Study Report

SR470 [2022]

Marginal abatement cost curves for the built environment: Developing a methodology

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Preface

This study report outlines the development of a method to construct marginal abatement cost curves (MACCs) for the New Zealand built environment. It is important to note that the graphs in this report are illustrative only and should not be used for analytical or decision-making purposes.

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Abstract

Although marginal abatement cost curves (MACCs) have been used to illustrate the cost and carbon reduction potential of replacement technologies relevant to housing in New Zealand, there has been limited application of MACCs at the individual building level. This research explores the processes, inputs and methodology necessary to produce MACCs relevant to new builds at the individual dwelling and projected cumulative stock levels.

Keywords

Marginal abatement cost curves, MACCs, New Zealand building and construction, embodied and operational carbon abatement potential, NPV, net present value, building envelope or fabric, interventions or technologies to reduce carbon or CO_2 emissions, energy modelling.

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Executive summary

Through summarising the results of complex scientific and economic data in visual format, marginal abatement cost curves (MACCs) are a convenient and simple way in which to communicate the cost and potential carbon savings of different measures (Saujot & Lefèvre, 2016) across an economy.

To date, there has been limited application of MACCs in the New Zealand building and construction sector. This study identifies the analytical parameters, inputs, processes, data and methodology necessary for the development of MACCs at the individual dwelling level relevant to the New Zealand building and construction industry.

Access to energy and construction simulation data enabled the experimental application of the methodology and the production of an albeit limited set of sample MACCs. Although the focus of the sample MACCs is on the carbon abatement potential and cost of alternative insulation interventions during the initial construction of a dwelling, the study could serve as a guideline for a range of bottom-up MACC applications. As such, the methodology put forward mirrors aspects of a study by Rysanek and Choudhary (2013) that focused on the marginal abatement cost and potential of retrofit interventions at the individual building level.

Energy and construction simulation data was used to develop sample MACCs that illustrate the carbon-saving potential and additional cost of a range of building envelope upgrades aimed at improving the thermal performance and carbon footprint of a typical single-level stand-alone dwelling. Projected construction activity data was then used to extrapolate sample MACCs that demonstrate the total annual and cumulative abatement potential and cost of the stock of single-level stand-alone dwellings to be constructed in New Zealand between 2020 and 2050.

The study exemplifies some of the limitations that permeate academic literature on the application of MACCs. In the absence of data on consumer preferences, the sample MACCs in this study exclude a consideration of the revealed preference of potential MACC end users. Sequential optimisation would furthermore have enabled researchers to identify least-cost additional measures when combined with first-order options. The MACCs in this study are therefore illustrative[1] and not reflective of the true cost and potential of abatement measures. However, marginal abatement cost analysis is complex, and this study only provides a partial solution to developing true MACCs.

Notwithstanding these limitations, MACCs provide an effective way to communicate the findings and likely environmental impact of research projects aimed at identifying optimal abatement strategies in building and construction. As such, increased application of MACCs at the individual building as well as stock level could add momentum to behavioural change through improved visualisation of carbon abatement options and their likely environmental impact.

[1] Illustrative MACCs simplify interactions between measures in order to circumvent any requirement for large-scale optimisation and/or physical simulation. True MACCs are created with the support of sequential optimisation modelling at each stage of development (Rysanek & Choudhary, 2013).

1. Research parameters

1.1 Research question

Transitioning to a net-zero carbon economy in less than 30 years (Ministry for the Environment, 2021) will require difficult decisions and costly trade-offs between ways in which to achieve this (Vogt-Schilb & Hallegate, 2014).

Marginal abatement cost curves (MACCs) – also known as McKinsey curves (Royal Society of New Zealand, 2016) – capture the relative financial cost or saving associated with options to reduce greenhouse gas emissions and the amount of emissions that could be avoided by each option over a set timeframe.

MACCs can add value in communicating the results of complex environmental modelling if used in conjunction with a broader set of decision-making tools (Ekins et al., 2011). However, to date, there has been limited application of MACCs in the New Zealand[2] construction sector compared to countries such as the UK and USA.

This Building Research Levy-funded BRANZ research is focused on answering the following question:

> What are the parameters, methodology and data inputs and outputs necessary to construct marginal abatement cost curves (MACCs) for the New Zealand building and construction industry?

Application of a consistent analytical framework to understand the carbon abatement potential and cost-efficiency of abatement measures across the building and construction sector is likely to contribute to New Zealand's net-zero carbon objectives being met.

1.2 Research scope

Given the wide range of stakeholders with a potential interest in the development of a method to construct MACCs for the New Zealand building and construction industry, a technical interest group (TIG) was convened in March 2020 to inform the scope of the research. The following agencies participated in the group:

- New Zealand Green Building Council (NZGBC)
- Ministry of Business, Innovation and Employment (MBIE)
- Energy Efficiency and Conservation Authority (EECA)
- Ministry of Housing and Urban Development (HUD)
- Ministry for the Environment
- MOTU
- Kāinga Ora.

[2] The absence of any published MACCs for key sectors in the New Zealand economy hampers technical analysis and public discussion about feasible mitigation options and pathways. They can provide a very useful means of gaining a better and quantitative understanding of New Zealand's options and choices towards a low-carbon future and could also be a useful tool to assist prioritising areas for R&D investment by government. However, given the shortcomings of MACCs, it is not suggested that they should dictate policy decisions about mitigation priorities (Royal Society of New Zealand, 2016).

The TIG provided the following feedback regarding the scope of the research:

- Given the potential complexity, time and cost associated with generating new as opposed to existing data, the TIG supported the use of existing environmental and economic modelling data to inform the research.
- The TIG was supportive of including operational and embodied carbon abatement potential but noted that the availability of data would ultimately dictate the scope of the current research.
- Given that the audience and likely end users of MACCs in the construction sector are expected to be decision makers at the pre-construction phase (builders, government agencies and potential owners), the TIG expressed a preference for the development of a consumer or end-user focused (bottom-up) methodology. Although a holistic or systems-driven (top-down) methodology could provide valuable insights regarding changes in the carbon footprint of housing or the construction sector, it would not necessarily be useful to inform the implementation of cost-efficient carbon abatement strategies at the consumer and industry level.
- TIG members noted that, from an end-user perspective, a MAC method that focused on the construction of new residential dwellings would potentially have the most application – and impact – across the building and construction sector. Although future research could consider the existing stock of residential and/or commercial buildings, the current research has been limited to the construction of (or yet to be constructed) residential dwellings.

In addition to identifying the parameters, methodology and data inputs and outputs necessary to construct MACCs, this study report also includes the application and validation of the MACC methodology put forward and the production of sample curves.

1.3 Research approach

A mixed-methods approach was used consisting of a literature review, industry guidance on scope and a cross-agency data analysis working group to test the logic of the theoretical framework underpinning the MACC methodology put forward in this study.

1.3.1 Literature review

Three independent literature reviews were undertaken during the research.

The study began with a systematic review of academic articles on the development and use of MACCs relevant to the construction sector in New Zealand or globally. It focused on identifying the technical requirements, assumptions, data inputs and calculation formulae necessary to undertake MACC analyses.

The search engines used included SAGE Journals, Taylor & Francis Online, Informit, SpringerLink, JSTOR and Google Scholar. No search restrictions (i.e. date of publication) were used to limit the scope of the search findings.

Search terms included: marginal abatement cost curves; MACCs; New Zealand building and construction; top-down vs bottom-up; methodology; embodied and operational carbon abatement potential; cost benefit analysis; MAC analysis; NPV or net present value; building envelope or fabric; residential vs commercial; cost of reducing carbon; interventions or technologies to reduce carbon or CO_2 emissions; wall, roof, floor insulation and glazing; design parameter; energy modelling; application and limitations; graphic illustration.

Article filtering was conducted to exclude articles that were not thematically relevant (i.e. relating to agriculture or transport). The search shed data files of non-academic articles such as book reviews, news items, editorial material, meeting abstracts and books.

Although the initial literature review identified numerous examples of the application of MACCs in other jurisdictions (see section 2.4), it produced limited evidence of the application of MACCs in New Zealand (see section 2.3). Following an analysis of the initial review findings, a second comprehensive literature review was undertaken by the BRANZ Research Librarian. This review produced no new results.

Towards the final stages of the study, the researcher commissioned a third literature review to identify the application of MACCs in the domestic or global construction industry. Although not yielding any additional results, this review validated the findings of the two previous literature reviews. The results of the literature reviews are discussed in sections 2.3 and 2.4 of this study Report.

1.3.2 Data analysis working group

A working group was responsible for testing the logic of the basic theoretical framework developed underpinning the MACC methodology put forward in this study.

The group consisted of:

- Edward Griffin, Principal Analyst Performance, MBIE
- Christian Hoerning, Senior Advisor Building Science, MBIE
- Daniel du Plessis, Senior Research Economist, BRANZ.

The group focused on overseeing the application and analysis of data associated with the residential insulation requirements of NZBC clause H1 *Energy efficiency* Acceptable Solution H1/AS1 for housing and small buildings.

1.4 Report structure

The remainder of this report is divided into five parts. Section 2 introduces the basic theoretical elements and concepts of MACCs. It describes what MACCs are and how they should be interpreted and identifies where and how MACCs have been applied in New Zealand and overseas.

With a focus on methodology, section 3 describes the range of approaches that could be taken to MACC analysis and the development of MACCs. It identifies the advantages and limitations of each approach and highlights the technical aspects to be considered when deciding on a specific MACC development approach.

Section 4 documents the process researchers followed to construct a pilot set of MACCs. It consists of 15 steps and provides a framework for developing bottom-up MACCs relevant to the New Zealand building and construction industry.

Section 5 provides a brief analysis of the sample MACCs that were produced based on the development methodology put forward in this study. It also documents some of the analytical concerns and limitations associated with MACCs.

The report concludes with research observations ad recommendations in section 6.

2. Marginal abatement cost curves (MACCs)

2.1 Introduction

The MACCs research TIG met in March 2020 to provide feedback on the potential scope and application of the research to be undertaken. By way of introduction, members were provided with a brief outline of some of the early findings of the initial literature review. This included a consideration of various definitions of marginal abatement cost (MAC) and marginal abatement cost analysis (MAC analysis) and the basic principles embodied in a marginal abatement cost curve (MACC) documented below.

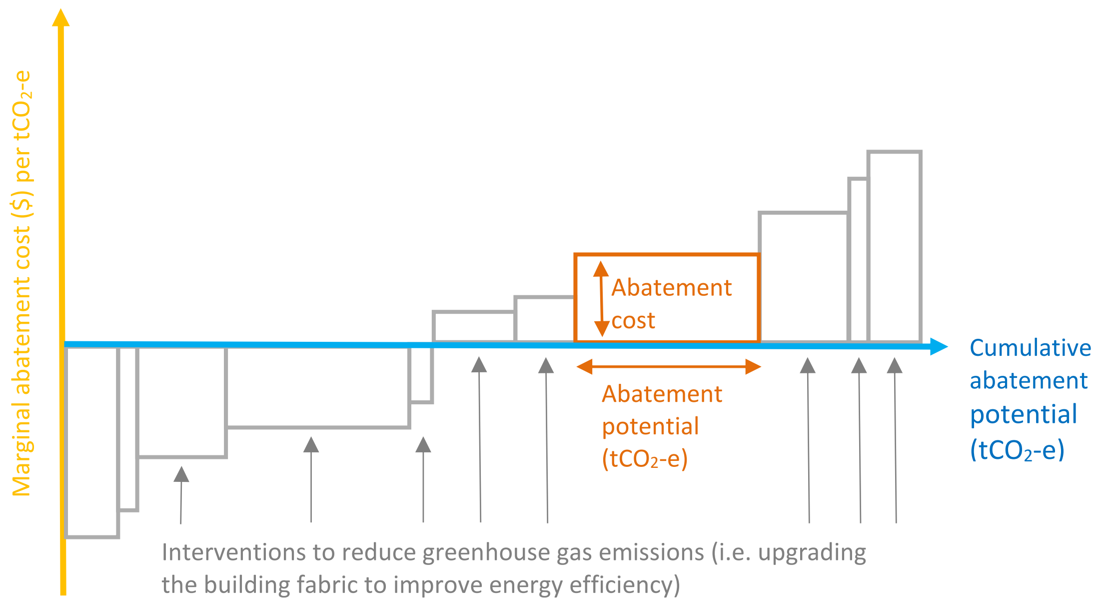
2.2 What is a marginal abatement cost curve (MACC)?

Kesicki (2011, p. 3) defines a MACC as:

> a graph that indicates the cost ($), associated with the last unit (the marginal cost) of emission abatement for varying amounts of emission reduction (tonnes of CO_2 equivalent).

By summarising the results of highly complex scientific and economic data in visual format, a MACC provides a simple visualisation of the cost-effectiveness of a range of interventions aimed at reducing greenhouse gas (GHG) emissions in terms of cost per tonne of carbon dioxide equivalent ($/t$CO_2$-e) saved. It provides a clear comparison of the range of interventions available, based on their relative cost per tonne of carbon saved, by grouping intervention options from least to highest cost per tonne (United Nations et al., 2005; Pye et al., 2008; Almihoub, Mula & Rahman, 2013; Requate, 2013; Vogt-Schilb & Hallegate, 2014; Saujot & Lefèvre, 2016; Department of Communications, Climate Action and Environment, 2019; Ministry for the Environment, 2020a).

A simplified hypothetical example of a MACC is shown in Figure 1.



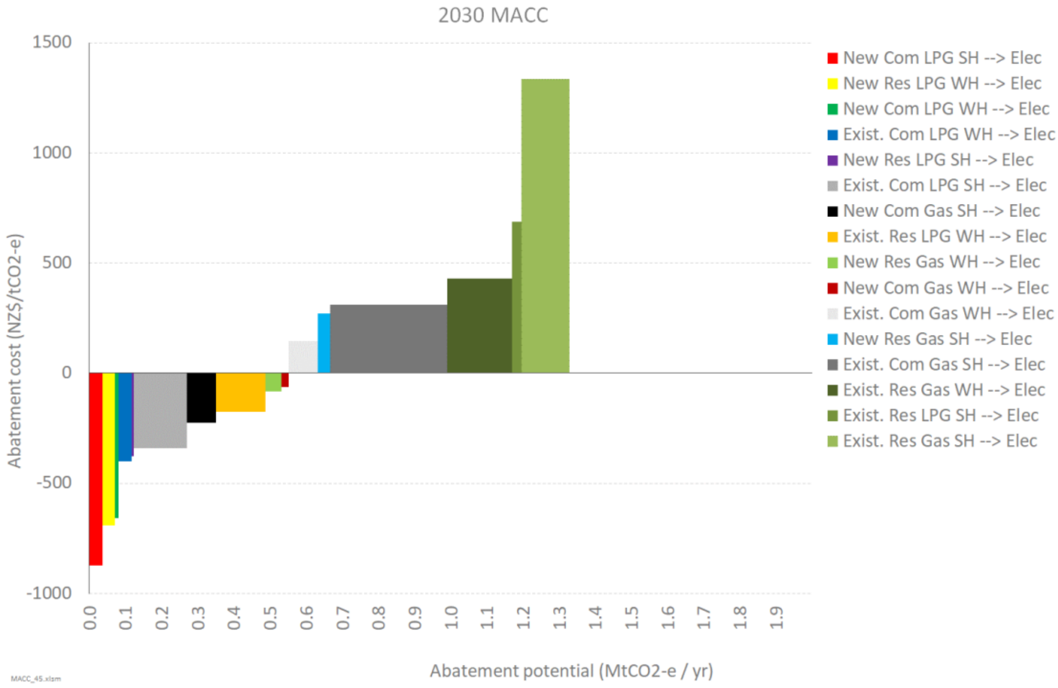
Source: Ministry for the Environment, 2020a.

Figure 1. Stylised example of a marginal abatement cost curve (MACC).

In Figure 1:

- marginal abatement cost (MAC) per tonne of CO_2 is measured along the y-axis and the cumulative abatement potential of all options under consideration is measured along the x-axis
- blocks that fall below the x-axis indicate a net marginal abatement saving and those above a marginal abatement cost – the x-axis intersects the y-axis at $0
- each block in the graph represents a specific abatement option
- block height (position on the y-axis) indicates the MAC of specific options while block width reflects the total amount of carbon that could potentially be avoided by each option.

Figure 2 is an example of a MACC for residential and commercial space and water heating.



Source: Ministry for the Environment, 2020a, p. 62.

Figure 2. Example of a MACC for residential and commercial space and water heating with 2030 as target date.

Moving from left to right on the x-axis, the first bar on the MACC indicates that using electricity in lieu of LPG for new commercial space heating purposes would result in a potential cost saving (negative marginal or no additional cost) of approximately $800 per tonne of tCO_2-e. Using electricity in lieu of LPG for new commercial space heating purposes would furthermore reduce current emissions by approximately 0.04 $MtCO_2$-e per year using 2030 as target date.

Likewise, the second bar indicates that using electricity in lieu of LPG for new residential water heating purposes would result in a potential cost saving (negative marginal or no additional cost) of approximately $650 per tonne of tCO_2-e. Using electricity in lieu of LPG for new residential water heating purposes would furthermore reduce current emissions by approximately 0.04 $MtCO_2$-e per year using 2030 as target date.

The most expensive option to reduce carbon, represented by the bar on the far right of the curve, would be to replace existing residential natural gas space heating with electricity – an additional cost of approximately $1,300 per tonne of CO_2-e. Doing so could be expected to reduce current emissions by approximately 0.1 MtCO_2-e per year using 2030 as target date.

2.3 Application of MACCs in New Zealand

The most comprehensive example of the application of MACCs in New Zealand was published by the Ministry for the Environment in 2020. The report describes the progress and results of stage 1 of the Ministry's work on MACCs for New Zealand. Although the report includes an analysis of space and water heating relevant to the building and construction sector, it focuses on technological options associated with switching away from the direct use of fossil fuels (natural gas and LPG) to electric space and water heating, from a national economic/public perspective (Ministry for the Environment, 2020a).

Queenstown Lakes District Council (QLDC) recently published a report (Comendant et al., 2020) that provides a summary of the scenarios and pathways developed for QLDC's emissions reduction roadmap and includes the use of MACCs.

In March last year, Ernst & Young (2021) published a report for Great South to establish a baseline for carbon abatement and a high-level economic assessment of achieving net zero greenhouse gas emissions at regional scale for Southland. Two emission reduction themes were explored: technology and innovation, and land use and agriculture. The analysis uses marginal abatement cost estimates to inform assumptions on start date and uptake rate of key technology options in the transport, electricity, LPG and waste sectors.

The challenge in the research for this study report was that successive literature reviews were unable to identify any previous attempts to develop a methodology to construct MACCs relevant to the New Zealand building and construction industry from a bottom-up or consumer/producer perspective. Most of these examples were developed using a top-down, national or planetary limit approach as opposed to the bottom-up methodology followed in this study.

2.4 Application of MACCs in other jurisdictions

The global application of MACCs as an analytical tool in environmental economics increased markedly since McKinsey published its first global greenhouse gas abatement curve (Creyts et al., 2007). National GHG abatement studies have since been undertaken in some of the world's largest economies including, but not limited to, the United States, United Kingdom, Ireland, Australia, China, Japan, India, Brazil, Russia, Germany and Sweden. Appendix A summarises literature review findings on the use of MACCs in other jurisdictions.

Countries such as the United Kingdom have adopted the use of MACCs for the macro-analysis of its building stock. As such, MACCs were used to inform the embodied energy analysis in the UK Low Carbon Transition Plan (Department of Energy and Climate Change, 2009). It was also an integral component of the work of the UK Committee on Climate Change (2008).

Recent examples of the use of MACCs in the UK relevant to the construction sector are summarised in Table 1.

Table 1. Application of MACCs in the UK construction sector

Year	Purpose and application	Methodological approach	Reference
2013	Explored a technique for generating marginal abatement cost curves for individual buildings.	Bottom up	Energy Efficient Cities Initiative, University of Cambridge – www.eeci.cam.ac.uk
2013	Used MACCs to highlight the significance of embodied emissions when considering GHG emissions reduction strategies.	Bottom up	Ibn-Mohammed et al., 2013
2013	Considered options to retrofit existing housing (suburban cavity-walled semi-detached house).	Bottom up	Passivhaus Trust UK – www.passivhaustrust.org.uk
2019	Considered the reuse of steel beams in construction and specifying optimal lightweight beams in construction.	Bottom up	Dunant et al., 2019
2019	Considered the utility impact and direct emissions of buildings.	Bottom up	London Borough of Hounslow – www.hounslow.gov.uk
2020	Explored decarbonisation options using energy systems analysis to derive system-wide MACCs. Decomposition analysis was then used to associate decarbonisation options with carbon abatement costs.	Top down	Yue et al. 2020
2021	Explored the carbon-reducing potential of individual space and water heating abatement measures on household greenhouse gas emissions.	Bottom up	Rafique & Williams, 2021

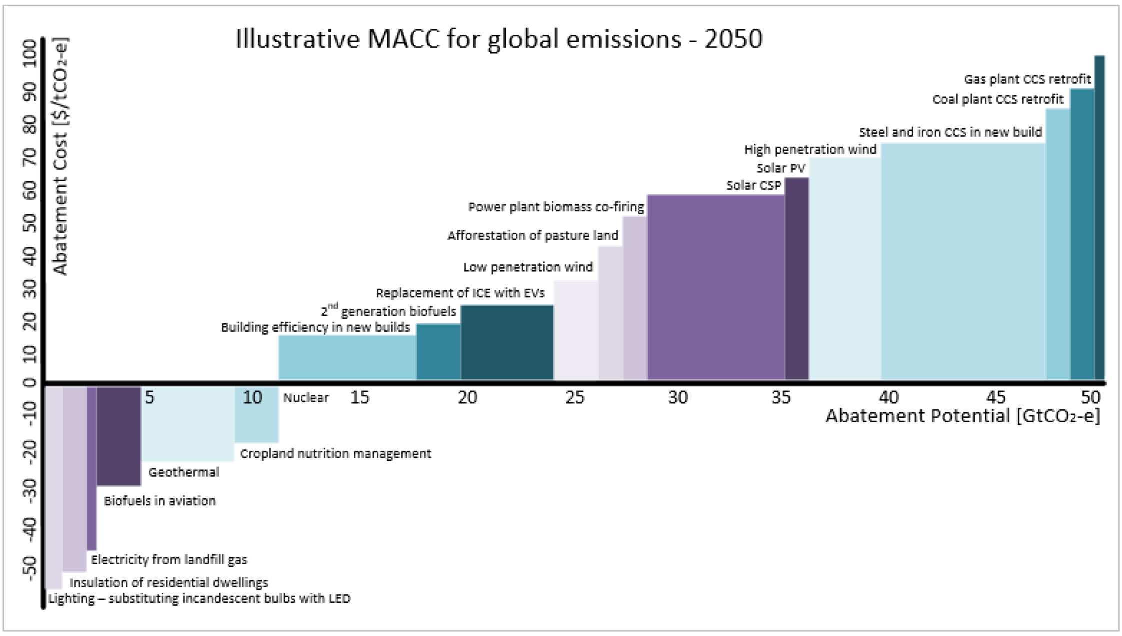
3. Analytical approaches to developing marginal abatement cost curves

There are several ways in which to approach the development of MACCs, each with its own merits and pitfalls (Almihoub et al., 2013). However, the most appropriate MACC development approach will generally be dictated by the scope and objective of the MAC research, data availability and the end user's intended application.

MACCs fall into two broad categories based on the underlying methodological approach taken during development. As such, MACCs are developed from either a top-down or bottom-up perspective (Kesicki, 2011).

3.1 Top-down or bottom-up development approach

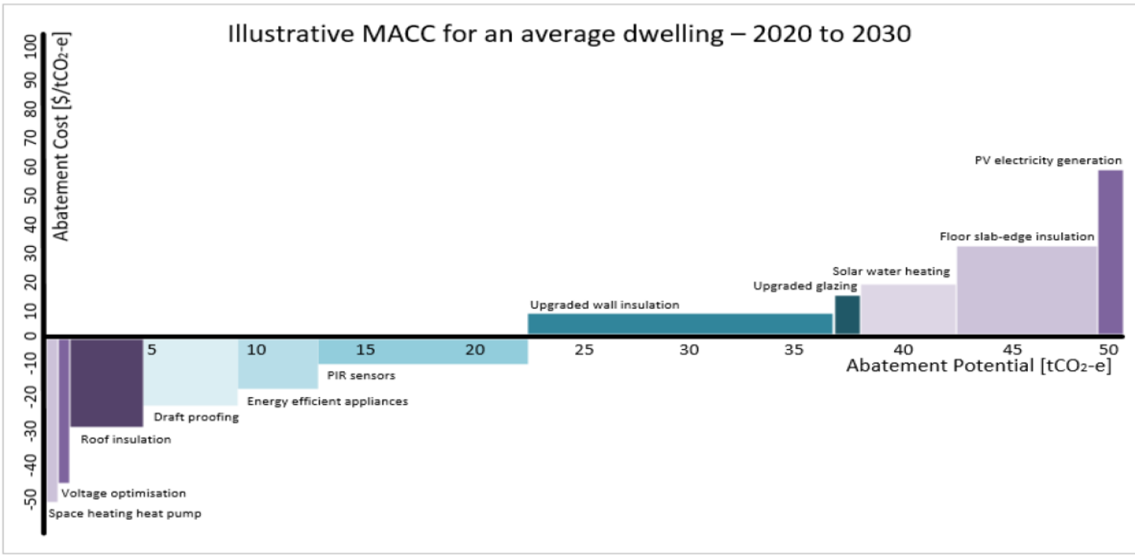
MACCs that have been developed following a top-down approach consider carbon abatement options and costs from a macro-economic or economy-wide perspective. Top-down MACCs generally use current (and estimated) global, national or sectoral CO_2-e emissions profiles as an analytical point of departure. Wholesale abatement measures are then modelled across a range of sectors in the economy and results plotted based on estimated cost per tonne of CO_2 potentially avoided. Figure 3 demonstrates a MACC that has been developed using a top-down approach.



Source: Illustrative.

Figure 3. Example of a top-down MACC.

MACCs that have been developed from a bottom-up perspective illustrate the relative cost of various abatement options from a consumer or producer input perspective (Dunant et al., 2019). MAC analysis from a consumer viewpoint provides an understanding of the likely market response to an emissions price or other policies (Ministry for the Environment, 2020a). Figure 4 demonstrates a MACC that has been developed using a bottom-up approach. It demonstrates the illustrative abatement potential and cost of carbon abatement measures associated with a single hypothetical dwelling over a 10-year period.



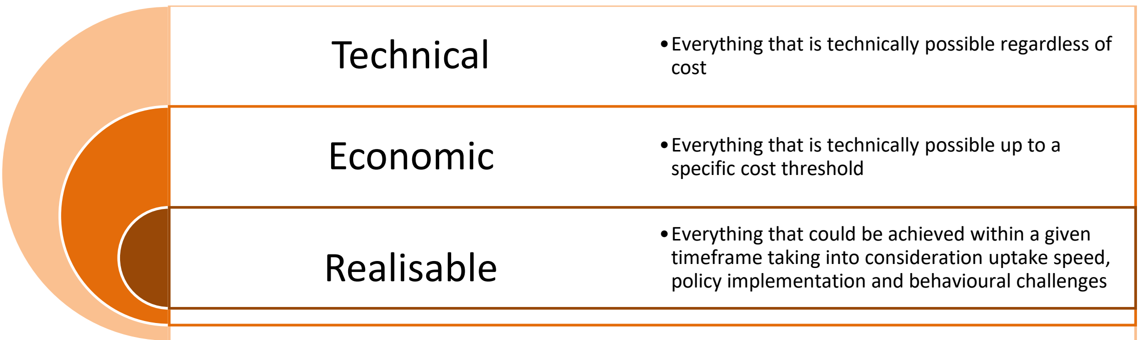
Source: Illustrative.

Figure 4. Example of a bottom-up MACC

Kesicki (2011) defines the difference between top-down and bottom-up MACCs as economy-oriented versus engineering-oriented MACCs. By providing more detail about the drivers of abatement, bottom-up MACCs permit the tracking of emissions reductions associated with a specific intervention. However, it is important to note that neither the top-down nor the bottom-up approach to developing MACCs has been shown to outperform the other. Research has shown that it is possible for one approach to complement the limitations of the other (Wing & Timilsina, 2016).

3.2 Analytical approaches to specifying abatement potential

The abatement potential that could be illustrated in a MACC will differ depending on the assumptions underpinning the MAC analysis. As illustrated in Figure 5, MACCs can demonstrate the technical (full), economic or realisable (achievable) potential of carbon abatement options.



Source: Ministry for the Environment, 2020a.

Figure 5. Abatement potential levels.

3.2.1 Technical or full-potential MACCs

Technical or full-potential MACCs assume the full realisation of technical (or theoretical) carbon savings and do not consider the likely impact of technological challenges, behavioural responses or the time it will take to realise the calculated abatement potential. In doing so, technical abatement potential runs the risk of overstating potential realistic carbon savings (Vogt-Schilb & Hallegate, 2014).

For example, in assessing the potential carbon savings associated with a wholesale replacement of all fossil fuel capacity in favour of nuclear power in the USA, Rubin and others (1992) used baseload and intermediate load operation, assuming nuclear power would be suitable for baseload and intermediate load but not for providing peak power (Vogt-Schilb & Hallegate, 2014). Likewise, a MACC that has been developed from a technical potential perspective would assume that the potential net carbon savings associated with retrofitting various elements of the New Zealand housing stock would accrue the total abatement potential of the entire housing stock from year one. In reality, time, potential cost barriers and end use would result in slower than anticipated uptake of some of the interventions and others never reaching their full technical abatement potential due to suboptimal utilisation or underutilisation.

3.2.2 Economic potential MACCs

MACCs that are developed to demonstrate economic potential are similar to technical or full-potential MACCs but have set economic and financial boundaries. Put simply, economic potential MACCs illustrate what is technically possible within a set budget (Fankhauser, Kennedy & Skea, 2009). Economic abatement potential may, however, never be fully realised due to non-financial factors in decision making (Ministry for the Environment, 2020a). For example, while it may be technically feasible to retrofit most of the existing housing stock in New Zealand in a short space of time, it may not be economically feasible to do so.

3.2.3 Realisable potential MACCs

MACCs that illustrate the realisable or achievable potential of abatement interventions incorporate assumptions regarding the projected uptake of interventions. These assumptions include the likely impact of factors such as government policy, behavioural change and diffusion of new technologies over time (Wilson et al., 2013).

Realisable MACCs will reflect lower abatement levels compared with MACCs that illustrate economic abatement potential given some of the implementation lags associated with technology uptake (Ministry for the Environment, 2020a). However, given that realisable potential MACCs incorporate a prospective dimension, they are subject to potential analytical subjectivity, which increases uncertainty.

4. Methodology to develop bottom-up MACCs relevant to the New Zealand building and construction industry

This section of the report captures the step-by-step process that was followed to develop MACCs relevant to the domestic building and construction industry. Figure 6 outlines the conceptual framework that underpinned the development of the methodology.

The framework embodies three core elements:

- The analytical context for the MACC analysis – the focus and scope of the analysis, its objectives and intended application.
- The MACC development approach underpinning the methodology and the analytical principles that guided its development.
- Specification of the analytical parameters and stepwise development of sample MACCs.

The MACC development process consisted of 15 steps:

- Steps 1 and 2 capture the analytical context, approach and principles underpinning the process.
- Step 3 outlines the analytical parameters applied during the development process such as the specification of a baseline and identification of abatement interventions.
- Steps 4–14 are focused on the production and analysis of various scientific and economic data inputs.
- Step 15 outlines the graphic illustration requirements associated with plotting MACCs.

4.1 Step 1: Clarify analysis objectives and expected application

The first step in undertaking a MAC analysis is to clarify the analytical objectives and expected application of the end results. However, as demonstrated in this study, it is possible to develop MACCs retrospectively based on pre-existing data.

4.1.1 Focus and scope of MACC methodology

Figure 7 depicts the total, national-level GHG mitigation potential and costs of key emissions-reduction measures for New Zealand by 2030. By capturing the cost and GHG-mitigation potential of several technologies in a very simple format, the MACC would be of particular interest to policy makers (Rysanek & Choudhary, 2013). A such, the top-down development approach underpinning the MACC could inform an analysis of the likely social costs of meeting carbon reduction targets or be used as a benchmark for carbon pricing.

Likewise, MACCs developed from a bottom-up or individual building perspective may be useful to investors, owners, architects and contractors during the initial planning stages of construction or retrofitting projects.

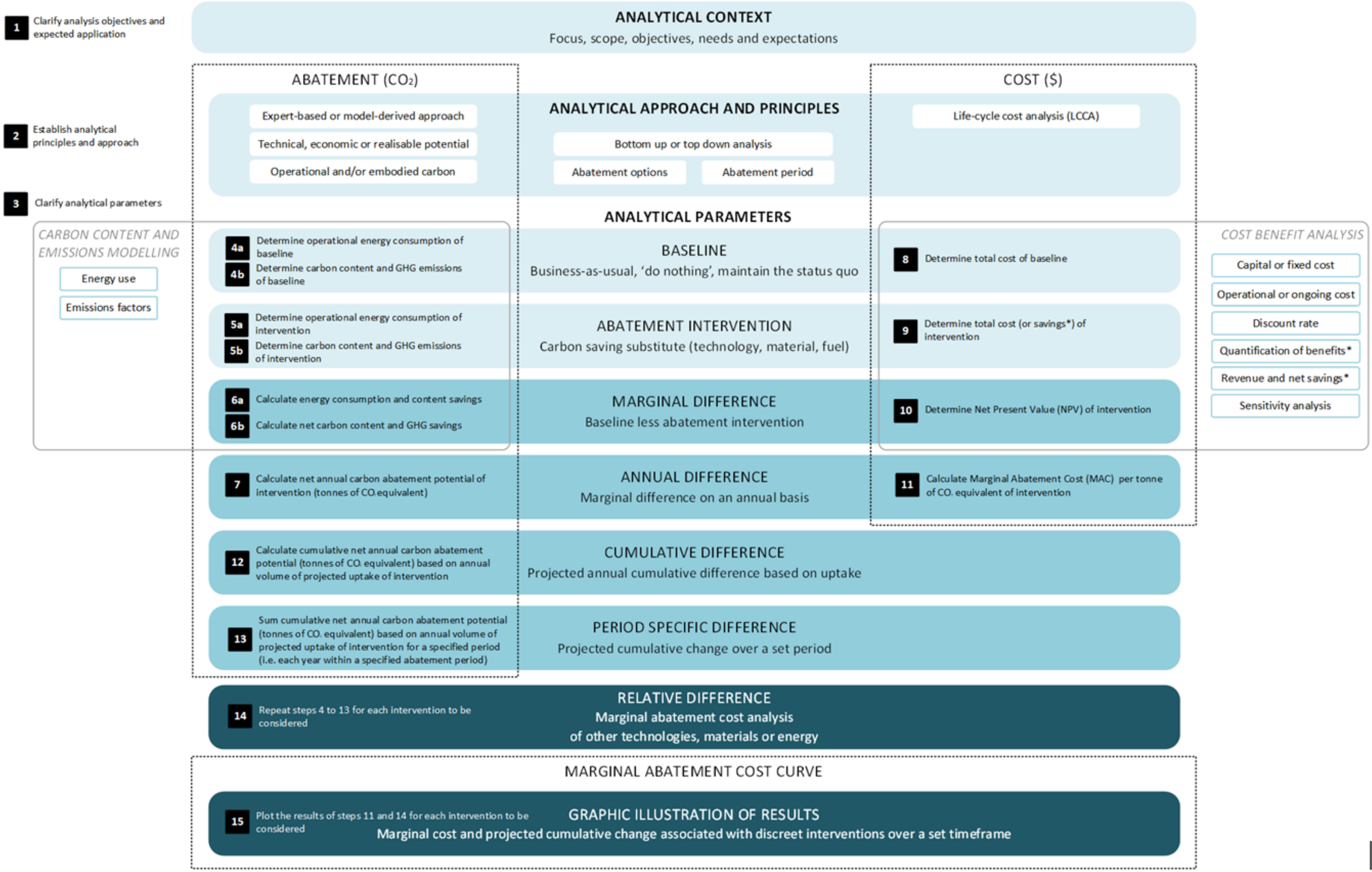
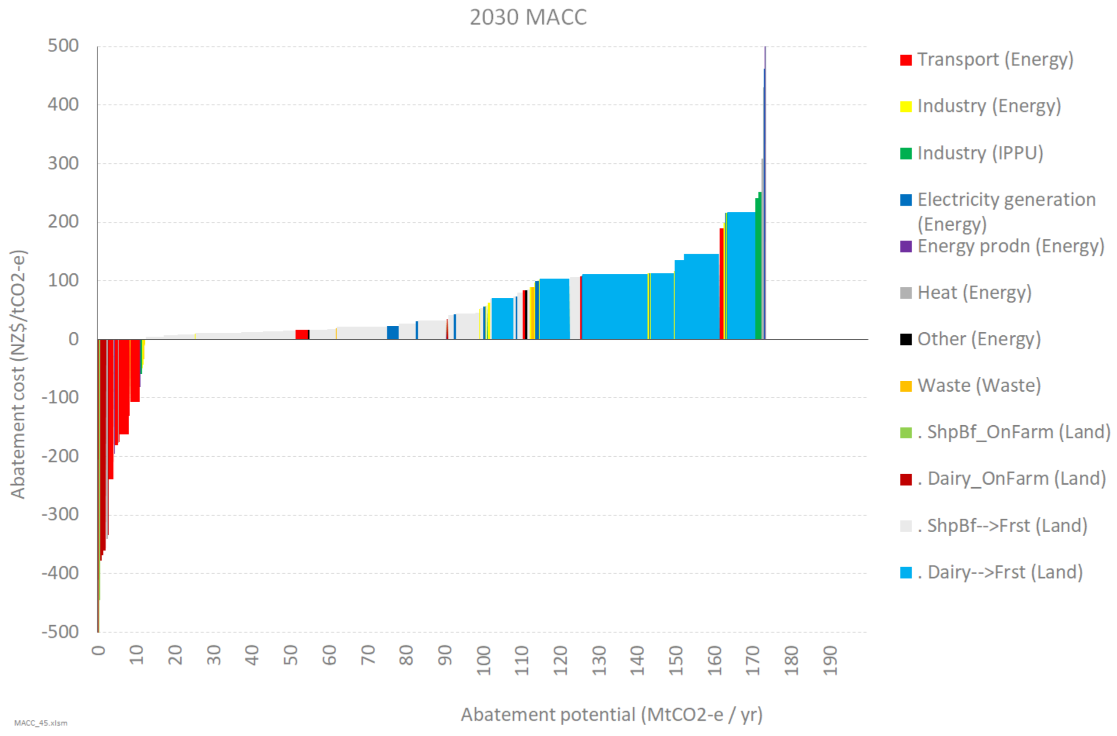


Figure 6. Conceptual framework for undertaking marginal abatement cost (MAC) analysis.



Source: Ministry for the Environment, 2020a, p. 12.

Figure 7. Top-down MACC for non-domestic buildings in the UK, 2008 data, 20-year time horizon.

The methodology put forward in this research mirrors aspects of a study by the Rysanek and Choudhary (2013). It is framed around a MAC analysis of residential insulation interventions for housing and small buildings in New Zealand.

In 2020, MBIE commissioned BRANZ to undertake a technical study to support its policy review of residential insulation requirements of NZBC clause H1 *Energy efficiency* Acceptable Solution H1/AS1 for housing and small buildings (Jaques et al., 2020). The data underpinning this research has been drawn from early analytical results of that MBIE commissioned study. Alignment between the MBIE H1 study and the current research enabled the application of real-world data to the otherwise theoretical scope of the study.

Other vital research inputs are related to the *National Construction Pipeline Report 2020* commissioned by MBIE (BRANZ & Pacifecon, 2020). The report includes projections of the expected number of new dwellings to be built in New Zealand on an annual basis. The BRANZ model underpinning the projections enabled researchers to estimate the number of new dwellings to be built in New Zealand up to 2070. Researchers were therefore able to account for the increase in cumulative carbon abatement potential based on the sequential increase in the housing stock going forward.

4.2 Step 2: Establish analytical principles and approach

The identification of the preferred analytical principles and approach underpinning a MAC analysis sets the technical boundaries of the methodology to be followed. Therefore, given that the objective of the current research is to develop a MACC methodology at the individual building level, it follows a bottom-up development approach.

Since the MACC methodology underpinning this study incorporates a prospective dimension – the gradual increase in abatement potential resulting from a gradual increase in the total stock of new dwellings – it reflects the realisable or achievable abatement potential of the interventions considered (Wilson et al., 2013). An advantage of this approach is that it includes reasonable assumptions regarding the possible implementation speed of the interventions (Vogt-Schilb & Hallegate, 2014).

The abatement period has been arbitrarily set at 31 years (2020–2050 inclusive) to coincide with the New Zealand Government's 2050 net-carbon zero target.

Given that the emissions modelling supporting the research includes both material and energy carbon components, the MAC analysis and graphics reflect embodied and operational carbon abatement potential. Embodied carbon emissions are related to the materials and processes used during construction. This also includes maintenance and periodic replacement during the service life of a building. Such emissions are assessed on a life cycle basis and account for all emissions over the lifetime of a material or product. Operational carbon emissions are associated with the ongoing use of a building, i.e. energy consumption (Ministry of Business, Innovation and Employment, 2020).

4.3 Step 3: Clarify analytical parameters

The third step in the MACC development process focuses on specifying the analytical components and parameters that will govern the analysis. This includes the specification of baseline intervention and emissions scenario and the identification of abatement interventions for comparison purposes.

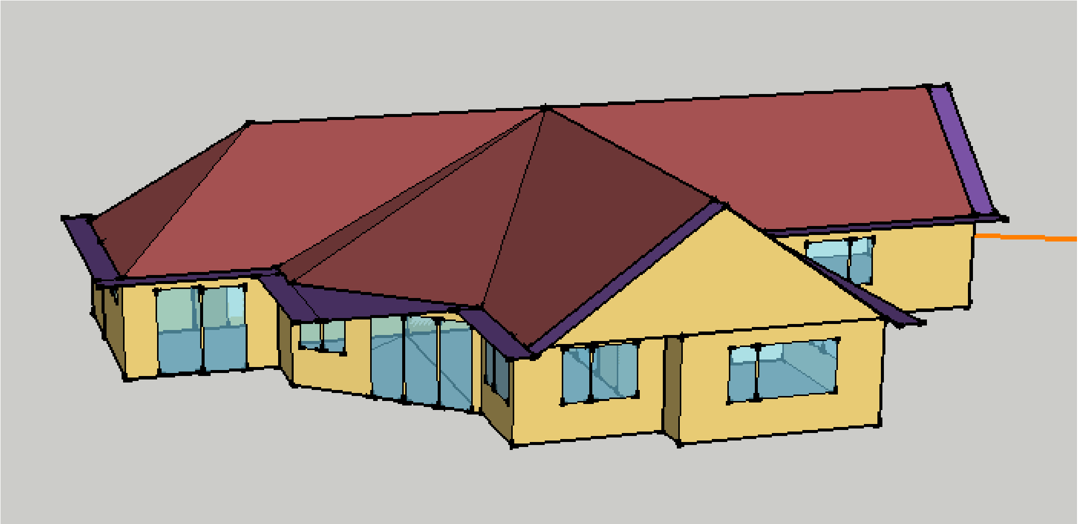
4.3.1 Specification of a baseline

The design parameters of the baseline dwelling used in the MAC analysis of residential insulation interventions for housing and small buildings in New Zealand are based on the baseline parameters applied during the MBIE H1 study (Jaques et al., 2020).

The baseline dwelling is a single-storey, detached house with four bedrooms and a double garage. It has approximately 156 m² of conditioned floor area and a window to wall area ratio of 19%.

The roof construction is based on a typical pitched roof with trusses at 900 mm centres and 90 mm bottom chords providing thermal bridging.

Walls are designed based on light timber-framed construction typical for New Zealand houses. The framing ratio is assumed to be 24%. The floor construction is concrete slab on grade, and aluminium frames are used for glazing scenarios. A three-dimensional schematic of the single-storey detached dwelling is illustrated in Figure 8.



Source: Jaques et al., 2020, p. 7.

Figure 8. Typical single-storey detached dwelling.

4.3.2 Specification of abatement interventions

The research considered a range of insulation upgrades (based on R-values) to selected components of the baseline building envelope as potential abatement interventions aimed at improving the energy efficiency of the baseline dwelling. Improvements in energy efficiency are indicative of a reduction in carbon emissions and the carbon footprint of the baseline dwelling. The technical specifications of the abatement interventions are outlined below.

Increasing roof insulation levels

To achieve higher R-values or levels of insulation, additional insulation is installed on top of existing layers to reduce thermal bridging. The R-values of various roof and ceiling insulation levels are summarised in Table 2.

Table 2. Ceiling insulation and roof construction R-values.

R2.9	**R3.3**	**R3.6**	**R4.3**	**R4.9**	**R5.9**	**R6.6**
R3.2 batts, 5% framing – assumed installed slightly inefficiently to bring R-value down to Code minimum (HIG[3] R3.1)	R3.6 batts, 5% framing – assumed installed slightly inefficiently to bring R-value down to Code minimum (HIG R3.4)	R4.0 batts, 5% framing	R5.0 batts, 5% framing	R3.2 batts between chords + R1.8 batts over top	R3.6 batts between chords + R2.6 batts over top	R3.6 batts between chords + R3.2 batts over top
HIG p. 29	HIG p. 29	HIG p. 29	HIG p. 29			

Source: Jaques et al., 2020, p. 12.

Increasing wall insulation levels

The R-values of various timber wall insulation levels are summarised in Table 3. Note that structural changes are required to increase R-values associated with wall insulation to any significant degree, thereby adding to the embodied carbon content of the dwelling. The additional embodied carbon consequently counteracts some of the operational CO_2 emissions reduction associated with upgrading the levels of insulation.

[3] BRANZ, 2014.

Table 3. External timber wall constructions and construction R-values.

R1.9	R2.0	R2.5	R2.9	R4.0	R4.6
R2.2 batts, 90 mm framing (24%)	R2.6 batts, 90 mm framing (24%)	R2.8 batts, 140 mm framing (24%)	R4.0 batts ultra, 140 mm framing (24%)	R2.2 + R2.2 batts, 2 x 90 mm staggered stud (24%)	R2.8 x 2 batts, 2 x 90 mm staggered stud (24%)
HIG p. 66	HIG p. 66	HIG p. 67	HIG p. 67	HIG p. 71	HIG p. 71

Source: Jaques et al., 2020, p. 13

Increasing glazing levels

The R-values of the glazing scenarios considered are summarised in Table 4.

Table 4. Windows scenarios used and their key values.

R0.26	R0.31	R0.31	R0.39	R0.62
SHGC 0.74	**SHGC 0.74**	**SHGC 0.7**	**SHGC 0.7**	**SHGC 0.4**
Double glazing, aluminium frame	Double glazing, thermally broken aluminium frame	Double glazing, aluminium frame, low-E coating	Double glazing, thermally broken aluminium frame, low-E coating	Triple glazing, thermally broken aluminium frame, low-E coating, argon fill
HIG Table 6	HIG Table 6	HIG Table 6	HIG Table 6	Industry figures

Source: Jaques et al., 2020, p. 14.

4.4 Step 4: Determine operational energy consumption and embodied carbon content and GHG emissions of the baseline dwelling

This step in undertaking the MAC analysis is aimed at determining the carbon footprint of the baseline dwelling. Determining the potential volume of embodied and/or operational carbon of a building is directly related to assumptions regarding the energy supply and occupational use of the dwelling.

4.4.1 Thermal modelling and simulation – determining operational energy consumption

Dynamic thermal modelling of the baseline dwelling (Jaques et al., 2020) was conducted using EnergyPlus (v9.2). Heating and cooling energy consumption were modelled across six climate zones. It is important to note that, as with any process that aims to model reality, thermal performance simulation is based on assumptions that simplify actual performance (BRANZ, 2014).

4.4.2 Thermal modelling and emissions factors – determining GHG emissions and embodied carbon content

Every source of energy (electricity, nuclear, solid fuels), when used, emits a unique amount of carbon (WALGA, 2014) per unit of consumption, referred to as an emissions factor. Multiplying the amount of energy use with its relevant emissions factor provides an estimate of the volume of carbon produced.

Determining the GHG emissions associated with the baseline dwelling

MBIE produces emissions factors for New Zealand (Ministry of Business, Innovation and Employment, 2021). The Ministry for the Environment (2021) produces New Zealand's Greenhouse Gas Inventory on an annual basis as part of New Zealand's obligations under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. The Ministry also publishes a range of guidelines and tools (Ministry for the Environment, 2020b) to assist stakeholders with measuring emissions.

Annual grid carbon intensity figures (expressed as kg CO_2 eq./kWh) were provided by MBIE based on 2019 electricity demand and generation scenarios. Since these figures were provided on a generation basis, they were adapted to include transmission and distribution losses so that they reflected a supply basis.

The final greenhouse gas impact factors were then used to determine the per square metre rate of greenhouse gas emissions of the baseline dwelling.

Determining the embodied carbon content of the baseline dwelling

Greenhouse gas impact factors were identified for materials and summarised in an Excel spreadsheet on a kg CO_2 eq./kg or kg CO_2 eq./m^2 basis. This data included greenhouse gas emissions from manufacturing, transport, use on a construction site and replacing end-of-life materials during the 50-year reference study period. When a material was replaced, this included manufacturing, transportation and installation of the new material as well as end of life of the old material.

In most cases, Jaques et al. (2020) took materials-related greenhouse gas emissions factors from data developed for the New Zealand whole-building whole-of-life framework (www.branz.co.nz/buildinglca) and embedded in publicly available BRANZ resources such as CO_2NSTRUCT (www.branz.co.nz/CO_2nstruct) and LCAQuick (www.branz.co.nz/lcaquick).

4.5 Step 5: Determine operational energy consumption and embodied carbon content and GHG emissions of abatement intervention(s)

Following the establishment of baseline parameters for the embodied and operational carbon components of the baseline dwelling, abatement options (such as the use of R0.31 thermally broken glazing in Auckland) was incorporated or substituted in the design of the baseline dwelling. Dynamic energy modelling was then conducted to determine the energy performance of the substituted material (intervention). Energy demand for heating and cooling was simulated across six different New Zealand climate zones. From this, the associated greenhouse gas emissions over 50 years were calculated assuming that the source of energy for heating and cooling was grid electricity.

4.6 Step 6: Calculate energy consumption and carbon content savings and net carbon content and GHG emission savings

The next step in the development of MACCs focuses on determining the marginal difference between the GHG emissions and carbon content of the baseline dwelling (step 4 above) and the dwelling that incorporates the alternative construction material (step 5 above). Subtracting the results of step 5 from that of step 4 produces the net or marginal amount of carbon that could potentially be avoided, saved or reduced over 50 years with the use of a specific alternative construction material.

Table 5 summarises the net carbon abatement results associated with incorporating a range of glazing abatement options or interventions during the construction of the baseline dwelling.

Table 5. Illustrative marginal carbon abatement potential of a range of glazing options in New Zealand

Climate zone	Abatement option (intervention)	Marginal abatement potential		
		50 years	Annual	
		kgCO_2-e		tCO_2-e
Zone 1 – Auckland	R0.31 (thermally broken)	511	10.22	0.0102
	R0.31 (low-E)	912	18.24	0.0182
	R0.39 (thermally broken and low-E)	1,401	28.02	0.0280
	R0.62 (triple glazing)	3,076	61.52	0.0615
Zone 2 – Napier	R0.31 (thermally broken)	819	16.38	0.0163
	R0.31 (low-E)	1,119	22.38	0.0224
	R0.39 (thermally broken and low-E)	1,983	39.66	0.0397
	R0.62 (triple glazing)	3,680	73.60	0.0736
Zone 3 – Wellington	R0.31 (thermally broken)	1,043	20.86	0.0209
	R0.31 (low-E)	936	18.72	0.0187
	R0.39 (thermally broken and low-E)	2,140	42.80	0.0428
	R0.62 (triple glazing)	2,616	52.32	0.0523
Zone 4 – Tūrangi	R0.31 (thermally broken)	1,318	26.36	0.0264
	R0.31 (low-E)	1,193	23.86	0.0239
	R0.39 (thermally broken and low-E)	2,702	54.04	0.0540
	R0.62 (triple glazing)	3,579	71.58	0.0716
Zone 5 – Christchurch	R0.31 (thermally broken)	1,389	27.78	0.0278
	R0.31 (low-E)	1,175	23.50	0.0235
	R0.39 (thermally broken and low-E)	2,797	55.94	0.0559
	R0.62 (triple glazing)	3,608	72.16	0.0722
Zone 6 – Queenstown	R0.31 (thermally broken)	1,730	34.60	0.0346
	R0.31 (low-E)	1,348	26.96	0.0270
	R0.39 (thermally broken and low-E)	3,388	67.76	0.0678
	R0.62 (triple glazing)	3,906	78.12	0.0781

4.7 Step 7: Calculate annual marginal abatement potential of intervention (tCO_2-e)

During step 7 of the MACC development process, the lifetime abatement potential of each intervention is annualised by dividing the lifetime abatement potential by 50 – the period underpinning the carbon analysis.

The annual kilogram-per-year results are then divided by 1,000 to determine the annual tCO_2-e savings for each intervention option. The results are shown in Table 5.

Determining the annual marginal abatement potential (expressed as tCO_2-e) of each abatement option provides one of two core components in the MACC development process. The other – the marginal abatement cost of interventions – is discussed in step 8.

4.8 Step 8: Determine total cost of baseline

Similar to marginal abatement potential, determining the marginal abatement cost component of a MAC analysis relies on specifying the baseline costs and the cost associated with abatement options.

Life cycle or lifetime cost analysis (Berg, Dowdell & Curtis, 2016) plays an important role in determining the marginal abatement cost of construction-focused carbon abatement measures. It is defined as the consideration of the total cost of ownership over the economic lifetime of a building, including the cost of acquiring, owning and disposing of a building (Fuller, 2010). An earlier BRANZ study defined the lifespan of a dwelling as:

> the period over which a house provides accommodation services appropriate for the current and potential resident household. The span is determined by structural, user specific and economic factors. (Page & Fung, 2009, p. 16)

In terms of operational energy-related cost, it is important to note that there is no explicit rule for how to allow for future resource costs in MAC analysis (WALGA, 2014). Operational costs or operating expenses in the context of the current research relate to the energy use throughout the lifetime of the baseline dwelling – specifically the difference in energy use between the baseline dwelling and various modifications relating to the insulation of the building envelope. Determining the ongoing operational cost differential (or saving) based on energy use is therefore closely associated with considerations related to the energy modelling and emissions factors underpinning the analysis.

To determine appropriate electricity tariffs when calculating energy-related costs, 150 randomly selected, recently constructed New Zealand dwellings were examined. Their tariffs were then investigated, and a region-weighted average tariff was calculated based on its respective new residential construction activity. It has been assumed that there is a 1.2% escalation rate (i.e. real inflation rate) in electricity prices each year.

4.9 Step 9: Determine total cost of abatement intervention

The initial and replacement cost of materials were based on *QV costbuilder* – a transparent online database accessible by industry. It should be noted that prices may vary significantly in practice (anecdotal evidence suggests variance of up to 50% dependent on scale). The total net cost estimates for discrete abatement interventions considered the:

- marginal or additional cost of materials based on R-values
- marginal additional replacement costs of those materials
- the energy cost savings as derived through thermal modelling.

The cost column in Table 6 summarises the marginal or additional cost increase associated with incorporating a range of glazing abatement options or interventions during the construction of the baseline dwelling.

Table 6. Illustrative marginal cost increase associated with incorporating a range of glazing abatement options during the construction of the baseline dwelling

Climate zone	Abatement options (glazing)	Total additional cost over the lifetime of the baseline dwelling
		$
Zone 1 – Auckland	R0.31 (thermally broken)	1,202
	R0.39 (thermally broken and low-E)	2,490
	R0.62 (triple glazing)	6,594
Zone 2 – Napier	R0.31 (thermally broken)	1,202
	R0.31 (low-E)	1,288
	R0.39 (thermally broken and low-E)	2,490
	R0.62 (triple glazing)	6,594
Zone 3 – Wellington	R0.31 (thermally broken)	1,202
	R0.31 (low-E)	1,288
	R0.39 (thermally broken and low-E)	2,490
	R0.62 (triple glazing)	6,594
Zone 4 – Tūrangi	R0.31 (thermally broken)	1,202
	R0.31 (low-E)	1,288
	R0.39 (thermally broken and low-E)	2,490
	R0.62 (triple glazing)	6,594
Zone 5 – Christchurch	R0.31 (thermally broken)	1,202
	R0.31 (low-E)	1,288
	R0.39 (thermally broken and low-E)	2,490
	R0.62 (triple glazing)	6,594
Zone 6 – Queenstown	R0.31 (thermally broken)	1,202
	R0.31 (low-E)	1,288
	R0.39 (thermally broken and low-E)	2,490
	R0.62 (triple glazing)	6,594

4.10 Step 10: Calculate net present value of intervention

Step 10 focuses on calculating the net present value (NPV) of an abatement option. The NPV is determined by summing all of the related costs and savings (step 9) and adjusting it for the time value of money by applying a discount rate.

4.10.1 Discount rate

A discount rate reflects the minimum return an investor or provider of funds could expect from a low-risk investment. It is applied to capital cost during investment decisions to allow for the diminishing value of the capital over time (WALGA, 2014) and is set by those making the investment decision. The purpose of using a discount rate when having to choose between the financial viability of one or more investments, interventions or project options is to account for the risk or uncertainty associated with the future value of the money being invested. Risk or uncertainty associated with an investment (or capital outlay) is generally directly correlated with the potential returns to be made. Low-risk investments generally provide low returns, while high-risk investments provide potential higher returns. From a return-on-investment perspective, a discount rate reflects the return an investor could expect on a near risk-free investment such as a fixed-term deposit with a registered bank. In New Zealand, the Treasury publishes guidance on a range of discount rates applicable to specific investment options and circumstances. Table 7 depicts the most recent rates. Based on the Treasury guidelines, a discount rate of 6% was applied.

Table 7. Treasury discount rate guidelines in New Zealand (The Treasury, 2020).

Category	Annual rate p.a.
Default rate (projects difficult to categorise including regulatory proposals)	6.0%
General-purpose office and accommodation buildings	4.0%
Infrastructure and special purpose (single-use) buildings: • Water and energy • Hospitals • Prisons • Hospital energy plants • Road and other transport projects	6.0%
Telecommunications, media and technology, IT and equipment, knowledge economy (R&D)	7.0%

4.10.2 NPV results

The NPV calculation results relating to various abatement options relevant to the baseline dwelling are shown in Table 8.

Table 8. NPV of a range of glazing abatement options

Climate zone	Abatement options (glazing)	NPV 50 yrs	(NPV)*-1
Zone 1 – Auckland	R0.31 (thermally broken)	-585	585
	R0.39 (thermally broken and low-E)	-620	620
	R0.62 (triple glazing)	-1,853	1,853
Zone 2 – Napier	R0.31 (thermally broken)	30	-30
	R0.31 (low-E)	486	-486
	R0.39 (thermally broken and low-E)	576	-576
	R0.62 (triple glazing)	-295	295
Zone 3 – Wellington	R0.31 (thermally broken)	310	-310
	R0.31 (low-E)	97	-97
	R0.39 (thermally broken and low-E)	669	-669
	R0.62 (triple glazing)	-2,369	2,369
Zone 4 – Tūrangi	R0.31 (thermally broken)	894	-894
	R0.31 (low-E)	643	-643
	R0.39 (thermally broken and low-E)	1865	-1,865
	R0.62 (triple glazing)	-356	356
Zone 5 – Christchurch	R0.31 (thermally broken)	730	-730
	R0.31 (low-E)	360	-360
	R0.39 (thermally broken and low-E)	1,446	-1,446
	R0.62 (triple glazing)	-1,206	1,206
Zone 6 – Queenstown	R0.31 (thermally broken)	1,969	-1,969
	R0.31 (low-E)	1,197	-1,197
	R0.39 (thermally broken and low-E)	3,771	-3,771
	R0.62 (triple glazing)	1,201	-1,201

Where costs exceed savings, the NPV will be negative, representing a net cost associated with a chosen abatement intervention. Conversely, where the savings exceed the costs, the NPV will be a positive number, signalling that the abatement intervention will produce a positive return on investment over the lifetime of the dwelling.

It is, however, worth noting that the CBA component of the current MAC analysis excludes consideration of co-benefits (Saujot & Lefèvre, 2016) such as energy security, air pollution, fuel poverty, and health and wellbeing benefits. This results in the undercounting of total net savings (Ministry for the Environment, 2020a).

4.11 Step 11: Calculate marginal abatement cost per tonne of CO_2 equivalent associated with abatement intervention

Calculating the marginal abatement cost of an intervention aimed at reducing greenhouse gas (GHG) emissions is based on a standard formula:

$$\text{Marginal Abatement Cost } (\$/\text{t } CO_2e) = \frac{-\ \text{Net Present Value } (\$)}{\text{Total GHG emissions abated over the life of the project}}$$

Where,

$$\text{Net Present Value} = \frac{\text{Total project costs} - \text{Total project savings}}{(1 + \text{discount rate})^{\text{project lifetime}}}$$

By dividing the NPV (results of step 10) of an abatement option by the total expected carbon savings associated with that intervention over a 50-year period (results of step 7), it provides the additional cost per unit of carbon saved. However, given that the cost analysis was based on per-kilogram metrics, the results were then multiplied by 1,000 to provide a cost per tonne of CO_2 equivalent measurement.

Important technical note: As shown in Table 9, in order to calculate the MAC of an intervention, it is necessary to multiply the NPV by negative one (-1). This is to demonstrate that abatement options with negative marginal abatement cost represent net cost savings over their lifetime.

Table 9 captures the marginal abatement cost per tonne of CO_2 equivalent associated with glazing abatement options during the construction of the baseline dwelling.

4.12 Step 12: Calculate cumulative net annual carbon abatement potential based on projected annual uptake

Although the research could have concluded with an illustration of MACCs depicting results associated with a single dwelling or unit, access to data on the projected future stock of dwellings (yet to be constructed) provided an opportunity to also develop MACCs from a projected stock-flow increase perspective. Steps 12 and 13 in the MACC development process are therefore optional. It does, however, demonstrate the potential of applying the MACC methodology to satisfy both bottom-up and top-down MACC-user requirements.

Table 9. MAC per tonne of CO_2-e associated with incorporating a range of glazing abatement options during the construction of the baseline dwelling.

Climate zone	Abatement options (glazing)	NPV		Marginal abatement cost	
		50 yrs	(NPV)*-1	$/kgCO₂-e	$/tCO₂-e
Zone 1 – Auckland	R0.31 (thermally broken)	-585	585	1.15	1,144.81
	R0.39 (thermally broken and low-E)	-620	620	0.44	442.54
	R0.62 (triple glazing)	-1,853	1,853	0.60	602.41
Zone 2 – Napier	R0.31 (thermally broken)	30	-30	-0.04	-36.63
	R0.31 (low-E)	486	-486	-0.43	-434.31
	R0.39 (thermally broken and low-E)	576	-576	-0.29	-290.47
	R0.62 (triple glazing)	-295	295	0.08	80.16
Zone 3 – Wellington	R0.31 (thermally broken)	310	-310	-0.30	-297.22
	R0.31 (low-E)	97	-97	-0.10	-103.63
	R0.39 (thermally broken and low-E)	669	-669	-0.31	-312.62
	R0.62 (triple glazing)	-2,369	2,369	0.91	905.58
Zone 4 – Tūrangi	R0.31 (thermally broken)	894	-894	-0.68	-678.30
	R0.31 (low-E)	643	-643	-0.54	-538.98
	R0.39 (thermally broken and low-E)	1,865	-1,865	-0.69	-690.23
	R0.62 (triple glazing)	-356	356	0.10	99.47
Zone 5 – Christchurch	R0.31 (thermally broken)	730	-730	-0.53	-525.56
	R0.31 (low-E)	360	-360	-0.31	-306.38
	R0.39 (thermally broken and low-E)	1,446	-1,446	-0.52	-516.98
	R0.62 (triple glazing)	-1,206	1,206	0.33	334.26
Zone 6 – Queenstown	R0.31 (thermally broken)	1,969	-1,969	-1.14	-1,138.15
	R0.31 (low-E)	1,197	-1,197	-0.89	-887.98
	R0.39 (thermally broken and low-E)	3,771	-3,771	-1.11	-1,113.05
	R0.62 (triple glazing)	1,201	-1,201	-0.31	-307.48

The cumulative abatement potential of an intervention at the individual dwelling level is determined by multiplying annual tCO_2-e savings (Tables 5 and 10) with the number of years under consideration (2050 less 2020 equals 30. The annual and cumulative abatement potential of glazing upgrades during the construction of a single dwelling is shown in Table 10, with 2050 being the target year. However, this only provides the abatement potential of interventions associated with a single dwelling from 2020–2050.

The econometric model central to the *National Construction Pipeline Report* (MBIE, 2020) enabled researchers to project the expected number of new dwellings to be built in New Zealand for every year up to 2070. This provided a mechanism to calculate and construct MACCs representing the cumulative abatement potential of abatement options from a national building stock perspective. From an analytical perspective, it enabled researchers to address an often-raised theoretical concern regarding MACCs – the absence of a mechanism to gauge the speed of implementation.

In order to determine the abatement potential of the total stock of baseline dwellings to be constructed in 2020 (year 1 of the analysis), the abatement potential of an intervention for a single dwelling (the shaded column in Table 10) is multiplied by the estimated stock of new baseline dwellings constructed during 2020. The results of calculating the annual and cumulative marginal abatement potential of glazing interventions are shown in Table 10.

Table 10. Marginal abatement cost and potential associated with incorporating a range of glazing abatement options during construction of the baseline dwelling.

Climate zone	Abatement options (glazing)	MAC	Marginal abatement potential tCO_2-e			
		$/$tCO_2$-e	Single dwelling		2020 Stock	
			Annual	2050	Annual	2050
Zone 1 – Auckland	R0.31 (thermally broken)	1,144.81	0.0102	0.3066	40.3	1,212.0
	R0.39 (thermally broken and low-E)	442.54	0.0182	0.8406	110.7	3,322.9
	R0.62 (triple glazing)	602.41	0.0280	1.8456	243.2	7,295.7
Zone 2 – Napier	R0.31 (thermally broken)	-36.63	0.0615	0.4914	64.76	1,942.5
	R0.31 (low-E)	-434.31	0.0163	0.6714	88.5	2,654.0
	R0.39 (thermally broken and low-E)	-290.47	0.0224	1.1898	156.8	4,703.3
	R0.62 (triple glazing)	80.16	0.0397	2.208	291.0	8,728.2
Zone 3 – Wellington	R0.31 (thermally broken)	-297.22	0.0736	0.6258	82.5	2,473.8
	R0.31 (low-E)	-103.63	0.0209	0.5616	74.0	2,220.0
	R0.39 (thermally broken and low-E)	-312.62	0.0187	1.284	169.2	5,075.7
	R0.62 (triple glazing)	905.58	0.0428	1.5696	206.8	6,204.6
Zone 4 – Tūrangi	R0.31 (thermally broken)	-678.30	0.0523	0.7908	104.2	3,126.0
	R0.31 (low-E)	-538.98	0.0264	0.7158	94.3	2,829.6
	R0.39 (thermally broken and low-E)	-690.23	0.0239	1.6212	213.6	6,408.6
	R0.62 (triple glazing)	99.47	0.0540	2.1474	282.7	8,488.7
Zone 5 – Christchurch	R0.31 (thermally broken)	-525.56	0.0716	0.8334	109.8	3,294.4
	R0.31 (low-E)	-306.38	0.0278	0.705	92.9	2,786.9
	R0.39 (thermally broken and low-E)	-516.98	0.0235	1.6782	221.1	6,633.9
	R0.62 (triple glazing)	334.26	0.0559	2.1648	285.2	8,557.5
Zone 6 – Queenstown	R0.31 (thermally broken)	-1,138.15	0.0722	1.038	40.4	1,212.0
	R0.31 (low-E)	-887.98	0.0346	0.8088	110.8	3,322.9
	R0.39 (thermally broken and low-E)	-1,113.05	0.0270	2.0328	243.2	7,295.7
	R0.62 (triple glazing)	-307.48	0.0678	2.3436	64.76	1,942.5

However, this only provides an indication of the annual and cumulative abatement potential of the stock of new stand-alone dwellings constructed during the first year of the analysis period – 2020.

4.13 Step 13: Determine the cumulative marginal abatement potential of intervention over a specific abatement period

Step 13 focuses on calculating total and cumulative marginal abatement potential – specific to a range of interventions aimed at improving the energy performance of dwellings of the total stock of dwellings to be constructed between 2020 and 2050.

The total marginal abatement potential (of a specific abatement intervention) of the total stock of dwellings constructed or to be constructed on an annual basis from 2020 onwards is calculated by adding:

- the annual abatement potential of newly constructed dwellings in a specific year – multiplying the annual abatement potential of a single unit by the number of units constructed or to be constructed in a specific year
- the annual total abatement potential of the existing stock of newly constructed dwellings (total stock abatement the year before).

For example, Table 11 captures the calculation of the total abatement potential associated with glazing interventions in Auckland (climate zone 1) between 2020 and 2024. Beginning with 2020 as a reference year, the annual abatement potential of R0.31 (thermally broken) glazing for the dwellings constructed (40.4 tCO_{2}-e) is calculated by multiplying the number of new dwellings constructed (3,953) by the annual abatement potential per dwelling (0.010 tCO_{2}-e).

Table 11. Marginal abatement cost and cumulative abatement potential associated with incorporating a range of glazing abatement options during construction of total stock of baseline dwellings between 2020 and 2050 in Auckland (climate zone 1).

Abatement year		**2020**	**2021**	**2022**	**2023**	**2024**
Option	Projected number of new baseline dwellings	3953	3430	4081	4250	4389
R0.31 (thermally broken)	Annual abatement per dwelling	0.010	0.010	0.010	0.010	0.010
	Abatement potential of new stock	40.4	35.05	41.71	43.43	44.86
	Abatement potential of existing stock	0	40.4	75.45	117.16	160.60
	Total stock abatement potential for the year	40.4	75.5	117.16	160.60	205.45
	Cumulative stock abatement since 2020	40.4	115.86	233.02	393.61	599.07
R0.31 (low-E)	Annual abatement per dwelling	0.018	0.018	0.018	0.018	0.018
	Abatement potential of new stock	72.10	62.56	74.44	77.52	80.06
	Abatement potential of existing stock	0	72.10	134.67	209.10	286.62
	Total stock abatement potential for the year	72.10	134.67	209.10	286.62	366.68
	Cumulative stock abatement since 2020	72.10	206.77	415.87	702.50	1069.17
R0.39 (thermally broken and low-E)	Annual abatement per dwelling	0.028	0.028	0.028	0.028	0.028
	Abatement potential of new stock	110.76	96.11	114.35	119.08	122.98
	Abatement potential of existing stock	0	110.76	206.87	321.22	440.31
	Total stock abatement potential for the year	110.76	206.87	321.22	440.31	563.29
	Cumulative stock abatement since 2020	110.76	317.63	638.86	1079.16	1642.45
R0.62 (triple glazing)	Annual abatement per dwelling	0.062	0.062	0.062	0.062	0.062
	Abatement potential of new stock	243.19	211.01	251.06	261.46	270.01
	Abatement potential of existing stock	0	243.19	454.20	705.27	966.73
	Total stock abatement potential for the year	243.19	454.20	705.27	966.73	1236.74
	Cumulative stock abatement since 2020	243.19	697.39	1402.7	2369.38	3606.12

The annual total abatement potential of the existing stock of newly constructed dwellings is represented by the total abatement potential of the previous year. Given that 2020 was the first year of analysis, there was no previous total abatement potential to account for. As such, the total abatement potential of incorporating R0.31 (thermally broken) glazing in the stock of baseline dwellings constructed in climate zone 1 since 2020 was calculated as 40.4 tCO_{2}-e.

Likewise, the total marginal abatement potential of incorporating R0.31 (thermally broken) glazing of the total stock of dwellings to be constructed during 2021 was calculated by summing the abatement potential of the new stock to be constructed (35.05 tCO_{2}-e) and the abatement potential of the existing stock constructed in previous years (40.4 tCO_{2}-e), resulting in a total marginal abatement potential of 75.5 tCO_{2}-e during 2021.

In order to determine the cumulative abatement potential of an intervention, such as incorporating R0.31 (thermally broken) glazing in all baseline dwellings to be constructed in climate zone 1 (Auckland) between 2020 and 2050, the total stock abatement potential of the current year is added to the total stock abatement potential in previous periods.

For example, the shaded row in Table 11 reflects the cumulative marginal abatement potential of R0.31 (thermally broken) glazing of all baseline dwellings constructed or to be constructed in climate zone 1 between 2020 and 2024. To calculate the cumulative abatement potential up to 2021 (circled in green), the total abatement potential of the stock of dwellings constructed during 2021 (circled in red) is added to the cumulative stock abatement of the preceding period, 2020 (circled in red). MACCs can then be developed based on any chosen year. Although Table 11 only captures cumulative abatement potentials up to 2024, the MACCs produced in this study demonstrate the abatement potential up to 2050 – the abatement period.

Table 12 captures the cumulative abatement potential associated with a range of wall insulation upgrades for the total stock of baseline dwellings constructed in New Zealand between 2020 and 2050.

Table 12. Cumulative abatement potential of wall insulation upgrades during the construction of baseline dwellings in New Zealand between 2020 and 2050.

Abatement option and climate zone	Marginal abatement cost	Marginal abatement potential
	$/tCO$_2$-e	tCO$_2$-e
Zone 6 – R2.9	-411.21	85,055.582
Zone 6 – R4.0 (staggered stud)	-17.54	151,476.822
Zone 6 – R4.6	232.92	159,847.718
Zone 6 – R2.5 (140 mm)	255.96	56,448.955
Zone 5 – R2.9	325.16	68,277.395
Zone 3 – R2.0 (Z3 min)	791.37	5,058.933
Zone 4 – R4.0 (staggered stud)	900.68	112,497.563
Zone 4 – R2.9	983.21	60,707.194
Zone 5 – R4.0 (staggered stud)	1,087.80	124,362.398
Zone 5 – R2.5 (140 mm)	1,128.51	45,312.024
Zone 5 – R4.6	1,461.71	128,802.6128
Zone 4 – R4.6	1,493.21	115,190.808
Zone 3 – R4.0 (staggered stud)	1,639.49	97,320.7648
Zone 3 – R2.9	1,650.85	53,682.920
Zone 2 – R2.0 (Z3 min)	1,808.51	3,421.0
Zone 4 – R2.5 (140 mm)	2,200.18	40,362.2768
Zone 2 – R2.9	2,299.73	1,819,760.689
Zone 3 – R4.6	2,333.71	97,721.112
Zone 2 – R4.0 (staggered stud)	2,424.81	75,993.178
Zone 3 – R2.5 (140 mm)	2,853.17	37,923.798
Zone 2 – R4.6	3,476.07	73,773.070
Zone 2 – R2.5 (140 mm)	3,772.38	28,461.0
Zone 1 – R4.0 (staggered stud)	4,666.67	52,955.016
Zone 1 – R2.9	5,201.20	24,239.203
Zone 1 – R4.6	6,521.67	47,859.688
Zone 1 – R2.5 (140 mm)	7,512.55	17,396.906
Zone 1 – R2.0 (Z3 min)	11,074.07	982.670

4.14 Step 14: Determine the relative abatement potential and cost of substitute technologies, materials or energy sources (repeat steps 4 to 13 for alternative interventions)

Although this study report has by way of illustration referenced the marginal abatement cost and potential findings relating to a wide range of interventions, the methodology is focused on determining the marginal abatement cost of a single intervention – providing data for one bar on a MACC.

Steps 4–11 of the MACC development process therefore must be repeated for discrete interventions in order to construct a MACC. As such, the analytical data framework that supported the development of MACCs in this study was based on repeating steps 4–11 for approximately 108 insulation-focused interventions.

4.15 Step 15: Graphic illustration and analysis of findings

The final step in the development of MACCs is to illustrate the findings. As shown in Table 12, to construct MACCs, abatement options first need to be sorted from lowest (often negative) to highest (or most costly) cost per tonne of CO_2-e abated. These values can then be plotted on a graph with marginal abatement costs on the y-axis and total abatement on the x-axis.

The standard graphics function of Microsoft Excel does not enable the plotting of MACCs without the assistance of macros, and even with the support of macros, the results are not entirely satisfactory from a graphic design perspective.

In this regard, researchers are grateful for the assistance provided by Andrew Pollard, Building Physicist at BRANZ, in identifying and testing a workable graphic-design solution to plot the initial MACCs for this study.[4] Although several generic tools to illustrate MACCs are available online, most presented challenges when trialled. Some were limited in the number of abatement measures that could be illustrated (maximum 10), while others were developed for specific sectors of the economy.

[4] The MACCs in this study report were constructed with the use of ©oCo Carbon v1.1 – an online tool licensed under Creative Commons Attribution Share Alike 4.0 International License https://oco-carbon.com/metrics/macc-marginal-abatement-cost-curve-excel/ – and are illustrative only.

5. Analysis of sample MACCs

Given that the current research is focused on identifying the parameters, methodology and data inputs and outputs necessary to construct MACCs, the analysis of MACC findings falls outside the current research scope. Any analytical observations and deductions are therefore illustrative only.

Much of the data underpinning the current graphs has been revised and updated since initial development and should therefore not be used for analytical or decision-making purposes. The current graphs do, however, demonstrate the usefulness of MACCs as a complementary tool to communicate complex datasets in visual format.

Figure 9 captures the marginal cost and abatement potential (see Table 12 for relevant data) of five wall insulation interventions across six climate zones aimed at increasing the thermal performance (and reducing the carbon footprint) of the total stock of single-level detached dwellings to be constructed by 2050.

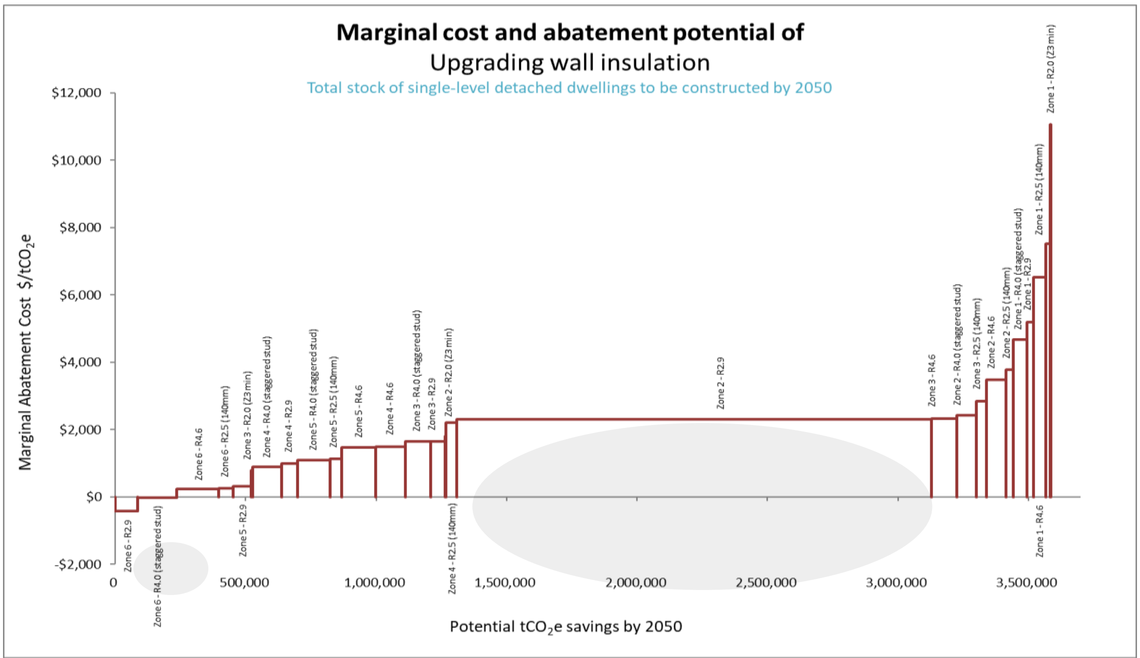


Figure 9. MACC for upgrading wall insulation levels across six climate zones (2050).

Based on Figure 9, the following basic observations could be made in terms of the marginal cost and abatement potential of upgrading wall insulation:

- The least expensive insulation intervention for the construction of single-level detached dwellings, representing an estimated cost saving of $411.21/t$CO_2$-e, would be the use of R2.9 wall insulation in climate zone 6. Doing so would avoid or abate approximately 85,000 tonnes of CO_2 by 2050 if applied to all new builds with immediate effect. Likewise, the use of R4.0 (staggered stud) in climate zone 6 would also result in an estimated cost saving of $17.53/t$CO_2$-e and abate approximately 151,476 tCO_2-e by 2050.
- Although there are a range of potential insulation interventions available below $2,000/t$CO_2$-e, the use of R2.9 in climate zone 2 has the largest abatement potential of 1.82 million tCO_2-e at $2,300/t$CO_2$-e.

Figure 10 ranks the marginal abatement cost for upgrading roof insulation levels across six climate zones for single-level detached dwellings to be constructed by 2050. Of interest is that all roof insulation interventions considered, irrespective of climate zone, will generate a negative marginal abatement cost (a net lifetime saving), albeit at different levels. Savings range from approximately \$15/tCO_2-e to more than \$2,200/tCO_2-e.

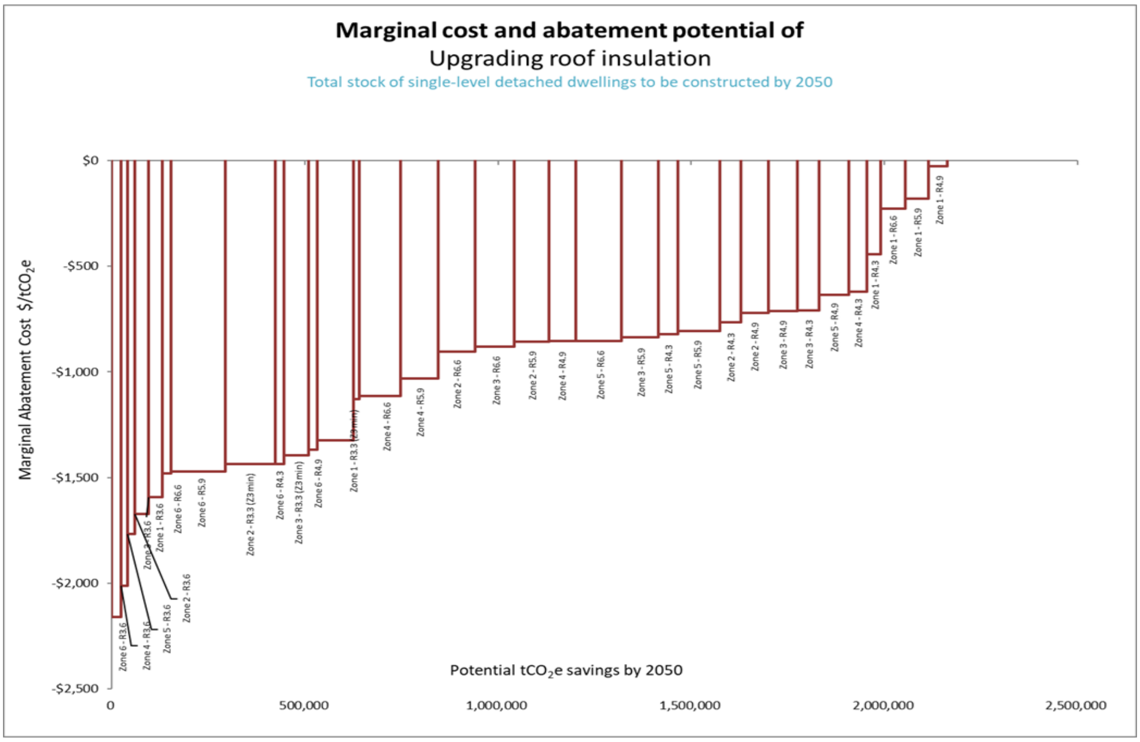


Figure 10. MACC for upgrading roof insulation levels across six climate zones (2050).

Figure 11 ranks interventions associated with upgraded glazing at various R-values for all single-level detached dwellings to be constructed by 2050 across six climate zones.

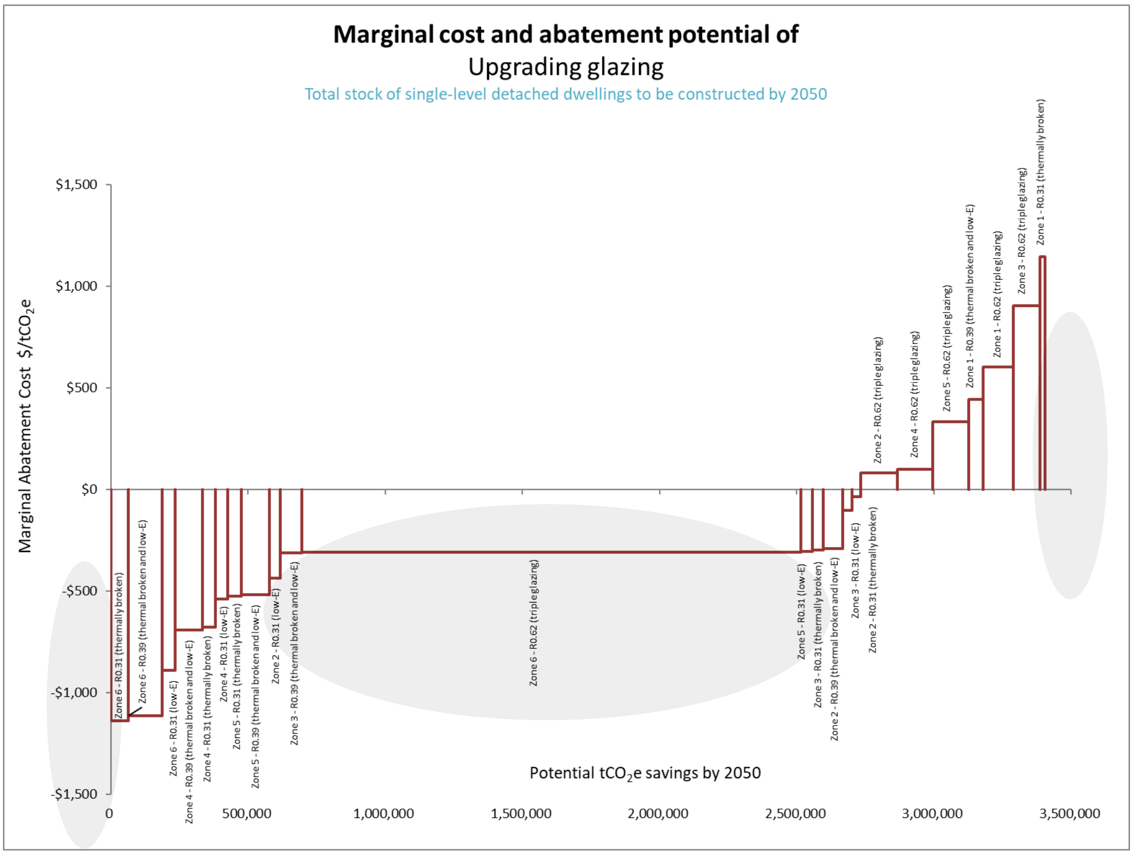


Figure 11. MACC for upgrading glazing across six climate zones (2050).

Based on Figure 11, the use of R0.31 (thermally broken) glazing in zone 6 would abate or avoid approximately 50,000 tCO_2-e by 2050 at a net cost saving of approximately $1,200 per tonne for single-level detached dwellings.

The costliest glazing intervention under consideration, R0.31 (thermally broken) in zone 1, would abate approximately 15,000 tCO_2-e by 2050.

5.1 Analytical observations

Although MACCs provide a unique way in which to collate and communicate the results of complex environmental and economic modelling, they are also subject to certain limitations.

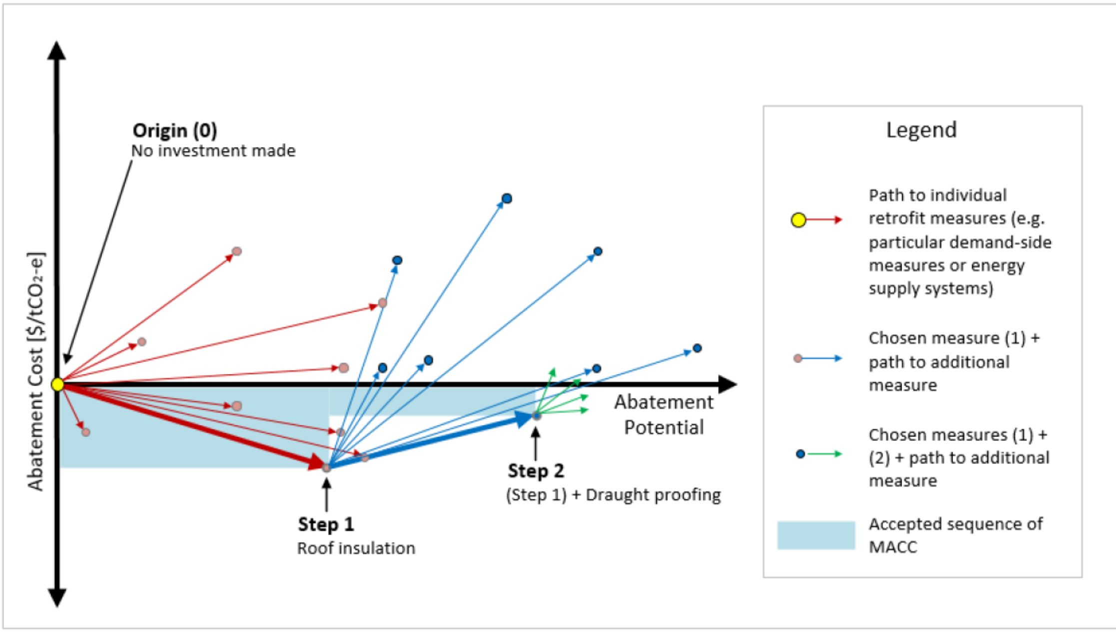
The way information is presented in a MACC suggests a merit order in which the abatement options could be implemented in order of increasing cost until the required level of abatement volume is met. However, as discussed below, misinterpreting MACCs can lead to suboptimal abatement strategies (Vogt-Schilb & Hallegate, 2014). For example, in Figure 11, the least expensive (or highest net saving) intervention associated with glazing would be the use of R0.31 (thermally broken) in zone 6, resulting in a relatively limited amount of carbon abatement (50,000 tCO_2-e by 2050). Likewise, the second least expensive (or marginally less net saving) intervention would be the use of R0.39 (thermally broken and low-E) resulting in approximately double the amount of tCO_2-e abatement. However, implementing a strategy based on the merit order suggested in Figure 11 could be expected to produce suboptimal results from a carbon abatement perspective due to use of cost per unit of CO_2 saved as a standard metric to rank negative-cost measures (Ibn-Mohammed et al., 2013).

As can be seen in Figure 11, although not being the lowest cost (or highest net saving) alternative, the use of R0.62 (triple glazing) in zone 6 could avoid up to 2,000,000 tCO_2-e by 2050 while still saving approximately $600 per tCO_2-e. Compared with this, the use of R0.31 (thermally broken) glazing in zone 6 as suggested by the MACC would only abate or avoid approximately 50,000 tCO_2-e by 2050 – albeit at a higher net cost saving of approximately $1,200 per tonne for single-level detached dwellings.

MACCs are often constructed based on the individual assessment of measures and not on the basis of a dynamic modelling system. The analysis therefore risks not capturing intersectoral and intrasectoral effects that could occur as a result of abatement policies (Ministry for the Environment, 2020a). As such, Rysanek and Choudhary (2013) distinguish between illustrative and true MACCs. Illustrative MACCs simplify interactions between measures in order to circumvent any requirement for large-scale optimisation and/or physical simulation. Figure 7 is an example of an illustrative MACC. Such MACCs do not explicitly assess the additionality of measures along the MACC, meaning that any additional cost or abatement potential cannot be truly marginal.

True MACCs are defined as those that are created with the support of sequential optimisation modelling at each stage of development. In addition, true MACCs are developed based on a specific as opposed to generic line of enquiry.

Figure 12 illustrates the way in which sequential optimisation, starting from a zero-investment position, enables the identification of the least-cost additional measure when combined with all preceding options.

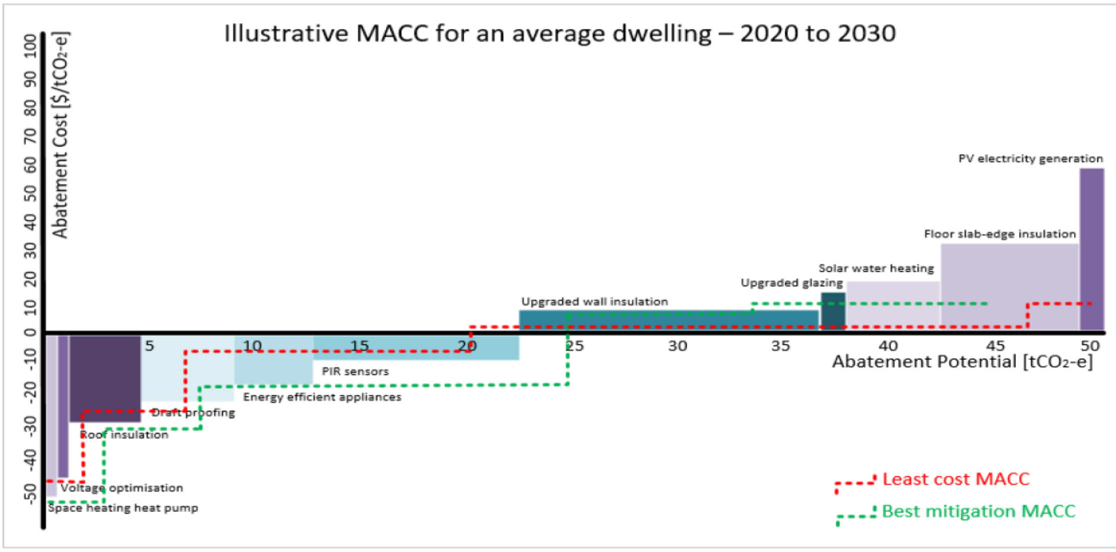


Source: Illustrative.

Figure 12. Sequential optimisation of abatement options.

The additional costs are therefore truly marginal because they consider the additionality associated with preceding abatement options. However, although sequential optimisation provides a more accurate indication of marginal abatement cost and potential, it may not be sensible given the absence of a specific economic and/or environmental target or objective (Rysanek & Choudhary, 2013). As illustrated in

Figure 13, carbon abatement strategies could follow different paths depending on the goals or objective being pursued.



Source: Illustrative.

Figure 13. Example of least cost and best carbon mitigation strategies.

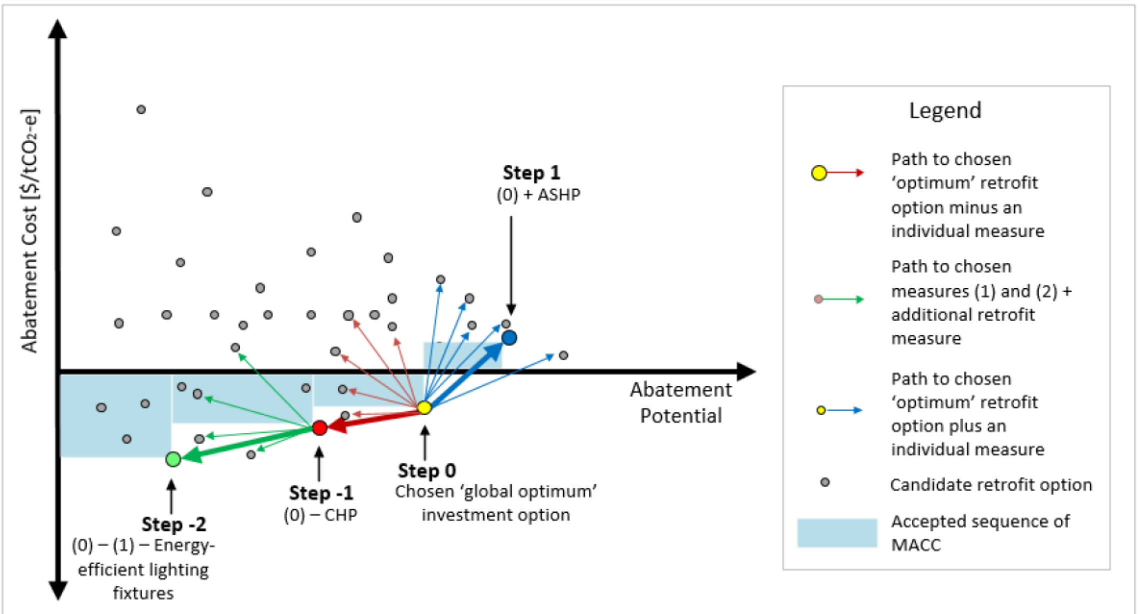
One way in which to overcome the issue of constrained optimisation is to begin the MACC development process by first determining the retrofit option that would best meet the decision maker's goals and to use this as the origin point of the MACC Rysanek & Choudhary, 2013).

Following this, the downstream and upstream portions of the MACC would be found by removing and adding installed measures during the sequential search process demonstrated in Figure 14.

6. Observations and recommendations

Notwithstanding the limitations underpinning the MAC analysis and curves developed in this study, MACCs can add significant value in communicating the results of complex environmental modelling.

Assuming consumers, designers and builders will become increasingly conscious of the need for sustainability – whether due to the increasing cost and uncertainty regarding a rapidly changing environment or global regulatory pressure for more accountability – the demand for tools to measure and communicate the various trade-offs to be considered during the building and construction process are bound to increase. Although the application of MACCs has been fairly limited in the New Zealand building and construction industry, the relatively concentrated character of the domestic industry should enable the standardisation of core MACC input elements among a greater proportion of industry participants.



Source: Illustrative.

Figure 14. Incorporating the decision maker's revealed preference.

The increased role of the government in providing social and more-affordable housing solutions and the move to increased urban densification are only some of the factors that will drive the demand for tools to inform the trade-offs between financial and sustainability focused considerations, especially at the pre-construction and individual building or development level. Developing bottom-up MACCs at the individual building level based on the revealed preference of owners, investors or developers could furthermore be expected to add momentum to behavioural change through improved visualisation and awareness of carbon abatement options and their likely environmental impact.

Recommendation 1: Increased application of true MACCs at the individual building level

Given the anticipated increase in demand for tools to inform financial and environmental trade-offs during the residential or commercial pre-construction phase, true MACCs at the individual building level could add demonstrable value during decision-making processes. MACCs should, however, be used in conjunction with a broader set of decision-making tools (Ekins, Kesicki & Smith, 2011), such as energy system optimisation models.

True MACCs at the individual building level could be especially useful to public sector organisations such as MBIE, HUD and Kāinga Ora as well as private and community developers that focus on the construction of multiple units that are based on standard design. However, given that there can be several possible pathways along which to achieve the emissions and financial objectives associated with a single dwelling, multiple MACCs will be required to identify an abatement pathway that best suits a decision maker's unique preferences (Ministry for the Environment, 2020a; Saujot & Lefèvre, 2016; Rysanek & Choudhary, 2013).

Recommendation 2: Collaborative research design and MAC analysis

The remainder of the recommendations focus on mechanisms to foster the increased application of MACCs at the individual building level in the New Zealand construction sector.

Most of the economic and environmental simulation data necessary for the development of MACCs, whether illustrative or true, are already being produced and applied during decision making but not for the development of MACCs. As demonstrated by the current study, although limited to producing illustrative realisable MACCs, as opposed to true realisable MACCs, the development of the MACCs was based on existing as opposed to primary or bespoke data inputs. Therefore, more consideration ought to be given to the potential application of MACCs during the early scoping of studies such as the BRANZ MBIE H1 study (Jaques et al., 2020) that supported a policy review of the residential insulation requirements of NZBC clause H1 *Energy efficiency* Acceptable Solution H1/AS1 for housing and small buildings. For example, based on the findings of this study, early alignment of future research intentions would enable the development of MACCs to support the communication of study results.

Recommendation 3: Standardisation of MACC development platform and associated analytical inputs and processes

Although future collaboration on research is expected to support increased application of MACCs, greater standardisation of MACC development platforms and associated analytical inputs and processes (i.e. baseline dwelling specifications, cost-benefit analysis, thermal simulation) could also be expected to support wider application of MACCs in the domestic building and construction industry.

Serious consideration therefore ought to be given to gaining sector-wide support for the standardisation of key analytical inputs and processes – baseline dwelling specifications, CBA componentry and thermal simulation inputs and modelling parameters. For example, the baseline dwelling specification in this study (based on Jaques et al., 2020) was also applied during a top-down marginal abatement cost analysis by Chandrakumar, McLaren, Dowdell and Jaques (2020). As such, should the 198 m² single-level detached reference dwelling be used consistently in future studies, it would enable increased development, comparison and application of MACCs research across the construction sector.

Recommendation 4: True MACC constrained sequential optimisation software solutions at the individual building level

The increased application of MACCs to support decision making will, however, be subject to existing and potential users' confidence in the accuracy of the analysis underpinning the graphics. The MACCs developed in this study could be classified as being an illustrative as opposed to true reflection of the achievable abatement potential of abatement measures.

As demonstrated in this study, generating true MACCs requires simulation modelling that incorporates sequential optimisation of end users' or developers' preferences. Consideration therefore ought to be given to identify existing sequential optimisation simulation software that could be adapted for application in the New Zealand building and construction industry. Alternatively, a bespoke software solution could be developed based on some of the existing data inputs being generated across the local building and construction sector and AI elements to identify or reveal the preference of individual MACC end users.

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Appendix A: Application of MACCs in selected jurisdictions

Country	Approach	Purpose	Reference
New Zealand	Top down	An early-stage report from the Ministry for Environment to develop a marginal abatement cost curves (MACCs) analysis for New Zealand looking at different sectors such as land, industry, transport, waste etc.	Ministry for the Environment, 2020a
New Zealand	Top down	Seeks to establish a baseline for carbon abatement and a high-level economic assessment of achieving net-zero greenhouse gas emissions at regional scale. Two emission reduction themes were developed and modelled in this analysis reflecting different focus areas: technology and innovation, and land use and agriculture. Corresponding mitigation options were identified and modelled to show the mitigation pathway to achieving net-zero emissions with an economic analysis undertaken to provide the marginal abatement costs associated with these options	Ernst & Young, 2021
New Zealand	Top down	Uses marginal abatement cost estimates to inform assumptions on start date and uptake rate of key technology options in the transport, electricity, LPG and waste sectors. Supports a broader project to develop an emissions reduction roadmap and relevant associated costs for Queenstown Lakes District Council (QLDC) in order to inform QLDC about the pathways for achieving net-zero carbon emissions by 2050 across the whole district.	Comendant et al., 2020
UK	Bottom up	Uses MACCs to highlight the significance of embodied emissions when considering GHG emissions reduction strategies.	Ibn-Mohammed et al., 2013
UK	Bottom up	Looks at reusing steel beams in construction, specifying optimal lightweight beams in construction, choosing smaller cars and specifying high-strength steel car bodies. The results show that these strategies could reduce UK steel demand and associated global emissions by approximately 12%.	Dunant et al., 2019
UK	Bottom up	Looks at buildings' utility impact and direct emissions	Tomes, Jamieson & Firth, 2019
UK	Bottom up	Explores a technique for generating marginal abatement cost curves for individual buildings.	Rysanek & Choudhary, 2013
UK	Bottom up	Looks at options to retrofit existing housing (suburban cavity-walled semi-detached house).	AECB, n.d.
UK	Bottom up	Looks at reducing household GHG emissions from space and water heating through low-carbon technology assessing the cost and carbon-reducing potential of single abatement measures.	Rafique & Williams, 2021
UK	Top down	Explores decarbonisation options using an innovative analytical approach that combines energy systems analysis and MACCs. System-wide MACCs are derived	Yue, Deane, O'Gallachoir & Rogan, 2020

Country	Approach	Purpose	Reference
		using scenario ensembles from Irish TIMES energy systems model. Decomposition analysis is then used to associate decarbonisation options with carbon abatement costs.	
Armenia/Georgia	Bottom up	This study develops a methodology to estimate MACCs for energy efficiency measures and apply in the building sector in both countries. The study finds that, among the various energy efficiency measures considered, the replacement of energy-inefficient light bulbs (incandescent lamps) with efficient light bulbs is the most cost-effective measure in saving energy and reducing GHG emissions from the building sector.	Timilsina, Sikharulidze, Karapoghosyan & Shatvoryan, 2017
Japan	Bottom up	Assesses the emissions reduction in houses through behavioural measures and finds that, to promote energy saving and in turn emission-saving behaviours, a higher carbon price is required. Using regression analysis, it also finds that larger houses, houses with fewer occupants and lower-income houses had higher costs savings from energy-saving measures than their counterparts.	Hamamoto, 2013
US	Bottom up	Analyses the viability and incremental cost for 2–4-storey multi-family apartment buildings to reach both annual and monthly net-zero energy performance throughout four climate zones in the US using baseline reference buildings that represent current construction practices. Building size plays a large role in determining the capability for a building model to reach annual or monthly net zero. Generally speaking, only small buildings in warm climates will be able to achieve monthly net zero without vastly oversizing photovoltaic systems and increasing costs without adequate payback.	McKittrick & Henze, 2021
US	Not stated	Explores the basic characteristics of MAC and marginal welfare cost (MWC) curves, deriving them using the MIT Emissions Prediction and Policy Analysis (EPPA) model finding that MACs are, in general, not closely related to MWCs and therefore should not be used to derive estimates of welfare change.	Morris, Paltsev & Reilly, 2008
US	Bottom up	Models energy and economic savings of efficiency upgrades for US single-family detached houses, accounting for differences in thermostat settings, climate zone, fuel prices and home characteristics. It considers five efficiency interventions: wall insulation, attic insulation, air sealing, high-efficiency furnaces and high-efficiency air conditioners.	Das, Wilson & Williams, 2021
Australia	Not stated – assumed to be bottom up	Uses Pareto principles to identify the primary contributors to these metrics, proposes alternative design strategies and uses MACCs to visualise direct and indirect impacts of the changes. The framework is tested on an 18-storey building in Sydney. Results show that embodied carbon makes up 27–58% of the building's total life cycle carbon emissions, depending on the future energy mix.	Robati, Oldfield, Nezhad, Carmichael & Kuru, 2021

Country	Approach	Purpose	Reference
Germany	Top down	Simulates greenhouse gas abatements and welfare costs of carbon taxes and subsidies on heating system investments until 2030 to deduce abatement curves. Given utility-maximising households, the results suggest a carbon tax to be the welfare efficient policy. Assuming behavioural misperceptions instead, a subsidy on investments might have lower marginal greenhouse gas abatement costs than a carbon tax.	Dieckhöner & Hecking, 2012
Australia	Not stated	MACCs were created to help prioritise energy efficiency initiatives and assist executive buy-in for Western Australia's leading membership organisation RAC.	CitySwitch Green Office, 2014
US	Not stated	Uses four scenarios to illustrate the discipline and value of LCCA analysis: the $/ton cost of using new solar power (utility or rooftop) to displace power-sector emissions in one market (California); the $/ton costs of new rooftop solar generation in several states with different solar resources, grid mixes and policy environments; the $/ton cost of various technology options to decarbonise a range of primary iron and steel production methods; the $/ ton cost associated with sustainable aviation fuels and direct air capture and storage of CO_2.	Friedmann et al., 2020
Colombia	Bottom up	Focuses on the MACCs for the commercial building sector in three Colombian cities (Bogotá, Medellín and Barranquilla). Two sets of MACCs were generated. The first set considered the total implementation cost, while the second set only considered technology costs.	Abt Associates Inc., 2013
Taiwan	Bottom up	Investigates energy savings and CO_2 abatement using an extended energy conservation supply curve (ECSC) and an extended MACC in the cement industry. The technical potential energy savings and CO_2 abatement were respectively estimated at 5.98% of the sector's final energy use and 3.88% of CO_2 emissions in 2018. Overall, 51.2% of the electricity savings and 92.5% of fuel savings could be implemented cost-effectively.	Huang & Wu, 2021