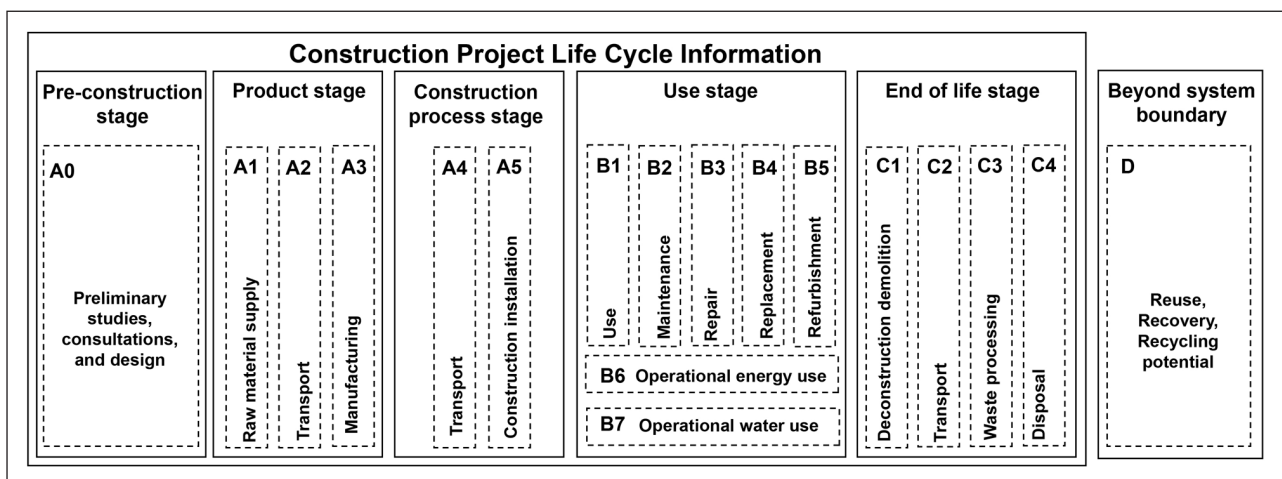


Figure 1: Building project life-cycle stages. Source: Crawford, Stephan, & Prideaux (2019), based on EN 15978:2011 and EN 15643-5:2017.

It has also been demonstrated by studies such as Crawford *et al.* (2016), that even when voluntary measures and incentives are incorporated into residential buildings (such as higher insulation levels or more efficient glazing systems) and higher star ratings are achieved, it may increase life-cycle GHG emissions. This is because often these higher star ratings typically require more materials which typically results in an increase in the building's embodied GHG emissions. At present there are no major incentives in place to help reduce a buildings' embodied GHG emissions. Zecca *et al.* (2015) have stated that there is a resistant audience when it comes to including embodied GHG emission-mitigation measures in buildings and that stricter building codes and financial incentives would help counteract this.

Most policy and incentive analyses focus on the technical aspects, and little effort has been made to understand what motivates consumers and industry. Policy is more robust and effective if it aligns with people's existing drivers for change (McGee *et al.* 2008).

2.5 Economic evaluation of GHG emissions

There has been an increasing effort to include an economic value for building-related GHG emissions due to the growing interest in building designs that balance economic, social and environmental factors (Robati *et al.* 2018). One of the driving forces of including an economic value is undoubtedly the perceived persuasiveness of economic language. Conveying what it is that the natural world provides us with in monetary terms is seen as a powerful means of communicating the importance of conservation to a wider (and perhaps previously unreceptive) audience (Atkinson, Bateman, & Mourato 2012). The idea of monetising GHG emissions dates back to studies such as Smith's *The Wealth of Nations* (1776) and Pigou's *The Economics of Welfare* (1920). The aim of these instruments was to internalise the costs to those responsible for the external negative effects in order to compensate those negatively affected. Hence, the internal cost for the polluter could be made equal to the cost for the caused damage in monetary terms (Schomers & Matzdorf 2013). The approaches to economic valuation has evolved since then to include two distinct methods namely the 'Revealed Preference' and 'Stated Preference' method (**Figure 2**) as defined by studies such as Musaoglu *et al.* (2014), Dobes, Leung, & Argyrous (2016) and Atkinson *et al.* (2012). Revealed preference is based on actual market behaviour of users of ecosystem goods and services and includes subsidiary approaches such as market price approach (*e.g.* a carbon tax), cost-based approach, hedonic approach and travel cost approach. Stated preference refers to a method used for environmental goods and services that are not traded in markets and therefore captures a user's willingness to pay/accept for ecosystem services and goods through methods such as surveys.

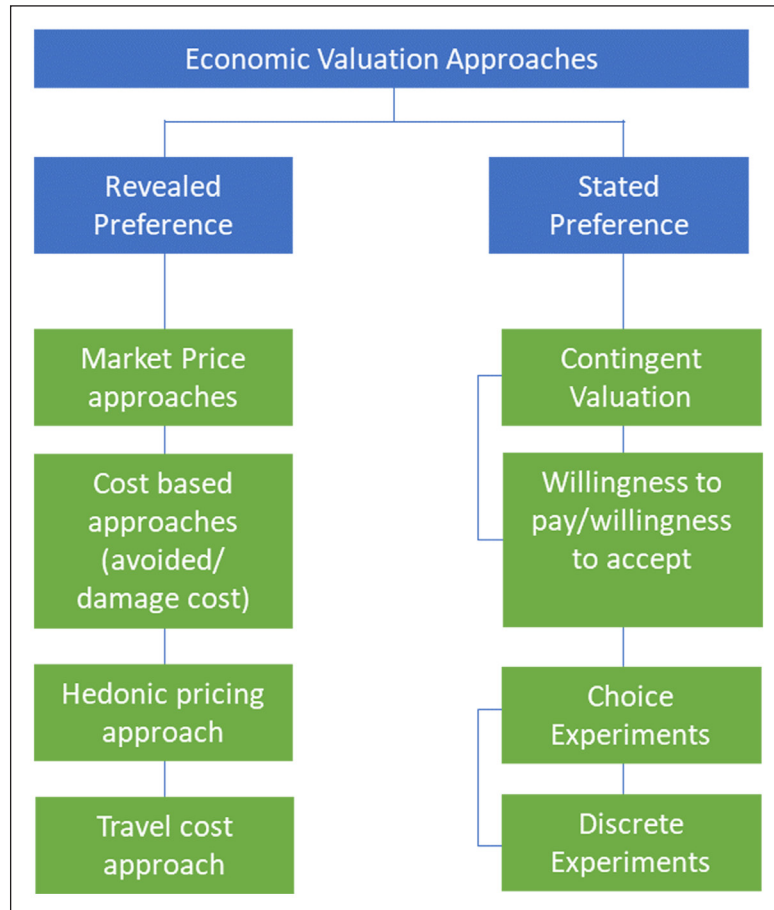


Figure 2: Economic valuation approaches.

Table 1: Advantages and disadvantages of economic valuation approaches.

Approach	Advantage	Disadvantage
Market price approach	Market data available and robust. Uses standard, accepted economic techniques	Value of emissions might not represent the social cost of climate change. Limited to market goods and services
Cost-based approach	Good for assessing the outcomes of mitigation options to inform related policy decisions	Lack of transparency when it comes to the use of integrated assessment models. There are different assumptions and has a 'black box' nature
Hedonic pricing approach	Versatile and can be adapted to consider several possible interactions between market goods and environmental quality	Relatively complex to implement and interpret, requiring a high degree of statistical expertise
Travel cost approach	Based on actual behaviour, and therefore more reliable than methods based on the hypothetical behaviour of the respondents	Limited in its scope of application because it requires user participation. Cannot be used to measure non-use values
Contingent valuation	Can capture all use and non-use values. The use of surveys enables an estimation of hypothetical changes and their impact before they have taken place	Potential bias in response. Hypothetical market (not observed behaviour); resource intensive
Choice experiments	Use of surveys enables the collection of relevant socio-economic and attitudinal data on the respondents that could be relevant for understanding the variables influencing social preferences and choices	Complex questionnaire development and data analysis. Budget and time demands are high

Studies such as Musaoglu *et al.* (2014), Dobes *et al.* (2016), Atkinson *et al.* (2012) and Preston (2015) have provided detailed insight into the advantages and disadvantages of each approach and are briefly summarised in **Table 1**.

2.6 Annualisation and economic relationships: deriving an economic value

The economic evaluation assessment of GHG emissions has established methodologies that consider economic value, market value, market price and marginal abatement costs, although these have not necessarily been examined from a building perspective. Economic value has a variety of interpretations both as a noun and verb; and it is not until context is provided that the reference to economic value is understood. When considering the capturing and valuing of environmental implications, clarity is needed on how environmental concerns should be valued, and which aspect of value is to be valued. There are two key realms of thought—ecological economics and environmental economics—particularly in the topics of the valuation of environmental resources and methodologies for calculation of value (Tietenberg & Lewis 2016).

Environmental economics focuses on the neoclassical approach whereby economic incentives (or disincentives) are used to shape human behaviour to achieve enhanced human welfare. The evaluation of embodied GHG emissions associated with buildings draws upon environmental economics to generate responsibility and informed decision-making through the use of financial levers. A range of economic assessment techniques can be used for the assessment and estimation of the value of GHG emissions, *e.g.* the damage cost approach, the abatement cost estimate, marginal abatement cost, willingness-to-pay estimates and market pricing of carbon (Dobes *et al.* 2016; Price, Thornton, & Nelson 2007). The most common accounting processes focus on the social cost of carbon (the economic cost expressed as an Australian dollar value of the economic harm as a result of damages resulting from emissions), market price of carbon or marginal abatement cost (Sustainable Propensity 2011). However, as suggested by Wu *et al.* (2015), the consideration has inherent barriers as a result of both the monetary and non-monetary values, particularly in the consideration of the embodied GHG emissions, which are inherently difficult for a layperson or market to fully understand. The literature suggests informed decision-making, combined with greater financial understanding and possibly incentives (or disincentives), would assist householders, designers and builders in the uptake of buildings with lower life-cycle GHG emissions.

2.7 Consumer decision-making

An extensive body of research exists on the relationship between building-related GHG emissions and energy ratings and the related cost implications and the effects this has on the decision-making of consumers, as well as willingness-to-pay models and historical empirical research examining housing price and rental data. In the Australian context, many studies have considered consumers' willingness to pay for more energy efficient and lower GHG emission-emitting buildings (Crabtree & Hes 2009; Buys *et al.* 2005; Sitar & Krajnc 2008; Mandell & Wilhelmsson 2011; Leviston *et al.* 2015). Although these studies have their limitations, as often stated behaviour or intentions do not necessarily equate to actual behaviour, evidence in the Australian context does exist. Two key residential quantitative studies have estimated the actual willingness to pay for residential of implied GHG-mitigation measures (energy efficiency ratings). Both of these studies examine the Australian Capital Territory (ACT)

housing market because it was the only location in Australia to implement a mandatory disclosure programme. The first is by the Australian Bureau of Statistics (ABS) in 2008, which found an increase in sales price for each half star rise in the energy rating. A later study, by Fuerst and Warren-Myers (2018), examined the same region, across a longer time period, and found premiums for certain levels of star ratings and energy-efficient features in both sales and rentals. The mandatory disclosure programme implemented in the ACT requires at point of sale or lease that an energy efficiency rating (EER) assessment was conducted and the rating is provided in all advertising material and information about the home. While information disclosure and understanding of ratings vary, the dollar value (payment) is clearly understandable as there is extensive research examining home buyers' trade-offs for houses with higher rates/taxes (starting with Oates 1969, then Palmon & Smith 1998 and, more recently, Dalton & Fuerst 2018).

3. An approach for evaluating GHG emissions in a building

This study investigates an integrated approach to consider all building-related life-cycle GHG emissions, monetise these at the current carbon price and incorporate them into a building's economic evaluation. The following sections discuss the elements of the approach followed by the method and an example of its application.

This research tests one approach out of several options, requiring three stages of assessment, firstly borrowing from the social cost of carbon approach, to assess the total life-cycle GHG emissions of a building. Second, using the market price of carbon, to estimate the present economic value of the GHG emissions over the life-cycle, to provide an understanding of the emissions cost in financial terms. Finally, for consumers to understand the cost and value implication of the building-related life-cycle GHG emissions, there is a need to consider these from a valuation perspective, and depending on the approach considered the translation of an intangible consideration into a tangible one (Wu *et al.* 2016). Whilst operational energy may be considered a tangible aspect for consideration and influence on value, as indirectly demonstrated by premiums for higher energy rated buildings suggesting an inference of lower operational energy use (as noted by Fuerst and Warren-Myers 2018), the considerations of embodied and life-cycle GHG emissions are rarely if ever explicitly treated in valuation (Wu *et al.* 2016). The real economy and the financial economy are linked by market price and replacement cost of productive capital, which is the motivation for monetary policy to intervene in financial markets (Keynes 1936; Tobin & Brainard 1976). Therefore, for life-cycle GHG emissions to be considered and valued, government intervention from a fiscal perspective is required. While a carbon tax on all emissions is one option, in Australia this has been a political football and unlikely to gain substantial traction in the market in the near future (Pearse 2017). One such way to create this transition is to consider the annual cost to the property as a form of tax (Yinger, Bloom, & Boersch-Supan 2016) and how this annual cost then forms a negative consideration in the determination of economic value (Craddock & Warren 2019). Therefore, the final stage requires the annualisation of the present economic value over the expected life of the asset.

3.1 Key elements and methodologies of the conceptual approach

The conceptual approach is illustrated in **Figure 3**. The key elements include quantifying the life-cycle GHG emissions of a building as well as the sequestered and offset GHG emissions. The findings of this assessment are then used to conduct the economic assessment. Each element of the approach is discussed in more detail below.

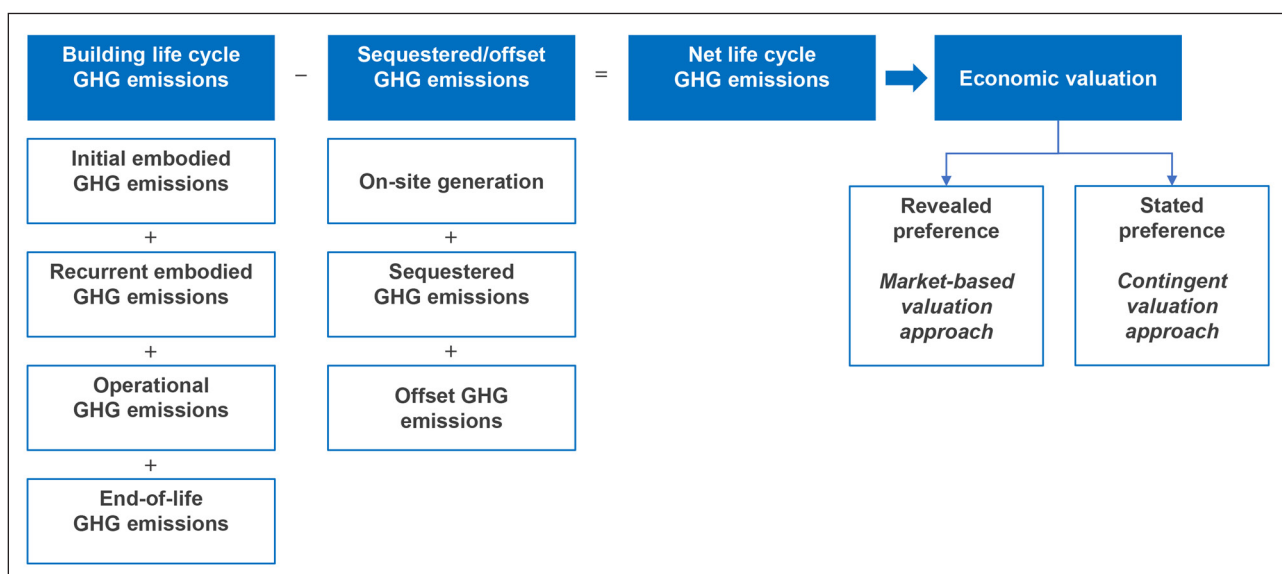


Figure 3: Key elements of the conceptual approach.

3.2 Method for quantifying life-cycle GHG emissions

The life-cycle GHG emissions of a building consist of the initial, recurrent, operational and end-of-life GHG emissions (Figure 3). The initial embodied GHG emissions represents the emissions occurring before and during the construction of a building and include the extraction and manufacturing of materials and their transportation to the building site, and the eventual construction of a building. The recurrent embodied GHG emissions are associated with the maintenance and replacement of the materials over a building's life. The operational GHG emissions are associated with the running and use of the building (heating and cooling, hot water, lighting, lifts, *etc.*).

Three key approaches are used to quantify the embodied GHG emissions associated with construction materials, products and whole buildings, including process analysis, environmentally extended input–output analysis and hybrid analysis, with hybrid analysis typically providing the most comprehensive results (Crawford 2019). The data obtained with the use of these approaches is captured in product databases and EPDs. Process analysis tends to underestimate embodied GHG emissions due to a limited system boundary. Environmentally extended input–output analysis is based on top-down data that generally lack specificity to any particular product or material (Omar, Doh, & Panuwatwanich 2014; Dixit *et al.* 2012; Rauf & Crawford 2015). The hybrid approach, more specifically the path exchange hybrid approach as discussed by Crawford *et al.* (2018) and data from the EPiC database, is selected for the embodied GHG emissions' calculation within this study due to their comprehensiveness and relevance to the Australian context. The initial embodied GHG emissions of the main materials that make up the fabric of a building (such as the ground floor, external walls, internal walls, roof and internal finishes) are most easily quantified by multiplying specific material quantities by an embodied GHG emissions coefficient for each material (such as those contained within the EPiC database which are based on the path exchange approach (Crawford *et al.* 2019). The recurrent embodied GHG emissions associated with material repair and replacement (and in some cases the deconstruction of materials) are quantified by multiplying the quantity of material replaced over the life of a building, based on predicted service life values, by the relevant embodied GHG emission coefficient. The operational GHG emissions of a building include the energy used to heat and cool the building, as well as for lighting, hot water and appliances. Dynamic simulation is one of the most popular approaches used for quantifying the anticipated operational GHG emissions of a building and has been shown to provide reliable results (Reeves, Issa, & Olbina 2012; Wang & Zhai 2016). Several simulation packages are available, each with its own inherent strengths and weaknesses (Ko & No 2015; Schwartz & Raslan 2013; Reeves *et al.* 2012). For the operational GHG emissions, a dynamic simulation approach was selected. The simulation software package Green Building Studio (GBS) (Autodesk 2019) was used due to its relevance for the early design stage (Stumpf, Kim, & Jenicek 2011).

3.3 Method for quantifying life-cycle GHGs associated with onsite generation, sequestration and offsets

Onsite energy generation from renewable sources can assist in offsetting some of the fossil fuel-based energy demand and related GHG emissions associated with a building (REN Energy 2019). The options can be broadly classified into solar thermal, rooftop solar, ground-mounted solar, bio-energy and onshore wind.

'Carbon sequestration' refers to the process of capturing and storing carbon, a key element of GHG emissions. Removing emissions-based carbon from the atmosphere has been deemed a necessary action to keep global warming below the 2°C threshold (IPCC 2019). There are various natural ways in which carbon can be sequestered, such as by planting trees that absorb CO₂ and store it in their trunks, roots, stems and leaves. Various studies have quantified the amount of CO₂ stored in wood, such as van der Lugt (2013), who states that 1 m³ of wood, with a density of 480 kg/m³, results in 1 tonne of carbon sequestered over the tree's lifetime. However, this result can change depending on the type of tree, its age, diameter, foliage and other factors such as climate (Bateman & Lovett 2000). Studies such as that by Jane (2010) have provided quantification methods for calculating more detailed carbon sequestration for trees and wood products, and this uses some general figures, included the assumption that 50% of the dry mass of the tree is carbon. The use of more wood products in buildings, as well as employing hardier and more resilient materials, or materials that are recycled or reused, has been shown to be a vital strategy in increasing the carbon sequestered in buildings (van der Lugt 2013).

Offsetting GHG emissions is an approach that compensates for the released GHG emissions by purchasing units that funds projects that remove or reduce emissions. For example, one can choose to purchase 'tree' credits, where a certain number of trees are planted as part of a forestation programme. Other approaches include carbon farming (where plants are used to sequester GHG emissions and transfer these to the soil), bio-energy and bury (where the CO₂ released from biomass is captured and trapped in materials such as concrete), and biochar (partly burning materials, which are then buried on farmland) (Hoff 2017). However, it is important to be aware that offsetting does not prevent emissions from occurring and every effort should be made to first reduce GHG emissions where possible.

For this study, the onsite generation for the case study building assumed a 5 kW rooftop solar system was installed, due to its growing popularity in Australian households (Australian Renewable Energy Agency (ARENA) 2018), with no solar hot water assumed. For the sequestration of GHG emissions, the carbon sequestered in the timber used within the building was considered. The quantification approach suggested by Jane (2010) was used where the mass of the wood products was considered with a range of factors such as the age of the tree, the amount of carbon stored in trees (50%) and the average rates of recovery after processing (50%). For the consideration of offset GHG emissions, although it generally does not form part of new residential design in Australia, for the demonstration of the conceptual approach, it has been assumed that the development of the building would involve planting five trees on site (due to backyard size

limitations of roughly 100 m²; Hall 2016) and another 55 trees offsite as part of a reforestation programme. The period of analysis selected for this study is the 10 years to 2030 and 30 years to 2050. The year 2030 was selected as Australia has a target of reducing emissions to 26–28% compared with 2005 levels by 2030 (as per the Paris Agreement). The year 2050 was selected due to Australia's target of achieving zero net emissions by 2050.

3.4 Method for quantification of net life-cycle GHGs

The embodied GHG emissions associated with building construction and ongoing maintenance and replacement are combined with the operational-related GHG emissions to determine the GHG emissions liability over the life of a building. Next, the GHG emissions offset due to any onsite renewable energy generation (which are either used on by the homeowner's site or can be exported to an electricity network), sequestration or purchased offsets are subtracted to provide a net GHG emissions liability.

3.5 Using conceptual real estate valuation approaches

Once the net GHG emissions liability has been calculated, the economic value of these emissions in today's dollars needs to be estimated using the current carbon price. This is to enable easy comprehension by home purchasers, designers and builders of the GHG-emission implications of the building. For this study, this applies a market-based approach, as many of the other approaches to monetisation can be quite complex and often generate unrealistic figures. Therefore, this research explores the adaption of the income-based approach used commonly in property valuation, business valuation (Wyatt 2008), more recently in the valuation of onsite energy generation (Leskinen, Vimpari, & Seppo 2020a) and also commonly used as a method of carbon pricing (Wyatt 2008). As the income approach can consider the capitalisation of an annual net cashflow or the present value (PV) assessment of discounted future cashflows; in particular the later approach could be considered a suitable option for modelling GHG emissions due to the ability to model the range of GHG emissions over the life-cycle including initial embodied energy, operational energy and recurrent embodied energy. The economic values generated use the current carbon price (at the date of assessment) and provide a monetary value that can potentially aid consumer understanding. Despite this, there is still great uncertainty surrounding carbon pricing (Aldy & Stavins 2012; Stavins 2019).

This research adapts the concept of the income approach, which presents some challenges, in particular in relation to the discount rate(s), growth rates, timeframes, and forecasting of recurrent embodied emissions and the variations in carbon pricing. However, dealing with these challenges is not the purpose of this paper. This research explores the income approach's two methods, namely the capitalisation approach and the discounted cash flow approach (Wyatt 2008; Reed 2007).

The income capitalisation approach takes the net annual income of a property and then capitalises the net annual income to calculate the economic value, as shown in equation (1) (Enever, Isaac, & Daley 2009). For the purpose of this research, to examine the net emissions on an annual basis, an annual monetary value is generated by taking the annual GHG emissions multiplied by the current carbon price, then capitalising these net emissions and making adjustments for one-off (recurrent embodied energy occurrences) and the initial embodied GHG emissions, to calculate the life-cycle GHG emission (GHG_{cv}), as shown in Equation (2):

$$\text{Economic value} = \frac{\text{Net income}}{\text{Capitalisation rate}} \quad (1)$$

$$\text{GHG}_{cv} = \left[\frac{(\text{OGHG} - \text{OfGHG})}{r} \right] + \text{PV}(\text{REGHG}) + \text{IEGHG} \quad (2)$$

where:

$$\text{PV}(\text{REGHG}) = \frac{\text{FV}(\text{REGHG})^1}{(1+r)^1} + \frac{\text{FV}(\text{REGHG})^2}{(1+r)^2} + \dots + \frac{\text{FV}(\text{REGHG})^n}{(1+r)^n} \quad (3)$$

where GHG_{cv} is the capitalised value of the total life-cycle GHG emissions; r is the appropriate periodic yield or discount rate, or the household's real discount rate; PV is the present value; IEGHG is the initial GHG emissions; REGHG is the recurrent GHG emissions; FV is the future value; and n is the year.

The PV of the total GHG emissions provides a total cost of the GHG emissions over the life-cycle of the building. This research suggests that consideration of life-cycle GHG emissions will be better understood by the general market stakeholders if a clear monetary value is provided. Therefore, in order to translate into an economic evaluation, there is a need to annualise this value over the expected life span of a building. This evaluation can then provide the basis for a form of annual tax that is beholden on the property, which accounts for the life-cycle GHG emissions liability. It would be anticipated that by creating an initial tax accounting for the life-cycle GHG emissions liability, that this may have implications for construction costs and affordability. Thus, the format of annualising the amount is important.

Therefore, to estimate the annual GHG emission cost (GHGC_{pa}), based on different timeframes, being 10 years (2030) or 30 years (2050), the time value of money annuity payment formula shown in equation (4) is used:

$$\text{GHGC}_{pa} = \frac{\text{GHG}_{CV}}{1 - (1 + r)^{-n}} \quad (4)$$

A limitation of the above method is that the net GHG emission costs are capitalised in the first instance assuming an in-perpetuity perspective, and this is highly sensitive to the rate used to capitalise the annual costs. Therefore, the second income method—the discounted cash flow approach—is also used to estimate the PV of the GHG emissions, which can be described theoretically as per equation (5):

$$\text{PV} = \frac{\text{CF}_1}{(1 + r)^1} + \frac{\text{CF}_2}{(1 + r)^2} + \frac{\text{CF}_3}{(1 + r)^3} + \dots + \frac{\text{CF}_n}{(1 + r)^n} \quad (5)$$

Therefore, adapting this approach to consider building-related life-cycle GHG emissions, the equation is transformed to:

$$\text{GHG}_{CPV} = \text{IEGHG} + \frac{(\text{REGHG} + \text{OGHG} - \text{OfGHG})_1}{(1 + r)^1} + \frac{(\text{REGHG} + \text{OGHG} - \text{OfGHG})_2}{(1 + r)^2} + \dots + \frac{(\text{REGHG} + \text{OGHG} - \text{OfGHG})_n}{(1 + r)^n} \quad (6)$$

The cash flow approach considers all positive and negative GHG emissions (in kgCO_2e) on a yearly basis and then discounts these values back to a PV. This PV can then be annualised by use of the annuity equation as aforementioned in equation (5) to generate the annualised cost.

4. A worked example

The following section provides an example of how the proposed evaluation approach can be applied to an individual building. This example demonstrates the type of results likely to be obtained and provides a practical example of the quantification of life-cycle GHG emissions and the economic evaluation. The use of case studies is popular in life-cycle GHG emission studies. Case study research provides a means to investigate a building in a specific context and helps to isolate specific variables related to the study (Zainal 2007).

4.1 Case study building

The location of the case study building is Melbourne, Australia. Detached buildings comprise 72% of all new residential buildings being built in Australia, and thus this typology was selected as the basis of the case study building (HIA Economics 2018). A popular floor plan from the largest volume builder in Australia, Metricon, was selected. The key characteristics of the building are detailed in **Table 2**.

The source of other data inputs used for the case study building include: material quantities were extracted from a bill of quantities for the building; material service life values were extracted from sources such as Rauf & Crawford (2015) and InterNACHI (2012); material costs were extracted from Rawlinson (2019); and hybrid coefficients were obtained from Crawford *et al.* (2019).

4.2 Life-cycle GHGs

Figure 4 shows the results of the life-cycle GHG emissions of the case study building for 2030 and 2050, by life-cycle stage and emissions type. The initial embodied GHG emissions of the case study building were found to be $168 \text{ tCO}_2\text{e}$ ($0.72 \text{ tCO}_2\text{e}/\text{m}^2$). The annual operational GHG emissions of the building were $8.5 \text{ tCO}_2\text{e}$ per annum, thus resulting in $85 \text{ tCO}_2\text{e}$ by 2030 and $255 \text{ tCO}_2\text{e}$ by 2050. The recurrent embodied GHG emissions were $34.5 \text{ tCO}_2\text{e}$ by 2030 and

Table 2: Characteristics of the case study building.

Building item	Detail	Building item	Detail
Gross floor area (m^2)	230	External wall material	Brick veneer with 90 mm timber frame
Ceiling height (m)	2.4	Roof material	Concrete tile with timber truss
Number of bedrooms	4	Window material	Single glazed with aluminium frame
Length \times width (m)	19.7×14.8	Floor material	Concrete waffle pod slab
Heating	3-star gas-ducted heating unit	Insulation	Wall: R2 Glasswool batt; ceiling: R4 Glasswool batt

126 tCO₂e by 2050. Once the sequestration, offsets and onsite generation were included, the total net life-cycle GHG emissions reduced to 266 tCO₂e for 2030 and 452 tCO₂e for 2050.

4.3 Economic assessment

The next step in the conceptual framework was to multiply the total life-cycle GHG emissions of the building by the current market price for carbon. The market price used for this study was A\$16.50/t (as reported by RepuTex Energy 2019, one of Australia's leading providers of pricing and advisory services for the local energy and environmental markets). The total market price of carbon cost for year 1 was calculated to be A\$2770. The subsequent year's cost is roughly A\$143 (with a 2% carbon price inflation each year), based on annual operational GHG emissions. However, by year 10, the cumulative cost increases to A\$4853, factoring in recurrent embodied GHG emissions (which in this case relates to the replacement of internal finishes such as paint, which has an average lifetime of 10 years; Fay, Treloar, & Iyer-Raniga 2000). The total carbon cost at 2030, based on the life-cycle GHG emissions with no included GHG emission offsets, is A\$6200, as shown in **Figure 5** (year 20). By 2050 the total cost increases to A\$10,437 (year 30).

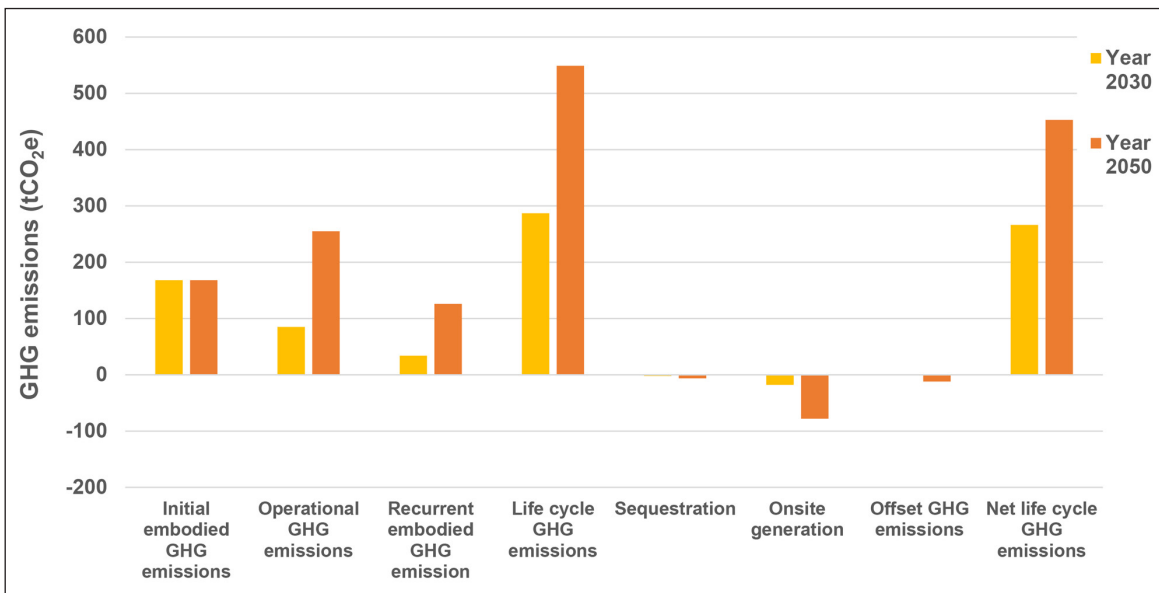


Figure 4: Total life-cycle greenhouse gas (GHG) emissions for case study building to 2030 and 2050.

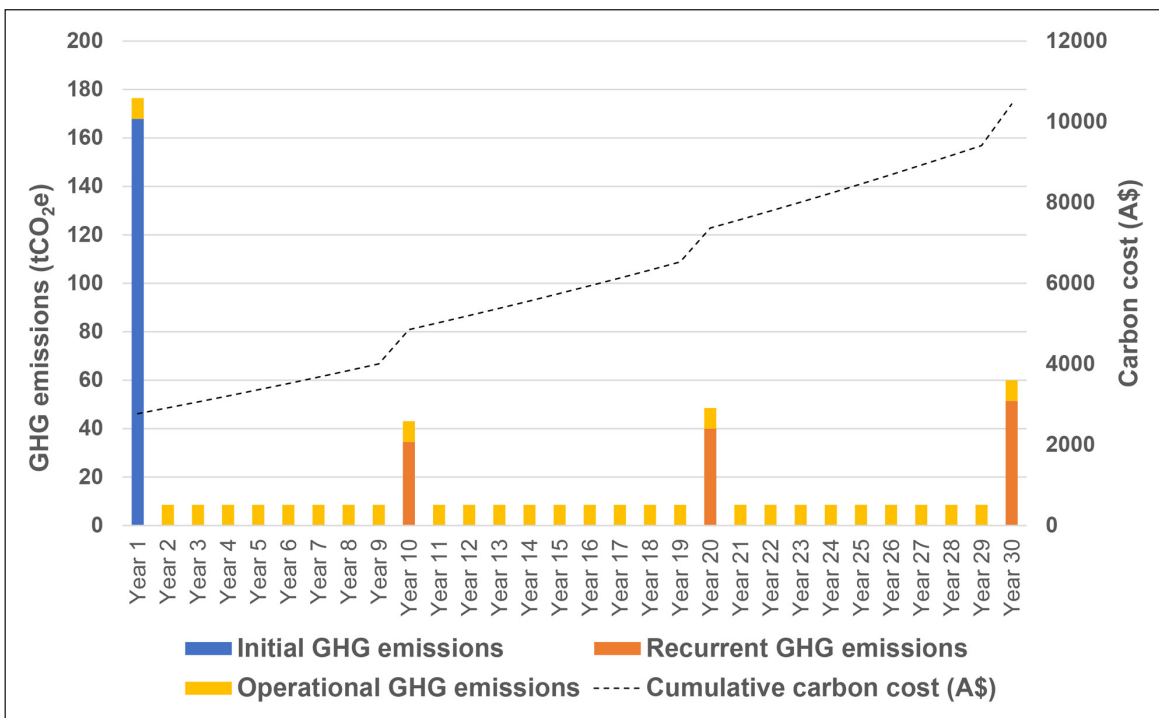


Figure 5: Cumulative carbon cost of case study dwelling.

Table 3: Economic assessment of the life-cycle greenhouse gas (GHG) emission costs for the case study building using the capitalisation approach.

Description	Method	2030 (10 years)	2050 (30 years)
Capitalised value of GHG emission costs: GHG_{cv}	Annual net GHG emissions multiplied by the carbon price capitalised, plus initial and recurrent embodied GHG emissions multiplied by the carbon price	A\$5854	A\$6767
Annualised capitalised costs: $GHGC_{pa}$	Total costs over a period are then annualised to provide an annual payment amount (2% discount rate)	A\$652	A\$302

Table 4: Economic assessment of the life-cycle greenhouse gas (GHG) emission costs for a case study building using a cash flow approach.

Description	Cashflow treatment	2030 (10 years)	2050 (30 years)
PV of life-cycle GHG emissions: GHG_{cpv}	PV of cashflows (GHG emissions \times carbon price)	A\$4652	A\$7860
Annualised PV of life-cycle GHG emissions: $GHGC_{cfpa}$	Annualised cost over the time period—discounted	A\$518	A\$351

Note: PV = present value.

The life-cycle GHG emissions modelling and translation to dollar values means the two income methods of assessing the economic value can easily be applied. The results of the capitalisation approach are shown in **Table 3**. Providing estimates of the capitalised value of GHG emissions (GHG_{cv}) with the two timeframes of 2030 (10 years) and 2050 (30 years). Key variation in values is a result of the variation in recurrent GHG emissions during the estimated timeframes. The annual GHG emission cost ($GHGC_{pa}$) is then shown for the different periods. This approach is highly sensitive to the rate used to capitalise the annual emissions and assumes an in-perpetuity perspective. Whilst a conservative economic value was used, this is an area for future research.

Table 4 provides the second income approach, which used the discounted cash flow approach, and which discounts the net annual GHG emissions to generate a PV, or net PV.

The cashflow approach demonstrates a more precise approach to modelling actual GHG emission changes across the life-cycle of a building, and also considers the life-cycle timeframes more accurately. The use of a cash flow approach is a common justification for complex property assets, where there are often multiple cash inflows and outflows, which change from year to year (Robinson 1989; Kishore 1996). The limitations of this approach include the consideration of the discount rate used, carbon pricing dynamics, inflation or growth rate sensitivity, and these require further exploration (Geltner & Mei 1995). The use of the cash flow approach provides a more dynamic, yet more complex, approach to estimating the PV of building-related life-cycle GHG emissions.

This case study provides a first attempt at integrating life-cycle GHG emissions into the conceptual evaluation of a residential building. A combination of the social cost of carbon and market pricing can be used to value GHG emissions across the building life-cycle. The income valuation approach then tested the two key methods: first, the capitalisation approach effectively capitalising the annual GHG emissions incurred; and second, the cash flow approach to ascertain the PV of year-on-year GHG emissions over the building life-cycle. Both approaches demonstrate challenges and highlight the implications of different time horizons and life-cycle periods. The cash flow approach provided greater sensitivity and ability to demonstrate the implications of the variations in GHG emissions at different points in time, particularly the consideration and timing of recurrent embodied energy and inflationary aspects of the time value of money. Further research is required to explore the justification of the household discount rates used in both approaches and the sensitivities of the growth factors (inflation measures) used in the cash flow.

5. Discussion

This research has demonstrated an approach for the economic evaluation of a building's life-cycle GHG emissions. The case study analysed demonstrates that embodied GHG emissions represent over 66% of the building's total GHG emissions to 2030, and over 50% to 2050. This demonstrates how critical it is to consider embodied GHG emissions in building-related GHG emission mitigation efforts, but also the considerable potential for creating an economic value understanding for these emissions to assist in these mitigation efforts. The analysis also demonstrates the potential role that GHG emission sequestration, offsets and onsite renewable energy generation can play in reducing building-related life-cycle GHG emissions liability. For the case study building, these aspects decreased the total GHG emissions by 20 tCO₂e by 2030 and 96 tCO₂e by 2050. As the sequestration forms part of the standard building design (due to the amount of timber included in the standard bill of quantities), it can be seen as an easy win in decreasing GHG emissions

liability for building owners at minimal or no additional cost. The inclusion of timber products in building designs (and potentially other materials capable of sequestering carbon) may be seen as a useful, low-cost approach for reducing GHG emissions.

As for onsite generation, not all new buildings have generation capacity included as part of their designs, but their popularity is growing, especially in Australia. However, it is important to be aware of the embodied GHG emissions of these technologies. A hybrid-based LCA study of solar PV found their embodied emissions over 30 years to be 0.03 kgCO₂e/kWh (Meier 2002). The payback period of solar PV systems can vary widely depending on system and contextual characteristics as well as on the scope of the study and its system boundary. The utilisation of real estate market fundamentals in the valuation of onsite generation has been recently explored by Leskinen *et al.* (2020a). Their analysis also used the fundamentals of the income approach, focusing on the discounted cash flow approach, due to its ability to model the cashflows over time, greater sensitivity with growth rates, discount rates and timeframes. Their exploration of the discount rate selection and its influence on the income approach demonstrated the implications of careful selection of variables and the longer term implications and the utilisation of property valuation fundamentals to provide insight into this area of growing interest (Leskinen, Vimpari, & Seppo 2020b).

GHG emissions results can be used to help provide a much-needed economic assessment and a conceptual evaluation of the GHG emissions associated with a building. When considered from an economic value perspective, although there is a range, the value of GHG emissions was found to be between A\$4650 and A\$7860 over 30 years. With studies such as that by Thorpe (2019) showing that, in a recent survey, 50% of homeowners want more environmentally friendly homes, and Kane (2016) showing that 89% of homeowners find environmentally friendly homes more attractive to rent or buy, this study's findings provide an example of the potential benefits of low-emissions buildings and the theoretical long-term economic cost implications of poorly performing buildings. A recent Australia-based study by Warren-Myers (2017) found that one-fifth of its survey respondents were not willing to pay for more environmentally friendly features in their homes, while one-third of the participants would consider paying up to 5–10% more. Based on the average new house in Australia costing A\$320,000 (although a range of factors affect this price) (Delahunty 2019), the economic evaluation of the case study's GHG emissions represents between 1% and 2% extra (which is well within the reported range provided by Warren-Myers 2017).

The economic findings from this study could form a basis for raising the awareness of new homebuyers, particularly if they are provided with options on how to reduce or further offset emissions. The sensitivity and modelling processes could then be used to develop dynamic assessment for consumers, so that decision-making at design inception can be better informed and consumers can see how their decisions will alter the GHG emissions outcome and potential costs. The approach may then be a new form of cost–benefit analysis, particularly if governments begin to consider carbon taxes and similar mechanisms, which may eventually affect the construction industry.

There is a need to accelerate life-cycle GHG emission considerations in new building design, and there needs to be market creation and policies that reward its uptake. One of the most obvious ways would be to implement a carbon price, which helps to translate the environmental benefit into a financial one. This study shows that the effective cost for one household would be over A\$2000 for the first year and culminating to almost A\$5000 in just 10 years. At present more than 40 governments worldwide have now adopted some sort of price on carbon; however, many carbon pricing programmes today are modest (Plumer & Popovich 2019). The success of carbon pricing can be seen in the UK, where GHG emissions have fallen to their lowest levels since 1890 with a carbon tax prompting electric utilities to switch away from coal, or in Canada which currently has one of the most ambitious carbon pricing programmes in the world (Plumer & Popovich 2019). The impact of this cost could possibly lead consumers to be more willing to pay more for energy efficiency or life-cycle GHG emissions-reduction measures if it leads to a potential decrease in total carbon price.

Ball (2018) argues that, in theory, carbon pricing makes sense, but in practice it is failing for two reasons: structurally, carbon pricing tends to constrain emissions mostly in the electricity sector, leaving the transportation and building sectors largely unaffected; and politically, even those governments that have imposed carbon prices have lacked the fortitude to set them high enough to significantly curb even electricity emissions. This study helps to counteract one of these reasons by demonstrating an economic evaluation of GHG emissions, and how this basis could form a starting point for changes in decision-making and potentially policy in the form of a carbon tax on buildings. Governments, however, will have to work towards counteracting the second hurdle of low pricing standards.

Embodied GHG emissions are often considered 'unseen' and there is a greater risk of building occupants and developers not caring about this environmental aspect. This is also reflected in the present focus of both policy-makers and the private sector, with operational energy at the forefront, due to the financial costs evident in the form of utility bills. The future liability of embodied energy and GHG emissions is also much more complicated, as, first, there is a great amount of uncertainty when it comes to the replacement rates of materials. For a homeowner to invest in a material that will most likely not affect them during their foreseen occupation of the building is much more unclear (a typical homebuyer, for example, is expected to move every 13 years, and younger households move more frequently) (ABS 2010). The inclusion of embodied GHG emissions in building analysis is still in its infancy and the economic value of this consideration is a critical area of further research to help increase its uptake. Studies that have considered this in more detail include Langston & Langston (2008) and Wu *et al.* (2015), who stated that the correlation between initial

embodied energy and capital costs is very strong; and Sturgis & Roberts (2010), who state that from a purely financial point of view, reducing embodied GHG emissions through design can be more effective than reducing operational emissions. In addition, a sole focus on operational GHG emissions may lead to increases in embodied GHG emissions, as demonstrated by Crawford *et al.* (2016), who found that by increasing the thermal performance of a building and theoretically reducing operational energy associated with heating and cooling, the increase in embodied energy from new materials and systems may outweigh the long-term operational energy savings.

6. Conclusions

A conceptual approach was presented for the economic evaluation of the life-cycle greenhouse gas (GHG) emissions associated with buildings. The novel aspect of this approach is the evaluation of a building's embodied GHG emissions. This approach provides an economic value that could better communicate to homeowners and developers the impact of their design decisions as well as the short- and long-term economic liabilities. A case study was used to demonstrate the application of the approach, which showed the significance of embodied GHG emissions across the life of a typical Australian house, the potential to reduce net GHG emissions through carbon sequestration, onsite energy generation and offsetting, and the potential economic liability associated with these emissions. It is anticipated that by integrating an understanding of a building's life-cycle GHG emissions with an attributed economic liability, decision-makers (*e.g.* architects, planners and urban designers) will be incentivised to make more considered choices in order to lower the short- and long-term liabilities for themselves, their clients and building occupants.

This research provides an initial demonstration of the challenges that need to be explored from the economic perspective. Future research includes the investigation of how GHG emissions can be incorporated and considered in real estate valuation; as identification of the 'value' will enhance decision-making in relation to GHG emissions and generate mainstream engagement with property stakeholders to reduce GHG emissions. For this to occur, further investigation of what metrics, assessment approaches and mechanisms are required to drive the financial consideration of GHG emissions across a building's life-cycle, and identify pivotal drivers for consideration in real estate valuation practice. In addition, applying this approach to more building typologies such as commercial buildings, to better understand the potential of this approach for reducing broader construction industry GHG emissions. Further work is also needed to test the approach on key stakeholders to gain a further understanding about whether such evaluations of building emissions would influence decision-making during the design, construction and use of buildings. This must include the identification of opportunities for how this approach could be implemented to drive changes in decision-making that would lead to the greatest reductions in GHG emissions across the building life-cycle.

Author contributions

R.C. and G.W.M. conceived the research and secured funding. M.S. conducted the case study analysis. M.S., R.C. and G.W.M. wrote the paper.

Competing interests

The authors have no competing interests to declare.

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