TOWARDS NET-ZERO HEALTHCARE SYSTEMS

Establishing the Economic Value of Carbon-Minimal Inhalers

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Sukanya Subramaniyan
Grace Hampson

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Sukanya Subramaniyan
Office of Health Economics, London

Grace Hampson
Office of Health Economics, London

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Corresponding Author:
Grace Hampson
ghampson@ohe.org

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Executive Summary

Climate change is a direct threat to human health (World Health Organization, 2023), with the potential to reverse decades of progress across global health and healthcare. Health systems in turn are substantial emitters, responsible for around 5% of greenhouse gas emissions (GHG) worldwide (Lenzen et al., 2020; Or and Seppänen, 2024; Romanello et al., 2023). Medicines are responsible for a substantial proportion of these emissions, at an estimated 25% of health service emissions in England (NHS England, 2022). Anaesthetic gases and inhalers are often highlighted as particularly problematic; in England they contribute two and three percentage points of total NHS GHG emissions respectively (NHS England, 2022).

Among the different types of inhaler, pressurised metered dose inhalers (pMDIs) are responsible for the greatest emissions, indicating the greatest scope for change. Indeed, carbon minimal pMDIs are in development, expected to reduce carbon emissions by around 90% compared to existing pMDIs, with no expected change in clinical outcomes or additional cost to the health service.

The primary purpose of this report is to establish the additional economic value of carbon minimal pMDIs compared to existing pMDIs with the same active ingredient. A secondary aim is to explore the feasibility of assessing the value of environmental impacts (in this case GHG emissions) in an economic evaluation, comparing different approaches for doing so. To meet these aims, a series of literature reviews were undertaken, followed by calculations of the economic value of the new carbon minimal pMDIs via simple economic modelling.

Key takeaways:

- Current inhalers offer health and economic value for asthma patients and health systems, but some, pMDIs in particular, generate substantial GHG emissions. These emissions are not routinely considered in health economic assessments or healthcare decision making.

- In the UK, a move to carbon minimal pMDIs would reduce emissions by 1,720–2,513 kgCO_2e per person with asthma over their lifetime (depending on the specific product used). The economic value of this reduction in emissions is £463–£676 per person with asthma over their lifetime (see Figure 1).

- The corresponding undiscounted values are savings of 2,886–4,218 kgCO_2e per person over their lifetime, valued at £776–£1,134.

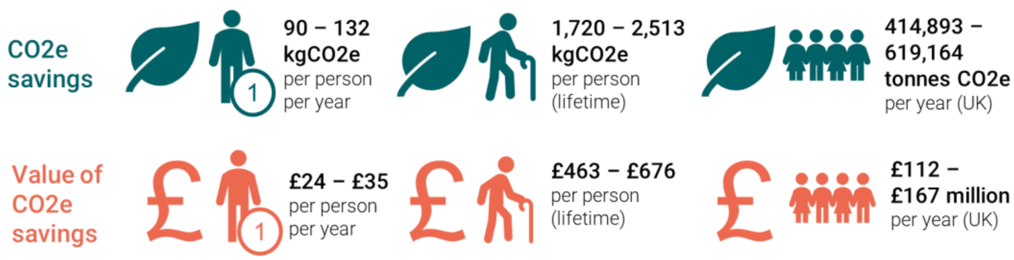
- This reduction in emissions would not be associated with any change in clinical outcomes, and if the carbon minimal pMDI is offered at the same price, there would be no increase in costs (including downstream resource utilisation).

- At a national level, if all people in the UK were to receive carbon minimal pMDIs instead of their current pMDI, it would save carbon emissions up to the value of £112 to £167 million annually depending on the specific product used.

- Transitioning to carbon-minimal pMDIs at the national level is estimated to save between 415,000 and 619,000 tCO_2e. This represents approximately 7% to 10% of the total

reductions needed to achieve the NHS's goal of reducing its carbon footprint from 6.1 million tCO2e to net zero by 2040 (Dodge, Watts and Bailie, 2021).

FIGURE 1: SUMMARY OF KEY RESULTS: CARBON FOOTPRINT AND CARBON VALUES FOR STANDARD AND CARBON MINIMAL PMDI



Notes: results 'per person' comprise all people with asthma in the UK; results 'per year' comprise all people using pMDIs (not limited to asthma).

In relation to our secondary aim of exploring the feasibility of including GHG emissions data in economic evaluations, we find that the additional value associated with lower emissions can be calculated as part of health economic evaluation, where data availability allows. This is typically achieved via two main alternative approaches: 1) **integrated evaluation**: whereby the carbon savings are converted into health or financial effects and incorporated into the usual incremental cost effectiveness ratio, or 2) **parallel evaluation**, whereby additional metrics (incremental carbon footprint effectiveness ratio [ICFER] or incremental carbon footprint cost ratio [ICFCR]) are calculated and presented alongside the usual ICER. We suggest that a metric reflecting the cost per kgCO2e saved (which reflects an incremental cost carbon footprint ratio, or ICCFR) has a more intuitive interpretation for decision makers than the ICFER or ICFCR.

In this case the carbon minimal pMDI dominates the existing pMDI (note this assumes the same active ingredient in both versions of the pMDI), as it is the same or superior across all categories of outcomes (health, financial and GHG emissions). The decision between the two technologies is therefore uncomplicated. However, the decision between two options will be less clear when an intervention does not dominate its comparator. Further research into how environmental data and related metrics can be used to inform healthcare decision making as part of an HTA process, for example via the development of decision rules, in such circumstances is required. Additional research into how the use of environmental data in economic evaluation and HTA can work alongside other incentives for the wider health system and related stakeholders to reach their net zero goals is also critical.

1 Introduction

Climate change is a direct threat to human health (World Health Organization, 2023), with the potential to reverse decades of progress across global health and healthcare. Through extreme heat, floods, droughts and other extreme weather events, climate change puts additional pressure on already overburdened health systems. Health systems in turn are substantial emitters, responsible for around 5% of greenhouse gas (GHG) emissions worldwide (Lenzen et al., 2020; Or and Seppänen, 2024; Romanello et al., 2023).

In recognition of this vicious cycle, over 40 health systems around the world have committed to net zero targets, ranging in deadline from 2030 to 2060 (World Health Organization, 2024). One example is the United Kingdom (UK) with its campaign for a Greener NHS, which includes a target for net zero emissions by 2040[1] (NHS England, 2022). To hit this target, radical change will be needed across the entire system, including changes to models of care, transport, travel, hospital infrastructure, NHS values, and crucially, medicines and supply chain. Medicines are indeed a critical component, estimated to account for 25% of NHS emissions (NHS England, 2022). With this in mind, some national health technology assessment (HTA) bodies allow for environmental impacts to be considered as part of their evaluations of new health technologies (MSAC, 2021; CADTH, 2020) (Health Technology Assessment Impact Report 2021 | HIQA, 2024), whilst others have begun exploring how environmental impact data could be included in their evaluations and guidance (NICE, 2024; Smith and Severn, 2023).

1.1 Why pMDIs?

Unsurprisingly, not all medicines are equal. Which medicines we use and how we use them has an impact on the health system's ability to hit the net zero target. Anaesthetic gases and inhalers are often highlighted as particularly problematic; in England they contribute two and three percentage points of total NHS emissions respectively (NHS England, 2022). These emissions primarily occur at the point of use, whereas the remaining emissions attributed to medicines (20% of total emissions) are primarily distributed across the manufacturing and supply chain (NHS England, 2022).

Inhalers play a vital role in pharmacological management of patients with asthma. In clinical practice, both controller or maintenance therapy for symptom control and future risk (inhaled corticosteroids [ICS], long-acting muscarinic antagonists [LAMA], long-acting β2 agonists [LABA]), as well as reliever therapy for acute symptom relief (short-acting muscarinic antagonists [SAMA] and short-acting β2 agonists [SABA]) alongside ICS are recommended to be used as needed in global guidelines as soon as the diagnosis is made (Global Initiative for Asthma, 2024). Despite the increasing availability of oral and injectable therapies, inhaled therapy is favoured because it delivers medication directly to the lungs, maximising its local effect while minimising the risk of systemic side effects (To et al., 2013). Inhaled therapy devices can be classified into different types based on their mechanism of delivering medication: the most common types include pressurised metered dose inhalers (pMDIs), dry powder inhalers (DPIs), and soft mist inhalers (SMIs). pMDIs deliver medication in aerosol form using a propellant, DPIs deliver medication in powder form and SMIs convert liquid medication into a fine mist to be inhaled slowly.

[1] *The UK as a whole is also committed to reaching net zero emissions by 2050 (Burnett et al., 2024), with government guidance stating that GHG emissions should be evaluated for* all *policies that may have a positive or negative impact on emissions, even where the primary objective of that policy is not related to the net zero target (Department for Energy Security & Net Zero and Department for Business, Energy & Industrial Strategy, 2024)*

Recognising the significance of emissions from inhalers, the National Institute for Health and Care Excellence (NICE) in the UK have published an asthma inhaler decision aid (NICE, 2022). The purpose of the aid is to help people with asthma think about reducing the environmental impact of their asthma treatment. The decision aid highlights that pMDIs are associated with greater GHG emissions, with emissions ranging from 28–35kg of CO2e per inhaler. At the upper end, this is comparable to the emissions from a 115-mile journey in a petrol car (NICE, 2022).

The decision aid does not provide the environmental profile of new carbon minimal pMDIs which are currently in development. These carbon minimal pMDIs are aiming to demonstrate equivalent clinical effects (Panigone et al., 2020) and if offered at the same price as current pMDIs, will lead to no difference in total costs (the sum of acquisition cost and downstream healthcare utilisation). Given recent evidence that up to 70% of all inhalers sold in the United Kingdom are pMDIs (whilst other European countries have pMDI usage ranging between 35% and 55%) (Pernigotti et al., 2021), carbon minimal pMDIs could make a substantial contribution to the race to net zero. Indeed, NHS England estimate that a switch to low carbon inhalers, such as DPIs as well as alternative inhalers containing low-GWP propellants, could save 374ktCO_2e, roughly a third of the required emissions savings across anaesthetic gases and inhalers[2] (NHS England, 2022).

1.2 This report

The primary aim of the report is to establish the additional economic value of carbon minimal pMDIs amongst people with asthma. A secondary aim is to explore the feasibility of assessing the value of these environmental impacts (in this case GHG emissions) in an economic evaluation, comparing different approaches for doing so. To meet these aims, we:

- review published economic evaluations of inhaler therapies
- review existing and emerging approaches to incorporating environmental metrics in economic evaluation
- utilise these approaches to practically demonstrate a range of ways in which environmental impacts of carbon minimal pMDIs can be captured in economic evaluation.

The remainder of the report is structured as follows: Chapter 2 sets out evidence from the literature on the economic value of existing inhalers and the environmental impacts of treatments for asthma. Chapter 3 looks at how environmental impacts have been incorporated into economic evaluation in the previous health economics literature. Chapter 4 presents the methods and results our case study analysis of the economic and GHG emissions impacts of carbon minimal pMDIs, and Chapter 5 provides a commentary and discussion of the results. Conclusions are set out in Chapter 6. Detail of the methods for the searches can be found in the Appendix.

[2] The remaining savings are expected to come from changes in the use of anaesthetic gases, reductions in the use of MDI, and green inhaler disposal (NHS England, 2022).

2 Evidence from the literature: economic and environmental impacts of inhalers

2.1 Economic value

The economic value of inhalers has been widely studied in the management of chronic respiratory conditions like asthma and chronic obstructive pulmonary disease (COPD). Evidence in the literature shows that inhalers, when used effectively, can significantly reduce direct healthcare costs by reducing hospitalisations, emergency department visits, and other costly healthcare interventions often triggered by poorly controlled symptoms and acute exacerbations (Bahadori et al., 2009; Rodriguez-Martinez, Sossa-Briceño and Castro-Rodriguez, 2018). Asthma-related healthcare costs are largely driven by acute exacerbations, with studies demonstrating that proper adherence to inhaler regimens prevent these exacerbations and lead to fewer hospital admissions and inpatient care visits (Lewis et al., 2016; Bårnes and Ulrik, 2015). Beyond healthcare savings, inhaler use also minimises indirect costs such as workplace absenteeism and decreased productivity due to poor symptom control. Consistent inhaler use leads to better asthma management, fewer symptom flare-ups, and improved daily functioning, enhancing patients' quality of life and contributing to overall economic productivity (Sadatsafavi et al., 2014).

Cost-effectiveness analyses highlight that maintenance therapy with inhaled corticosteroids has been found to be very cost-effective in patients with asthma (Bahadori et al., 2010). While certain inhalers, such as combination inhalers, may have higher upfront costs, they are still observed to be an effective therapeutic option (Willson et al., 2014; Sadatsafavi et al., 2021). Studies have highlighted that inhaled therapies, particularly inhaled corticosteroids combined with long-acting beta-agonists (ICS/LABA), generally yielded better health outcomes at lower costs than biologic therapies for patients with moderate to severe asthma (McQueen et al., 2018). Newer biologics such as omalizumab have only demonstrated cost-effectiveness for carefully selected patient populations and have been observed to require discounted acquisition prices in order to further improve value (McQueen et al., 2018). In Table 1, we present the results from cost-effectiveness analyses published since 2012 that compare the use of standard therapy, which involves inhaled therapies (typically a combination of LABA and LAMA or SABA), with alternative therapies such as biologics or non-pharmacological treatments. Inhaled therapies outlined in the below table can either be of pMDI, DPI or SMI form.

TABLE 1. RECENT COST-EFFECTIVENESS ANALYSES OF ASTHMA TREATMENTS

Study	Country	Intervention	Comparator	Incremental costs	Incremental QALYs	ICER
(van Nooten et al., 2013)	Netherlands	Add-on omalizumab	Standard care	NR	NR	€38,371/QALY
(Norman et al., 2013b)	UK	Omalizumab	Standard care	NR	NR	£83,822/QALY for overall adult population; £46,431/QALY for hospitalisation subgroup
(Willson et al., 2014)	UK	Tiotropium (long-acting muscarinic antagonist) in addition to ICS and LABA	Standard care (ICS and LABA)	£5,238	0.24	£21,908/QALY
(Faria, McKenna and Palmer, 2014)	US	Omalizumab	Standard care (ICS and LABA)	NR	NR	Above £80,000/QALY for the overall population; below £30,000/QALY only if asthma mortality is above 1.7 deaths per 100 persons-years (no evidence for this in the literature)
(Altawalbeh et al., 2016)	US	ICS + LABA	ICS + LTRA	$5,823	0.03	$209,090/QALY
(Zafari et al., 2016)	US	Bronchial thermoplasty	Omalizumab, standard therapy	NR	NR	BT vs standard therapy: $78,700/QALY Omalizumab vs BT: $3.86 m/QALY Omalizumab vs standard therapy: $552,000/QALY
(Zafari et al., 2018)	US	Tiotropium (long-acting muscarinic antagonist) in addition to ICS and LABA	Omalizumab, standard therapy	NR	NR	Tiotropium vs standard therapy: $34,478/QALY Omalizumab vs tiotropium: $593,643/QALY
(Sadatsafavi et al., 2021)	Canada	Budesonide-formoterol (steroid plus LABA)	Low-dose maintenance ICS plus short-acting β2-agonist	−$9882.90	0.02	NR

Abbreviations: ICER: incremental cost-effectiveness ratio; ICS: inhaled corticosteroids; LABA: long-acting β2 agonists; LTRA: leukotriene-receptor antagonists; QALY: quality-adjusted life year; NR: not reported.

2.2 Environmental impact of asthma interventions

Many economic evaluations of inhalers fail to account for environmental impacts. Most studies primarily focus on direct healthcare costs of inhalers and patient outcomes, thereby overlooking the environmental consequences of asthma treatments. This oversight can skew decision-making processes, leading to the continued endorsement of inhalers such as pMDIs that contribute significantly to GHG emissions.

From the few studies that do consider environmental impacts, switching to inhalers containing low GWP propellants has been shown to offer both substantial carbon reductions and potential cost savings. An analysis of NHS prescription data from 2017 found that for every 10% of pMDIs replaced with the cheapest equivalent DPIs, drug costs could decrease by £8.2 million annually (Wilkinson et al., 2019). Additionally, switching pMDIs for DPIs offers reductions in carbon footprint, with an estimated 58 kt CO_2e saved annually for every 10% of pMDIs changed to DPIs (Wilkinson et al., 2019). Other studies analysing the costs and benefits of substituting currently available pMDIs with DPIs globally show that 2% and 5% year-over-year increase in DPI market shares relative to pMDIs would result in reductions in CO_2 emissions of 38% and 58%, respectively (Kponee-Shovein et al., 2022). However, there is a general lack of consensus regarding the impacts of switching between inhalers, with some studies suggesting pMDI to DPI switches leadto better asthma control and others demonstrating higher exacerbation rates and more outpatient visits (Woodcock et al., 2022; Ekberg-Jansson et al., 2015).

Recent evidence on non-medical switching[3] in patients with asthma shows that patients are likely to face decreased medical adherence, which can result in an increased frequency of emergency department visits and contribute to poorer outcomes (Williams et al., 2004; Gilbert et al., 2020). Decreased adherence can have an indirect effect on environmental outcomes; a recent study estimating the total economic burden of the asthma in the UK found that inhaler switching may lead to subsequent loss of disease control amongst asthma patients due to reduced adherence, increasing GHG emissions and associated healthcare costs. As inhaler prescriptions shift towards less carbon-intensive alternatives (e.g. from pMDIs to DPIs), it is worth considering the potential downstream effects on patient outcomes and healthcare system burdens, ensuring that environmental policies are carefully balanced with the goal of maintaining optimal clinical care.

Transitioning to pMDIs with the same formulation and with novel low GWP could possibly reduce GHG emissions from inhalers. pMDIs manufactured with a new low GWP propellant, HFA152a, are likely to reduce the carbon footprint of currently available inhalers by 85%–90% (Panigone et al., 2020), and may remove the challenges associated with switching between different types of inhaler. Research on the relative effectiveness of substituting pMDIs with DPIs compared to the development of pMDIs with a low-GWP propellant demonstrates a higher potential for the latter to reduce overall carbon footprint (Pernigotti et al., 2021). Evidence in this area is however limited and there is a clear lack of economic evaluations that would supplement and enable decision-making processes at the health system level.

[3] *When a patient's treatment is switched for non-medical reasons.*

3 Incorporating Environmental Impact in Economic Evaluations

3.1 Existing methods

The incorporation of environmental impacts into health economic evaluations and health technology assessments (HTAs) has emerged as a critical area of research, driven by the growing recognition of healthcare's role in climate change and sustainability. Recent literature has explored various methodologies and related challenges, demonstrating how environmental considerations can be employed to complement economic metrics. A comprehensive review by Williams et al., (2024) outlines the key methods for integrating environmental considerations into HTA, which vary from direct incorporation of impacts within health economic modelling to consideration of impacts beyond standard modelling frameworks. Toolan et al., (2023) also distinguish between four main approaches for incorporating environmental impacts into HTAs: information conduit, parallel evaluation, integrated evaluation, and environment-focused evaluation. Other scoping reviews discuss the key approaches used to convert environmental spillovers into health benefits or monetary units as well as anticipated challenges related to guideline production and HTA (Desterbecq and Tubeuf, 2023; Marsh et al., 2016b; Pinho-Gomes et al., 2022; Polisena et al., 2018). Several other studies in the literature illustrate the feasibility of calculating environmental impacts alongside traditional cost-effectiveness analysis in a range of therapeutic indications, including melanoma surveillance, hemodialysis and obesity treatment (Marsh et al., 2016a; Williams et al., 2023; de Preux and Rizmie, 2018; Kindred, Shabrina and Zakiyah, 2024). Collectively, these studies stress the importance of developing robust, standardised approaches for assessing environmental impacts in healthcare decision-making, while addressing key challenges such as data limitations, methodological questions, and the need for consensus on valuing environmental impacts relative to health outcomes.

Based on the above, we highlight two broad categories of methods for the inclusion of environmental impacts in economic evaluation:

1) **Integrated evaluation**: Convert environmental impacts to monetary or health values and include them in cost-utility analysis.
2) **Parallel evaluation**: Calculate alternative metrics, such as an incremental carbon footprint cost ratio, for consideration alongside typical cost-utility analyses. [4]

Note the focus of this analysis is on economic evaluation, thus the inclusion of environmental impacts in wider HTA processes is not considered further here.

Integrated evaluation

Integrated evaluations allow for the inclusion of environmental impacts either in the cost or utility side of the cost-effectiveness analysis, either by converting impacts into costs or health gains/losses (Toolan et al., 2023). GHG emissions are often measured in carbon dioxide equivalent units (CO2e) using process-based life cycle analysis (LCA) and then converted for inclusion into economic analyses (Williams et al., 2024). In the literature, impacts are most commonly converted into

[4] There are additional methods to include environmental impacts in an HTA, such as including environmental impacts within multi-criterion decision analysis (MCDA) alongside other factors and freely considering environmental impacts during the HTA deliberation process. We excluded these methods as they involve additional calculations or discussions outside of health economic modelling and are thus beyond the scope of this report.

monetary units; studies have used the social cost of carbon, value of carbon and other published units as conversion factors (Williams et al., 2024). Table 2 presents some financial conversion factors sourced from the literature. Less commonly used DALY conversion factors are presented in Appendix A2.

TABLE 2. CONVERSION FACTORS TO VALUE ENVIRONMENTAL IMPACTS IN MONETARY UNITS

Factor	Country	Value	Source
Value of carbon	UK	£269/tCO_2e in 2022 £ (adjusted for 2024)	(Department for Energy Security & Net Zero and Department for Business, Energy & Industrial Strategy, 2024)
Social cost of carbon	US	$51 per metric ton CO_2 in 2020 $, assuming a 3% discount rate[1]	(United States Government, 2021)
Cost rate for carbon dioxide	Germany	€250/tCO_2e in 2020 €	(Matthey and Bünger, 2023)
Social value of mitigation activities	France	€250/tCO_2e in 2018 €	(France Strategie, 2019)
Social cost of greenhouse gases	Canada	$266/t$CO_2$e in 2021 $ (adjusted for 2024)	(Government of Canada, 2024)

Abbreviations: tCO_2e: tonnes of carbon dioxide equivalent.
Notes: [1]This value has been contested in the literature; a new estimate based on improved methodologies is found to be approximately 3.6 times higher (Rennert et al., 2022)

Parallel evaluation

Parallel evaluations include environmental impacts in the form of value judgements alongside clinical and cost outcomes, involving no change to existing metrics (e.g. the incremental cost effectiveness ratio [ICER] is not impacted). This may include calculating a separate metric to accompany existing metrics in the economic analyses or considering environmental impacts freely during HTA deliberation (Toolan et al., 2023). Given our emphasis on economic evaluation rather than HTA more broadly, this report focuses primarily on new metrics found in the literature that accompany standard ICERs, such as the incremental carbon footprint effectiveness ratio (ICFER) and incremental carbon footprint cost ratio (ICFCR), which can be used to highlight whether an intervention carries a carbon reduction or increase.

$$ICFER = \frac{Incremental\ carbon\ footprint}{Incremental\ QALYs}$$

$$ICFCR = \frac{Incremental\ carbon\ footprint}{Incremental\ costs}$$

3.2 Application of existing methods

Methods for incorporating environmental impact in economic evaluations have been employed in a few areas. In the public health field, economic evaluations of interventions, particularly those related to the natural environment, have begun to employ methods of incorporating environmental impacts such as evaluations of urban green spaces and strategies to reduce indoor and outdoor air pollution (Bojke et al., 2018). In critical care, while health economic evaluations have not yet fully incorporated methods to assess environmental impact, there have been efforts to use LCAs to quantify the environmental impact of different medical supplies, equipment, and procedures in this field (Carrandi et al., 2024).

The use of these methods in formal HTA decision-making processes is, however, still limited. While environmental considerations are increasingly recognised as important, their formal integration into HTA decision-making remains in its early stages (NICE, 2024; Smith and Severn, 2023). The methods are still evolving, and there are ongoing challenges in fully integrating environmental considerations into economic evaluations across all sectors. While the above methods offer various options of how to incorporate environmental impact in economic evaluations, there is still consensus on the most appropriate method. There is a need for further exploration to determine the robustness and applicability of approaches, to aid decision-makers in choosing environmentally sustainable healthcare interventions.

4 Case study: Carbon Minimal pMDIs

This chapter investigates the potential economic value of carbon minimal pMDIs for asthma, relative to current standard pMDIs. We apply the approaches outlined in Chapter 3, thereby capturing the environmental impacts (limited to GHG emissions) of carbon minimal pMDIs within economic evaluation.

4.1 Methods

Intervention and comparator

This analysis focused on three carbon minimal pMDI products:

1) Clenil (beclomethasone dipropionate) pMDI,

2) Foster (extrafine beclometasone/formoterol) pMDI

3) Trimbow (extrafine beclometasone/formoterol/glycopyrronium) pMDI.

In each comparison the existing pMDI (the comparator) was compared to the carbon minimal pMDI (the intervention).

Approach

The analysis employed a partial economic evaluation framework. Given the carbon minimal and the corresponding current standard pMDIs are expected to be clinically equivalent, the analysis did not involve clinical outcomes or downstream resource use, as these would offset each other in an incremental analysis. Instead, the evaluation centred around the following key components:

1) environmental impact: the reduction in GHG emissions associated with the carbon minimal pMDIs, measured in carbon dioxide equivalent (CO2e) per dose;

2) incremental costs, or the additional upfront cost of carbon minimal pMDIs relative to current pMDIs.

Two evaluation approaches were considered in the analysis:

- **Integrated evaluation**: this approach incorporated the GHG emissions directly into the economic evaluation, by converting carbon emissions to either costs or DALYs. Emissions were converted to costs using the UK value of carbon (price per tCO2e) (Department for Energy Security & Net Zero and Department for Business, Energy & Industrial Strategy, 2023). As an alternative method, emissions were converted to DALYs to reflect health damage factors (i.e., changes in DALYs per unit of CO2 emissions) (Tang et al., 2018, 2019).

- **Parallel evaluation**: this approach involves calculating metrics from the literature, such as the ICFER and ICFCR (see Chapter 3). We also calculate an additional metric which we introduce here which could be called the *incremental cost carbon footprint ratio (ICCFR),* and represents the *cost per kgCO2e saved*. We suggest this has a more direct and intuitive interpretation than the other two metrics. The ICCFR is calculated as[5]:

$$-\frac{Incremental\ costs}{Incremental\ carbon\ footprint}$$

Outcomes were calculated per patient. The analysis allowed for the cost-based integrated evaluation (i.e., carbon emissions converted to costs) and parallel evaluation approaches to be calculated per patient over a year, or over an assumed lifetime horizon for the average asthma patient. This is calculated to be 32 years, based on mean patient age of 49.6 years in asthma patients (Jackson et al., 2021) and average life expectancy as estimated in national ONS life tables (Office for National Statistics, 2024). Results for a more conservative treatment period of 10 years are presented in the appendix.

The DALY-based integrated evaluation was applied for both time horizons, and the values were calculated for an estimated asthma patient population in the UK to allow for easier comparison of results; given that the available health damage factors quantified in the literature were based on population-level variables, the values calculated per patient was increasingly small and hinder comparison.

Data

Environmental impact

Environment impact, measured in carbon footprint, was sourced from published life cycle assessments, which quantified carbon emissions for the current standard pMDIs (containing a HFA134a propellant) as well as for the carbon minimal pMDIs (containing a propellant with lower GWP, HFA152a). Table 3 outlines the carbon footprint, in gCO2e per actuation for selected pMDIs.

TABLE 3. CARBON FOOTPRINT, COST AND DOSAGE FOR SELECTED PMDIS

Treatment	Strength (µg /actuation)	Actuations per inhaler	CF (gCO2e/actuation)		Cost per inhaler	Daily dose (µg)
			With HFA134a (certified)	With HFA152a		
Clenil (beclometasone dipropionate)	100	200	83.1	9.39	£7.42	400
Clenil (beclometasone dipropionate)	200	200	81.96	9.31	£16.17	750
Foster (beclometasone dipropionate/formoterol)	100/6	120	94.42	12.1	£29.32	300
Foster (beclometasone dipropionate/formoterol)	200/6	120	118.56	14.05	£29.32	600
Trimbow (beclometasone dipropionate/formoterol/glycopyrronium)	87/5/9	120	118.99	14.34	£44.50	300

Abbreviations: CF: carbon footprint; GWP: global warming potential; HFA: hydrofluoroalkane; pMDI: pressurised metered dose inhaler.
Notes: HFA134a, 1,1,1,2-tetrafluoroethane (GWP value 130); HFA152a 1,1- difluoroethane (GWP value 138).
Sources: Panigone et al., 2020; NICE 2024; GINA 2024.
Trimbow 172/5/9 is not included in the analysis as it was not available at the time of publication of Panigone et al., 2020. and thus its carbon footprint was not provided in the paper.

[5] *The negative conversion is critical to allow the interpretation as cost per kgCO_2e saved.*

Costs

Costs were derived from list prices available in the British National Formulary website (NICE, 2024), presented in Table 3. Unit costs for carbon minimal pMDIs were assumed to be the same as the standard pMDIs in the base case analysis, with this varied in sensitivity analyses.

The cost of carbon is the UK Treasury's carbon value of £269 per tonne of CO2e (Department for Energy Security & Net Zero and Department for Business, Energy & Industrial Strategy, 2023)

Dose

Average daily doses were assumed based on the midpoint of the GINA-recommended medium total daily dose for adults/adolescents on inhaled corticosteroids (Global Initiative for Asthma, 2024), with two exceptions (see Table 3):

- The dose for Clenil (beclometasone dipropionate) 100 was assumed to be 400 µg/day. This is within the range of the low adult and adolescent dose and represents the upper bound of the children's medium dose. This dose was chosen as this is often used amongst child and adolescent populations.

- The dose for Foster (beclometasone dipropionate/formoterol) 200 was assumed to be 600 µg/day (within the high adult daily dose in the GINA recommendations), as this is a higher strength product.

Discounting

There is no clear consensus on the appropriate discounting factor to use when evaluating interventions with long-term future impacts. This is highlighted in the Stern Review, wherein the choice of a specific discount rate for assessing climate change impacts is left undecided (Stern, 2006). Other economic evaluations in the literature assessing environmental impacts apply a discount rate for monetised emissions at the same rate as it would for any other health care costs, but disregard discount rates for environmental benefits, such as GHG emissions in kilograms of CO2e. This is to maintain intergenerational equity, i.e., by placing greater value on the well-being of future generations (Marsh et al., 2016a; Kindred, Shabrina and Zakiyah, 2024).

As per the HM Treasury Green Book and the NICE reference case, discounting is applied here at a rate of 3.5% per year in the base case. Undiscounted results are also presented.

Sensitivity analyses

To assess the robustness of the findings, the following sensitivity analyses were conducted:

List prices: Prices were varied within a range of +20% to reflect potential fluctuations in market pricing or manufacturing costs.

Carbon prices: Given the dynamic nature of carbon pricing and its influence on the value of GHG, we tested changes in the value of carbon across low and high carbon pricing scenarios as per low and high values outlined by the HM Treasury Green Book supplement (low value: £134/tCO_2e, high value: £403/tCO_2e) (Department for Energy Security & Net Zero and Department for Business, Energy & Industrial Strategy, 2023).

Daily dose: The average daily dose for adults on inhaled corticosteroids was also varied based on the lower and upper bounds of the total daily ICS dose (Global Initiative for Asthma, 2024). For Clenil 100 and 200 this was 200–1000 µg, whilst for the remaining products this was 100–400 µg.

Indicative national level analysis: We also used prescription data to scale the potential savings to the national level. Data indicates 60 million inhalers are prescribed every year in the UK, with 70% of these pMDIs (NHS England, 2023; Lavorini et al., 2011). We model the impact of all of these inhalers being swapped for carbon minimal pMDIs to provide an upper bound[6] of the impact of carbon minimal pMDIs. This analysis is not specific to people with asthma but indicates the potential carbon saving across all people with lung disease using inhalers in the UK.

4.2 Results

Environmental impacts

We find a decrease in the per patient carbon footprint of roughly 88% for carbon minimal pMDIs. Current pMDIs were estimated to produce 103 kg to 150 kg of CO2e per person per year, whereas the carbon minimal pMDIs produced 13 kg to 18 kg of CO2e per person per year. The reduction in carbon equates to an average saving of 90–132 kg CO2e per patient, depending on the specific product and usage patterns (see Table 4).

TABLE 4. PER PATIENT INCREMENTAL CARBON FOOTPRINT

Treatment	Incremental CF, annual ($kgCO_2e$)	Incremental CF, lifetime ($kgCO_2e$)	
		Undiscounted	Discounted 3.5%
Clenil (beclometasone dipropionate), 100 µg	-108	-3,446	-2,054
Clenil (beclometasone dipropionate), 200 µg	-100	-3,184	-1,878
Foster (beclometasone dipropionate/formoterol), 100/6 µg	-90	-2,886	-1,720
Foster (beclometasone dipropionate/formoterol), 200/6 µg	-115	-3,665	-2,184
Trimbow (beclometasone dipropionate/formoterol/glycopyrronium), 87/5/9 µg	-132	-4,218	-2,513

Abbreviations: CF: carbon footprint; $kgCO_2e$: kilograms of carbon dioxide equivalent;

Integrated evaluation: cost based

The carbon savings from switching to carbon minimal pMDIs amounted to £24–£35 per patient per year, up to £676 over a patient's lifetime (Table 5).

[6] It represents an upper bound as not all inhalers that are prescribed may be used fully. The carbon footprint analyses of pMDIs used here includes disposal, but assumes the product is fully used. If not fully used, the impact of any remaining propellant depends on how the unused inhaler is disposed of. If not disposed of properly, remaining GHGs are released into the atmosphere (Asthma + Lung UK, 2023).

TABLE 5. RESULTS OF INTEGRATED EVALUATION, CONVERSION OF INCREMENTAL EMISSIONS TO INCREMENTAL COSTS

Treatment	Inc. cost of carbon, annual (£)	Inc. cost of carbon, lifetime (£)	
		Undiscounted	Discounted 3.5%
Clenil (beclometasone dipropionate), 100 µg	-£29	-£927	-£552
Clenil (beclometasone dipropionate), 200 µg	-£27	-£856	-£510
Foster (beclometasone dipropionate/formoterol), 100/6 µg	-£24	-£776	-£463
Foster (beclometasone dipropionate/formoterol), 200/6 µg	-£31	-£986	-£587
Trimbow (beclometasone dipropionate/formoterol/glycopyrronium), 87/5/9 µg	-£35	-£1,134	-£676

Given that the inhalers are considered clinically equivalent, incremental QALYs were 0; as a result, it was not possible to calculate ICERs.

Parallel evaluation

In this analysis, neither the ICFCR nor the ICFER could be calculated, given the treatments were considered clinically equivalent (i.e. incremental QALYs = zero) and of equivalent cost (incremental cost = zero). This highlights that neither the cost to the health system or the health outcomes for the patient are likely to change, despite the CO2e savings.

The ICCFR was calculated to be zero, again highlighting that there is no additional cost incurred for the carbon savings associated with the carbon minimal pMDI.

Sensitivity analyses

List price

Changes in the list price of carbon-minimal pMDIs had no impact on the incremental cost of carbon or the incremental carbon footprint. The total cost, which is the sum of the incremental inhaler cost per patient and the incremental cost of carbon per patient, varied with variations in list prices, as observed in Table 6.

Variations in list prices also resulted in variations within the parallel evaluation metrics, such as the ICFCR and ICCFR, as shown in Table 6. The cost per kgCO2e saved for carbon-minimal pMDIs is £0.05–£0.71 per patient over their lifetime.

TABLE 6. SENSITIVITY RESULTS WITH LIST PRICE INCREASE OF 10% AND 20%

Treatment	10% increase			20% increase		
	Inc. total cost (£)	ICFCR (kgCO2e/£)	ICCFR (£/kgCO2e)	Inc. total cost (£)	ICFCR (kgCO2e/£)	ICCFR (£/kgCO2e)
Clenil (beclometasone dipropionate), 100 µg	-£449	-19.87	£0.05	-£346	-9.93	£0.10
Clenil (beclometasone dipropionate), 200 µg	-£299	-8.99	£0.11	-£88	-4.49	£0.22
Foster (beclometasone dipropionate/formoterol), 100/6 µg	£48	-3.37	£0.30	£558	-1.68	£0.59
Foster (beclometasone dipropionate/formoterol), 200/6 µg	-£77	-4.28	£0.23	£434	-2.14	£0.47
Trimbow (beclometasone dipropionate/formoterol/glycopyrronium), 87/5/9 µg	£215	-2.82	£0.35	£1,105	-1.41	£0.71

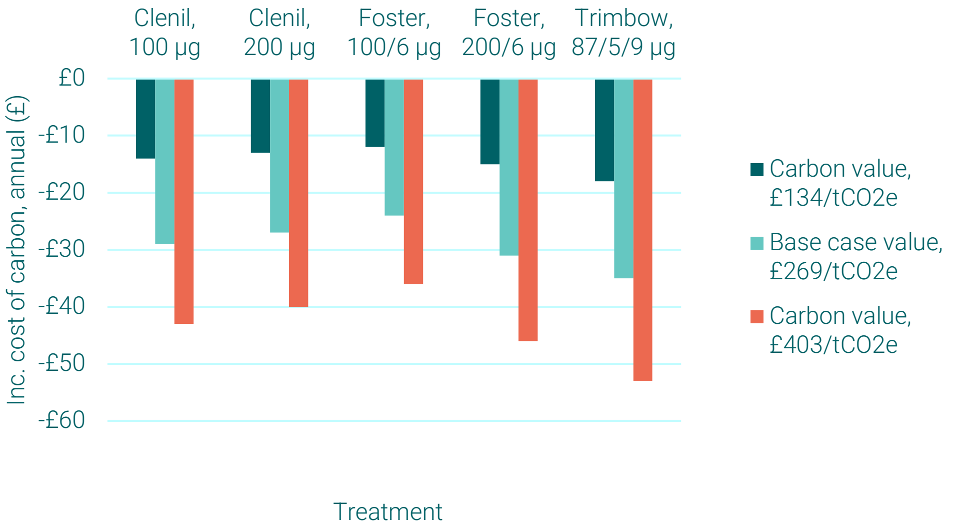
Abbreviations: ICCFR: incremental cost carbon footprint ratio; ICFCR: incremental carbon footprint cost ratio.

Carbon values

The results utilising the higher and lower carbon values are presented in Figure 2. Switching to carbon minimal pMDIs resulted in carbon savings of £12–£18 per patient per year in the low carbon value scenario and carbon savings of £36–£53 in the high carbon value scenario, as compared to £24–£35 in the base case.

Impact on ICERs could not be calculated as the incremental QALYs were zero given that the inhalers are considered clinically equivalent. Similar to the base-case analysis, neither the ICFCR nor the ICFER could be calculated, and the ICCFR was calculated to be zero.

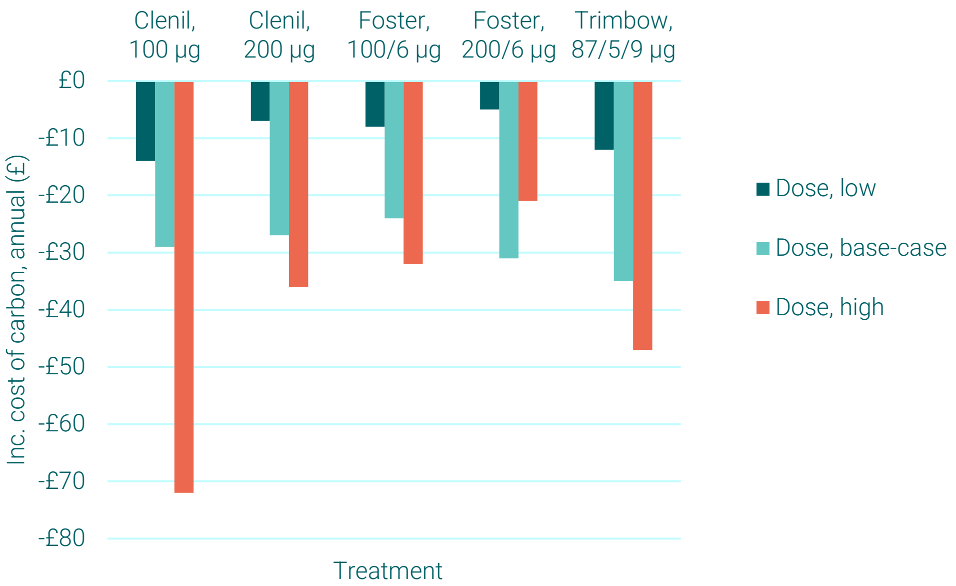
FIGURE 2. SENSITIVITY RESULTS OF VARIATION IN CARBON VALUES



Dose

As observed in Figure 3, carbon minimal pMDIs still dominate the existing pMDIs despite variability in patient usage and compliance.

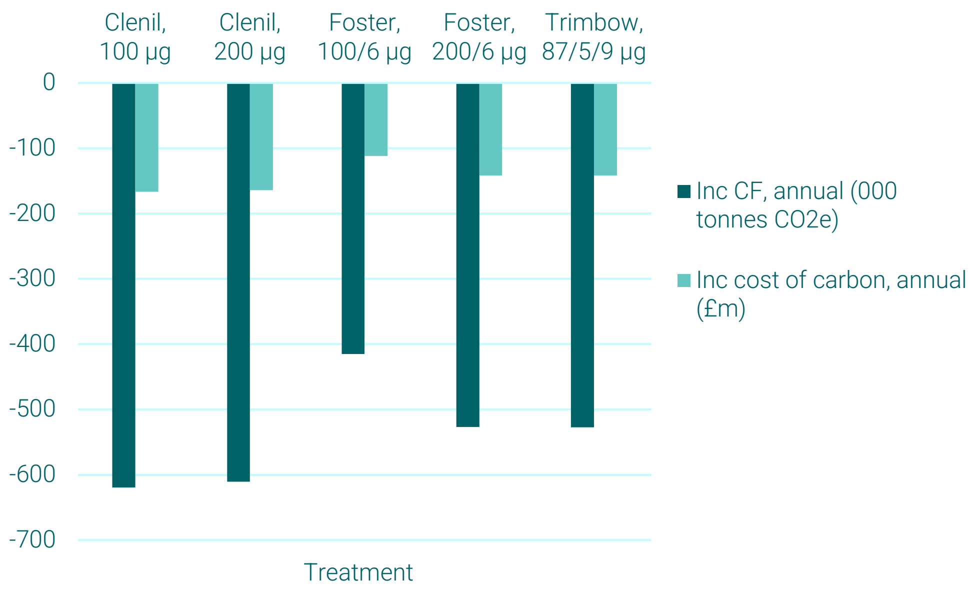
FIGURE 3. SENSITIVITY RESULTS OF DOSAGE FREQUENCY, INTEGRATED EVALUATION



Indicative national level analysis

Figure 4 highlights that if all people currently prescribed inhalers are switched to carbon minimal pMDIs we could observe average savings of 414,292–619,164 tonnes CO2e in one year, corresponding to average savings in cost of carbon of £112–£166 million, depending on the specific product and usage patterns.

FIGURE 4: SENSITIVITY RESULTS OF INDICATIVE NATIONAL LEVEL ANALYSIS



5 Interpretation and discussion

5. 1 Commentary on results

We estimate an additional value of carbon minimal pMDIs compared to standard pMDIs in the region of £463–£676 per person with asthma over their lifetime. At a population level, if all people currently being prescribed pMDIs transitioned to the corresponding carbon minimal pMDIs this could save carbon emissions up to the value of £112–£166 million annually in the UK alone.[7] This added value demonstrates the environmental and economic benefits available from switching from existing pMDIs to carbon minimal pMDIs where clinical outcomes are equivalent.

This analysis also demonstrates that it is possible to value the incremental GHG emissions of different pMDIs within an economic evaluation, particularly where the assumption of clinical equivalence can be applied as this reduces the data requirements for the analysis. LCA provides a comprehensive view of a product's environmental impact across its entire lifecycle, while carbon footprint calculations specifically focus on quantifying GHG emissions in terms of CO2 equivalents. Integrated and parallel evaluation provide a means of incorporating these measures into economic analysis.

In addition to the value calculated here, reducing the GHG emissions of healthcare products will reduce healthcare systems' contributions to climate change. A cleaner environment is associated with reduced respiratory diseases and other health conditions linked to pollution (Manisalidis et al., 2020), thereby potentially leading to further long-term capacity and cost savings for the health system

5. 2 Gaps and limitations

Using the results in decision making

In this case the carbon minimal pMDIs dominates the corresponding existing pMDI, as it is the same or superior across all categories of outcomes (health, financial and GHG emissions). The decision between the two technologies is therefore uncomplicated. Indeed, NICE are exploring the feasibility of evaluating the environmental impacts of medicines that have minimal differences in health or cost outcomes, stating that it may be sensible to prefer the least environmentally harmful option in such cases (NICE, 2024). However, the decision between two options will be less clear when an intervention does not dominate its comparator.

Integrated evaluation

Whilst the integrated evaluation option allows for calculation of an ICER, a metric which is well understood by healthcare decision makers, this ICER cannot be treated in the same way as before. Where opportunity cost cost-effectiveness thresholds, such as that used by NICE in the UK, are linked to healthcare budgets, it is not appropriate to use these thresholds as decision rules for metrics that include costs that fall outside of the typical healthcare budget. A different decision rule or set of decision rules would therefore be required to interpret the new integrated ICER. A cost-effectiveness threshold based on willingness to pay (such as that suggested by the UK Treasury)

[7] *Note that this assumption does not remain valid if a patient switched to a product containing different active ingredients or formulation*

may provide a starting point for further analysis and deliberations, with the threshold applied to carbon emissions across various sectors.

Parallel evaluation

These new metrics (ICCFR, ICFCR, ICFER) do not come with pre-established decision rules (such as cost-per-QALY thresholds), and thus do not directly infer a decision in cases of non-dominance. In addition, it may be difficult for decision makers to base decisions on multiple metrics.

We calculate an additional metric (the ICCFR) which can be interpreted as the cost per kgCO_2e saved. This metric is consistent with the UK Treasury Green Book guidance, which suggests calculating the average cost of saving each tonne of carbon dioxide (equivalent) (Department for Energy Security & Net Zero and Department for Business, Energy & Industrial Strategy, 2023). This has a much more intuitive interpretation than the ICFCR or ICFER, as it can be compared directly to the value of carbon. If the ICCFR is lower than the value of carbon (£0.27 per kgCO2e), the intervention could be considered favourable (on balance of cost and GHG emissions).

Still, this will mainly be useful when decision makers are faced with decisions across cost and environmental impacts only, such as in the case of our sensitivity analysis around price. Here, if carbon minimal pMDIs were to cost 20% more than standard pMDIs, only the low carbon Clenil (beclometasone dipropionate) would have a cost per kg carbon saved (ICCFR) lower than the UK's cost of carbon (see Table 6; for reference the UK cost of carbon is 0.27 per kg)).

Where decision makers also need to consider differences in health outcomes, a different type of economic evaluation, such as cost-benefit analysis (where all outcomes are converted into financial values), may be more useful. Further research into how environmental data and additional metrics can be used to inform decision making is required, including how this information can be used within HTA processes and methods. Developing standardised methods for incorporating these factors into economic evaluations would help ensure that the broader societal costs of carbon emissions are consistently represented in decision-making processes, should this be considered appropriate.

Data availability

It was possible to calculate the GHG and economic impacts in this case because data on the carbon footprint of both products exists (Panigone et al., 2020), which may not always be the case. Moreover, assuming clinical equivalence between the carbon minimal pMDIs and the standard pMDI, any change in healthcare utilisation could be considered negligible in our analysis. In cases where a new product may be more (or less) effective than that which it is intended to replace, a full environmental analysis would also need to look at the impact of changes in downstream healthcare utilisation, such as changes in number of appointments, hospitalisations, or other medication. The carbon footprint (and indeed other environmental impacts) of all of these elements would be needed to provide a comprehensive assessment of the environmental impact. This requires a substantial amount of data that is not routinely available at present.

Outcomes

Further, this report solely focuses on carbon emissions as a measure of environmental impact, primarily due to the high GHG emissions associated with pMDIs and the availability of data in terms of carbon footprint. There are many other important environmental outcomes, such as resource utilisation, waste production, and broader ecological effects, that were not addressed in our evaluation. Future evaluations would benefit from incorporating these additional factors to provide a more comprehensive assessment.

Conversion factors

The results heavily depend on the accuracy of the financial conversion rates used for environmental impacts (carbon values or prices), and/or the health conversion factors (health damage factors). There are various ways in which each of these can be calculated, each with their own limitations and uncertainties (Department of Energy and Climate Change, 2009). The UK's current approach to estimating the value of carbon is based on abatement cost curves and therefore reflect the cost of implementing measures to reduce emissions to meet specific carbon targets, rather than the social value of the benefits of reducing carbon. Under certain assumptions these values would be the same, but these conditions are unlikely to hold in reality (Department of Energy and Climate Change, 2009). Nevertheless, the abatement cost curve approach is considered to be more credible that the social cost of carbon approach due to greater transparency, less reliance on unobserved factors, and alignment with the net zero target. As shown by our analysis of the different prices of carbon (Figure 2), this input has a substantial impact on the scale of the economic benefits.

We consider the health damage factors (Appendix A2) to be particularly uncertain. Further research into this relationship may not be necessary given an emerging preference amongst practitioners and decision makers for emissions to be expressed as costs in policy evaluations (e.g. HM Treasury).

In the parallel evaluation approach, which runs alongside traditional economic evaluations, environmental impacts are analysed without converting them into monetary or health units. This avoids the limitations of conversion, but the challenges around interpretation and use in decision making remain.

The role of incentives in meeting net zero targets

There are various ways of incentivising manufacturers to produce more environmentally friendly products. Financial, reputational, regulatory, and market based (i.e. pricing and reimbursement) incentives all could have a potential role to play. Incorporating environmental data into economic evaluation within HTA is a market-based incentive that could be one piece of the puzzle in the race to net zero. It will not be sufficient on its own, particularly given HTA is largely conducted concentrated on new products. Additional approaches, evaluations and incentives must be designed to target the wider health system (including existing medical technologies) if the required change is to be achieved. Further research into the design of a matrix of incentives is required.

Real world implementation of carbon minimal pMDI

In our sensitivity analysis we calculated the impact of transitioning all current pMDIs in the UK to corresponding (i.e. same active ingredients and equivalent clinical effect) carbon minimal pMDIs, with substantial impacts. This represents an upper bound of the potential impact of carbon minimal pMDIs in the UK, as in reality some users may switch to other options, such as DPI, with potential consequences on clinical outcomes.

In addition, we make an implicit simplifying assumption that there is no additional cost from transitioning from a standard pMDI to the carbon minimal pMDI. In some cases, an additional appointment or interaction with the health service may be required, as has been modelled in the case of switching from pMDIs to DPIs (Attar-Zadeh, Lewis and Orlovic, 2021).

6. Conclusions

Healthcare decision makers around the world are beginning to recognise the role that health systems have to play in climate change, and the potential impacts this could have on the way health systems are able to operate. Managing the environmental impact of health systems is therefore critical, with reductions in the impact of medicines, and inhalers in particular, playing an important role.

Current inhalers offer health and economic value for asthma patients and health systems, but some, pMDIs in particular, generate substantial GHG emissions. These emissions are not routinely considered in health economic assessments or healthcare decision making.

New carbon minimal pMDIs are in development, and it is possible to measure and value the reduction in carbon emissions that they offer. In the UK, a move from the current pMDIs to a carbon-minimal pMDIs with the same active ingredients and equivalent clinical efficacy would reduce emissions by 1,720–2,513 kgCO_2e per person with asthma over their lifetime, with no expected increase in cost. The economic value of this reduction in emissions is £463–£676 per person with asthma over their lifetime. Based on an assumption of price parity with the current comparable pMDI, this change would have no impact on health care costs or clinical outcomes. At a national level, if all people in the UK with respiratory conditions were to receive the corresponding carbon minimal pMDI instead of the current pMDI, it would save carbon emissions up to the value of £112–£166 million annually. The carbon savings (415,000 to 619,000 tCO2e) associated with this transition would represent 7%–10% of the NHS commitment to reduce carbon emissions from 6.1 million tCO2e to net zero by 2040 (Dodge, Watts and Bailie, 2021).

This additional value of carbon savings can be reflected in economic evaluations, although challenges remain related to data availability and in the interpretation of new metrics in cases of non-dominance, where the economic evaluation is to be used for decision making. In the case of carbon minimal pMDIs this is not a concern as the carbon minimal pMDIs offers substantial carbon savings, with no expected increase in cost or change in clinical outcomes.

A.1. Appendix 1: Literature Review

In this section, we present the methods and results of the literature reviews, the aims of which were:

1. Review and identify the current methods for incorporation of environmental impacts into health economic models

2. Capture information on existing economic evaluations for pMDIs in asthma

Methods

Scope

This review comprised of two searches to address each of the aims. Our first search involved a rapid evidence assessment and focused on papers that directly focused on methods and metrics for quantifying environmental impact within health economic evaluations. The rapid review conducted sought to obtain relevant published and grey literature (including reports and statements from HTA bodies), to gain insight into the most up-to-date thinking and novel methodology.

To address our second aim, we performed a targeted literature review to identify existing economic models evaluating pMDIs in asthma. This search prioritised identifying evaluations or reviews of evaluations with a UK perspective, but grey literature from a wider international perspective were included when they were particularly relevant.

Search Strategy and Databases

We conducted the literature reviews using Google Scholar and PubMed, as detailed below in Table 7 and Table 8 below. Our searches were restricted to only identifying terms included in the title or abstract of the paper. We also restricted our search to papers that are published in the English language. The search was further restricted to papers published between January 2014 and September 2024 to prioritise the more recent literature, as consideration of environmental impacts in health economic evaluations is more common and likely in more recent literature. Further, we reviewed the reference lists in the literature identified by the outlined search strategy to capture additional relevant literature, including those that fall outside the time range.

TABLE 7: SEARCH STRATEGY FOR RAPID REVIEW ON METHODS OF INCORPORATING ENVIRONMENTAL IMPACT

	Search Command
	economic evaluation* OR economic model* OR cost-effectiveness OR cost-of-illness
AND	
	environmental impact OR footprint OR emission*

TABLE 8: SEARCH STRATEGY FOR TARGETED REVIEW OF EXISTING ASTHMA-RELATED ECONOMIC EVALUATIONS

	Search Command
	economic evaluation* OR cost-effectiveness
AND	
	asthma OR inhaler*
AND	
	United Kingdom OR UK OR England

To identify relevant grey literature, we conducted searches of key websites including and not limited to NICE, NHS England, NHS Wales, Scottish Medicines Consortium, Canadian Drug Agency, Haute Autorité de Santé (France), Institute for Quality and Efficiency in Health Care (Germany) and Pharmaceutical Benefits Advisory Committee (France).To identify additional information related to the price of carbon in the United Kingdom, we also conducted a Google search using terms such as 'social cost of carbon' and 'valuation of emissions'.

A.2. Appendix 2: DALY conversion factors and results

A small number of studies have converted GHG emissions into disability-adjusted life years (DALYs) using "damage factors" that take into account the impact of hypothetical socioeconomic scenarios on CO2 emissions (Tang et al., 2018, 2019) Table 9 presents conversion factors sourced from the literature.

TABLE 9. CONVERSION FACTORS TO VALUE GHG EMISSIONS IN HEALTH UNITS

Hypothetical scenario	Conversion factor (DALY per kgCO_2-e)	Source
A1B, a scenario with rapid economic growth with a decline in global population	2.0×10^{-7}	Tang et al., 2018
A2, a scenario with regionally oriented economic development and increasing global population	6.2×10^{-7}	Tang et al., 2018
B1, scenario A1B with the economy tending towards a service and information economy	2.1×10^{-7}	Tang et al., 2018
B2, scenario A2 with a lower growth rate and lower rate of technological development	4.2×10^{-7}	Tang et al., 2018
SSP1, a scenario with high economic growth	1.3×10^{-6}	Tang et al., 2019
SSP2, a scenario with economic growth between scenarios SSP1 and SSP3	1.5×10^{-6}	Tang et al., 2019
SSP3, a scenario with low economic growth	2.0×10^{-6}	Tang et al., 2019

Abbreviations: kgCO_2e: kilograms of carbon dioxide equivalent; SSP: socioeconomic pathway.

Results

Over a 1-year time horizon for the population of the UK with asthma, DALYs associated with carbon minimal pMDIs were consistently lower than for standard pMDIs across several scenarios corresponding to different 100-year climate change scenarios projected by the Intergovernmental Panel on Climate Change (IPCC) (Table 10).

TABLE 10. RESULTS OF INTEGRATED EVALUATION, CONVERSION OF EMISSIONS TO DALYS BASED ON DIFFERENT SCENARIOS

Treatment	Incremental DALYs						
	A1B	A2	B1	B2	SSP1	SSP2	SSP3
Clenil (beclometasone dipropionate), 100 µg	-77	-240	-81	-163	-504	-581	-775
Clenil (beclometasone dipropionate), 200 µg	-72	-222	-75	-150	-465	-537	-716
Foster (beclometasone dipropionate/formoterol), 100/6 µg	-65	-201	-68	-136	-422	-487	-649
Foster (beclometasone dipropionate/formoterol), 200/6 µg	-82	-255	-87	-173	-536	-618	-824
Trimbow (beclometasone dipropionate/formoterol/glycopyrronium), 87/5/9 µg	-95	-294	-100	-199	-616	-711	-948

Abbreviations: DALYs: disability-adjusted life years
For definitions of scenarios see footnote to Table 9.

A.3. Appendix 3: Time horizon of 10 years

We performed scenario analysis on the time horizon for asthma patients, assuming a treatment period of 10 years for the average asthma patient. This was based on the York Economic Assessment of the cost-effectiveness of omalizumab for asthma, with the 10-year duration considered appropriate by clinical advisors (Norman et al., 2013a). The carbon footprint savings from switching to carbon minimal pMDIs amounted 750–1,096 $kgCO_2e$ per patient over an assumed treatment duration of 10 years (Table 11).

TABLE 11. PER PATIENT INCREMENTAL CARBON FOOTPRINT, TEN YEAR TIME HORIZON

Treatment	Incremental CF, annual ($kgCO_2e$)	Incremental CF, 10 years ($kgCO_2e$)	
		Undiscounted	Discounted 3.5%
Clenil (beclometasone dipropionate), 100 µg	-202	-1,077	-896
Clenil (beclometasone dipropionate), 200 µg	-100	-995	-828
Foster (beclometasone dipropionate/formoterol), 100/6 µg	-90	-902	-750
Foster (beclometasone dipropionate/formoterol), 200/6 µg	-57	-1,145	-952
Trimbow (beclometasone dipropionate/formoterol/glycopyrronium), 87/5/9 µg	-132	-1,318	-1,096

Abbreviations: CF: carbon footprint; $kgCO_2e$: kilograms of carbon dioxide equivalent;

We estimate an additional value of carbon minimal pMDI compared to standard pMDIs in the region of £202–£295 per person with asthma for an average treatment duration of 10 years (assuming discounting; Table 12).

TABLE 12. RESULTS OF INTEGRATED EVALUATION, CONVERSION OF INCREMENTAL EMISSIONS TO INCREMENTAL COSTS, TEN YEAR TIME HORIZON

Treatment	Inc. cost of carbon, annual (£)	Inc. cost of carbon, 10 years (£)	
		Undiscounted	Discounted 3.5%
Clenil (beclometasone dipropionate), 100 µg	-£54	-£290	-£241
Clenil (beclometasone dipropionate), 200 µg	-£27	-£268	-£223
Foster (beclometasone dipropionate/formoterol), 100/6 µg	-£24	-£243	-£202
Foster (beclometasone dipropionate/formoterol), 200/6 µg	-£15	-£308	-£256
Trimbow (beclometasone dipropionate/formoterol/glycopyrronium), 87/5/9 µg	-£35	-£355	-£295

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