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The truth about co-benefits: a multidimensional feasibility assessment for thailand and beyond

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Abstract

Research has yielded increasingly robust estimates of the co-benefits from mitigating climate change while reducing air pollution, improving health, and meeting other development needs. Though quantifying these often hidden benefits could ease cost concerns and lower technological constraints for development-friendly climate solutions, achieving co-benefits frequently requires overcoming difficult-to-measure social and institutional barriers. This study extends insights from research focusing on quantitatively assessing the feasibility of a 1.5 °C future to build a multidimensional framework for measuring different barriers to achieving co-benefits. The framework offers a novel yet generalizable approach for bringing context-appropriate assessments of different dimensions of feasibility into the integrated assessment modelling that underpins work on co-benefits. It then outlines five steps for applying that framework to evaluate the size of different barriers for transport, agricultural and residential energy co-benefit solutions in Thailand. The results demonstrate that the sum of the delays from social/institutional barriers exceed economic/technological barriers for four out of six studied solutions. These delays also lead to increases of 24% to 31% in PM_{2.5} emissions relative to a no-barriers effective implementation scenario between 2015 and 2030 and 2040. The feasibility framework can be integrated into not only national policy scenarios but also project assessments, following trends in carbon finance. An international barriers database as well as strengthening links to work on barriers and technological diffusion, transaction costs, and multi-level transitions can also help spread multi-dimensional feasibility assessments across countries and scales.

1. Introduction

In recent years, policymakers have realized that the climate crisis is less a possibility than an inevitability. This realization has led to a growing interest in transitions aimed at limiting warming below 1.5 °C compared to pre-

industrial levels (IPCC 2018 2022).¹³ The sociotechnical changes that can support these transitions have also drawn growing interest. Many changes in the transport, agricultural and residential sectors featuring in these transitions can mitigate greenhouse gas (GHGs) as well as air pollutants. Some of those air pollutants are also short-lived climate pollutants (SLCPs) (Bond *et al* 2013, Shindell *et al* 2017).¹⁴ By helping to control multiple pollutants, these options can deliver co-benefits and contribute to the Sustainable Development Goals (SDGs). For example, many of the relevant projects and policies in this article reduce air pollution, cut seven million early deaths annually, and avoid millions of tons of crop damages and associated economic losses (UNEP/WMO 2011a, WHO 2014, Haines *et al* 2017, Hoffmann *et al* 2021).

Underlying much of the research on co-benefits is a key point: co-benefits can offset mitigation costs and encourage policymakers to invest in climate projects and policies (Krupnick *et al* 2000, Pearce 2000, Uchida and Zusman 2008, Farzaneh *et al* 2021). One might infer from this key point that policymakers would be inclined to implement options with multiple benefits when formulating transition pathways. In fact, several high-profile reports have underlined the potential for co-benefits from measures that curb emissions from vehicles, cookstoves, and burning of biomass (UNEP/WMO 2011b, UNEP APCAP and CCAC 2019). These reports rely heavily on integrated assessment models to identify how much technological and social changes contribute to climate and other development goals.

While the above models are critical to assessing the size of benefits, they have limitations (McMichael 1997, Schneider 1997, Norgaard and Baer 2005, Ackerman *et al* 2009, Mathias *et al* 2020). An important limitation is integrated assessment models do not explicitly consider the feasibility of implementing recommended solutions (Nielsen *et al* 2020, Brutschin *et al* 2021, Hickmann *et al* 2022).¹⁵ The inattention to social and institutional feasibility may be particularly problematic because effective implementation of co-benefit interventions often requires social and institutional enabling reforms (UNEP/WMO 2011, UNEP APCAP and CCAC 2019). To some degree, the limited attention to these issues is understandable: the difficulties measuring the effects of administrative capacity/coordination (i.e. institutional dimensions) or awareness/user acceptability (i.e. social dimensions) make their integration into modeling difficult (Nielsen *et al* 2020, Brutschin *et al* 2021, Hickmann *et al* 2022). Yet, the failure to include these constraints into models may generate false hope about achieving possible results (Li, 2017). The exclusion of these consideration may also weaken recommendations for enabling reforms¹⁶ such as the interagency coordination and capacity building mechanisms required to implement solutions at scale.

The purpose of this study is to demonstrate a novel approach for incorporating feasibility into co-benefits modeling. To illustrate that approach, the article uses original survey data from Thailand on barriers to implementing solutions from the transport, agricultural and residential energy sectors. The study shows that the institutional and social constraints could often slow the implementation more than economic and technological constraints. A policy-level application of the findings suggests the delays result in increases of 24% to 31% in PM_{2.5} emissions relative to a no-barriers effective implementation scenario in Thailand between 2015 and 2030 and 2040 respectively. The feasibility framework can also be used to analyze barriers at smaller scales—for example, carbon finance projects.

The study is divided into five sections. The second section reviews literature on co-benefits and feasibility. The third section outlines an approach for bringing feasibility into modeling frameworks with the case of Thailand. The fourth section discusses the implications of this approach for research and policy. The final section reiterates conclusions and highlights areas for future research.

2. Literature review on co-benefits and feasibility

This article brings together literature on co-benefits and feasibility. Research on co-benefits traces back more than three decades (Schneider 1989, Ayres and Walter 1991, Glomsrød *et al* 1992, Pearce 1992, Elkins 1996). The

¹³ The IPCC defines transitions as ‘the process of changing from one state or condition to another in a given period of time [for] individuals, firms, cities, regions and nations, and can be based on incremental or transformative change.’ In this article, transitions will apply chiefly to changes at the national level and the changes that countries make to their policies and enabling environments that would help achieve the 1.5 °C targets under the Paris Agreement.

¹⁴ Recent research has suggested that the impacts of black carbon on warming are lower than initially anticipated (Takemura 2020). However, the impacts on regional climate systems through, for instance, changes in precipitation patterns are still envisaged as being significant (Ramanathan *et al* 2005).

¹⁵ The IPCC defines ‘feasibility’ as ‘the potential for a mitigation or adaptation option to be implemented [and notes that feasibility] depends on geophysical, environmental-ecological, technological, economic, sociocultural and institutional factors that enable or constrain the implementation of an option.’ (E1. Footnote 72).

¹⁶ The IPCC suggests that ‘enabling conditions’ refers to conditions that enhance the feasibility of adaptation and mitigation options. Enabling conditions include finance, technological innovation, strengthening policy instruments, institutional capacity, multi-level governance and changes in human behavior and lifestyles’ (E1. Footnote 73).

earliest first wave of studies on co-benefits demonstrated that climate policies such as a carbon tax could limit air pollution and bring significant health benefits in *developed* countries (Elkins 1996, Pearce 2000). The health benefits were often large enough to offset mitigation costs—for instance, air quality co-benefits could be more than ten times larger than climate benefits in some developed country cases (Pearce 1992). These savings could conceivably motivate policymakers to support reforms needed to achieve the estimated gains (Pearce 1992, Krupnick *et al* 2000, Pearce 2000).

A second wave of co-benefits research looked at a broader range of sectoral policies and projects in *developing countries* (Bussolo and O'Connor 2001, Aunan *et al* 2004, Morgenstern *et al* 2004). These studies often found greater potential savings for a more diverse set of interventions (Li and Crawford-Brown 2011, Menikpura *et al* 2013, Chalcharoenwattana and Pharino 2015, Dhar and Shukla 2015, Jiang *et al* 2016, Pathak and Shukla 2016, Dhar *et al* 2017, Li *et al* 2018, Liu *et al* 2018, Shi *et al* 2022). The larger size of benefits was due to poorer air quality and higher population densities in developing countries (Nemet *et al* 2010). Therefore, efforts to mitigate climate change would also lead to greater reductions in air pollution for more people (Bollen *et al* 2009). This finding could lower concerns that investing in climate mitigation would divert resources from other priorities in developing countries (Zusman 2008).

Following this second wave of developing country-focused research, some of a third wave of work on co-benefits has concentrated on influencing policy (Cai *et al* 2023, Karlsson *et al* 2023, Roggero, Gotgelf, and Eisenack 2023). To illustrate, several overview studies have mapped connections between energy policies and streams of different benefits to help increase impacts on policy (Karlsson *et al* 2020). To offer another example of the policy-orientation, many studies have focused on solutions that curb air pollutants known as SLCPs such as black carbon, tropospheric ozone, and methane (UNEP/WMO 2011b, Bond *et al* 2013, Shindell *et al* 2017).¹⁷

A related trend is an interest in how to not only change policy but trigger action on the ground. To illustrate, with the support of international and regional initiatives such as the Climate and Clean Air Coalition (CCAC) and Asia Pacific Clean Air Partnership (APCAP), high-profile reports have identified 25 action-oriented clean air solutions that could improve air quality and mitigate near- and long-term climate change in Asia (UNEP APCAP and CCAC 2019). Similar reports have been developed for Latin America and Africa (CCAC and UNEP 2016, Hannah *et al* 2021) as well as countries such as Bangladesh and Cambodia (Kuylenstierna *et al* 2020, Malley *et al* 2022); a sub-regional report for Southeast Asia is near publication (CCAC 2023).

While this third wave of research on co-benefits has become more policy-relevant and action-oriented, it has still placed a greater emphasis on modelling potential benefits than assessing barriers to achieving them. The inattention to implementation is arguably a function of the fact that much of the work on co-benefits relies on methods that do not integrate feasibility into their analyses. Some studies have acknowledged these shortcomings (Ürge-Vorsatz *et al* 2014, Mayrhofer and Gupta 2015). Others have made modest attempts to overcome them by emphasizing implementation barriers in specific countries (Dubash *et al* 2013) and sectors (Brown *et al* 2008).

Another branch of research focusing on feasibility could help bring implementation barriers into a fourth wave of co-benefits research (see figure 1 for an illustration of these waves). Some early work in this space has looked at how different dimensions of feasibility influence whether policies achieve their stated objectives (Majone 1975a, 1975b). Others have taken this insight a step further to use expert surveys and literature reviews to analyze barriers to adopting energy efficiency reforms and renewable energy technologies, paralleling the approach used in this study (Sovacool 2009, Sorrell *et al* 2011, Backlund *et al* 2012). Much of the interest in implementation barriers has considered multiple dimensions of feasibility (Staub-Kaminski *et al* 2014). For instance, some have argued for a '2nd best analysis of climate policy' to give a more realistic assessment how poorly designed policies impact the likelihood of achieving modelling results (Krieglner *et al* 2012).

Yet others have sought to use a similar reasoning to assess the feasibility of 1.5 °C or net zero future (Staub-Kaminski *et al* 2014, Nielsen *et al* 2020, Brutschin *et al* 2021, Hickmann *et al* 2022, Steg *et al* 2022, Ven *et al* 2023). Some studies have underlined that feasibility is critical to close potentially large gaps between integrated assessment models and the real world but acknowledged the difficulties of making the concept sufficiently concrete to integrate into modelling scenarios (Warszawski *et al* 2021). Some have sought close these gaps by using a simple coding technique from an expert literature review for a systematic assessment of different dimensions of feasibility for a range of sectoral mitigation options at the global level (Steg *et al* 2022). Others have shown that there is a need to move beyond sectoral options to demonstrate that social and institutional dimensions of feasibility may limit the likelihood of implementing packages of interventions in broader scenarios at the global and regional levels (Brutschin *et al* 2021). A recent extension of work has used proxy indicators for difficult-to-assess social and institutional constraints (World Bank governance indicators) to

¹⁷ Note that IPCC Joint 1st and 2nd IPCC Expert Meeting on Short-lived Climate Forcers (SLCFs) recommends using 'SLCP' for warming species of air pollutants. For species that have both a warming and cooling effect, it calls for using 'SLCFs.'

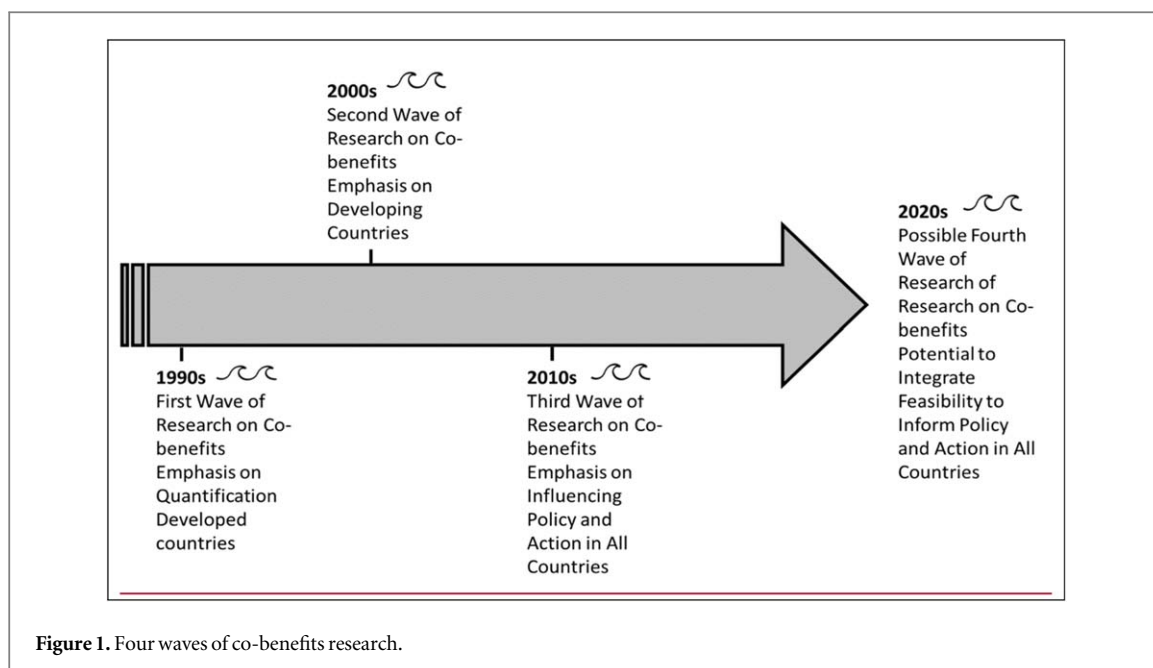


Table 1. Selected options.

Sector	Option	Brief description
Residential Energy	Replace Traditional Stoves	Adoption of higher efficiency or cleaner stoves, including fan assisted stoves
Transport	Switch to LPG	Switch from solid fuel to liquid petroleum gas powered for cooking
	Promotion of Electric Vehicles (EV)	Adoption and spread of electric vehicles
	Tighter Emission Standards for Vehicles	Introduction of tighter emission standards and energy/fuel efficiency standards for vehicles
	Vehicle Inspection and Maintenance	Vehicle inspection and maintenance that enable early detection and elimination/repair of high emitting vehicles
Agriculture	Control Open Burning and Sustainable Use of Agricultural Residues	Banning or controlling the open burning of agricultural residues, including rice straw, sugarcane and corn

empirically estimate how institutional feasibility of realizing reductions in a wide range of modelling scenarios (Bertram *et al* 2024).

The growing attention to feasibility of implementing scenarios in integrated assessment models is welcomed given the urgent need for accelerating 1.5 or net zero transitions. However, none of the recent work on feasibility has focused on creating a generalizable framework that can assess the implementation prospects of national or lower level solutions with co-benefits. The lack of attention is significant because even the more policy and action-oriented work on co-benefits is grounded in the belief that accounting for co-benefits can lower cost concerns and induce technological changes. However, for many of the solutions with the greatest co-benefits, social and institutional barriers may stand in their way of their implementation. There is hence scope to extend work on multiple dimensions feasibility to research on specific co-benefit solutions. The next section describes the case selected to demonstrate how an approach employing expert surveys and literature reviews can integrate feasibility into the co-benefit modelling for a subset of options in Thailand.

3. Case selection: transport, residential energy, and open burning solutions in Thailand

To look at feasibility in Thailand, this study focuses on options in the transport, residential energy, and agriculture sectors (table 1). These solutions were selected for three reasons.

The first is the options are featured in ongoing policies and projects in Thailand. For instance, Thailand adopted a National PM_{2.5} Control Plan in 2019 that includes provisions related to transport (Section 2.1 of the PM_{2.5} Control Plan), open burning (Section 2.3 of the PM_{2.5} Control Plan), and clean cooking (Section 2.5 of the PM_{2.5} Control Plan) (Pollution Control Department 2019). In addition, Thailand is also drafting a Clean Air Law that is likely to aim to curb open burning and vehicle emissions (Walker 2024). Further, to cite a local level

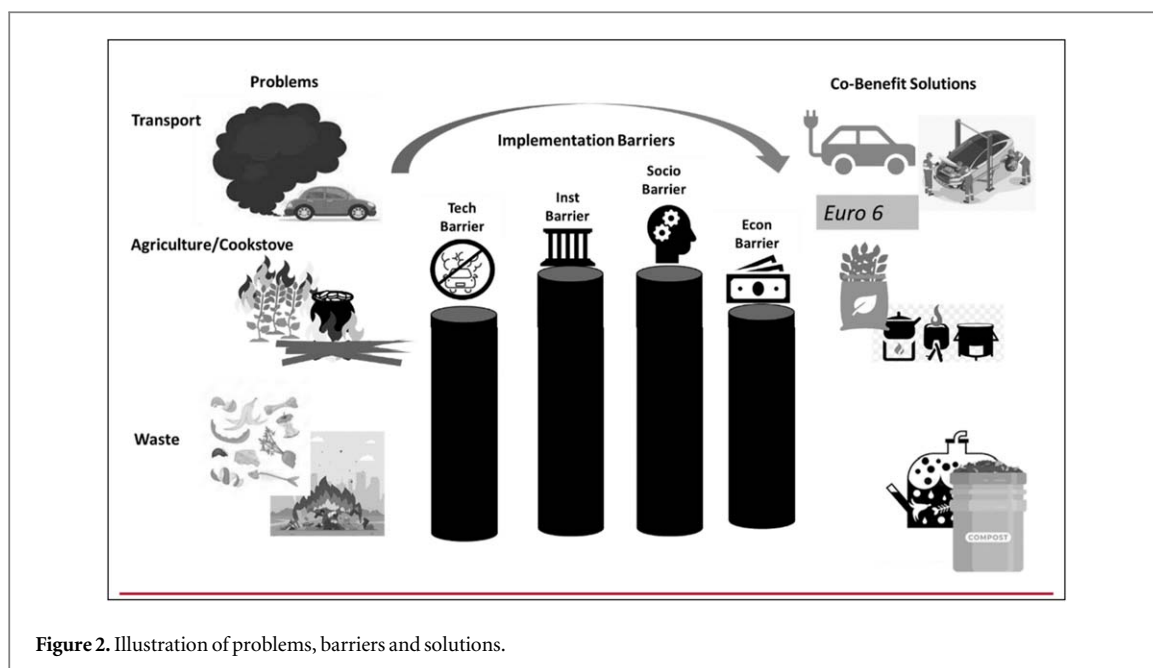


Figure 2. Illustration of problems, barriers and solutions.

Table 2. Defining barriers.

Technological	Access to cleaner technology/fuels and technologies/infrastructure enabling implementation.
Economic	Costs of cleaner technology fuels as well as policies (i.e. subsidies) that lower prices of resource-intensive options.
Institutional	Lack of interagency coordination/capacity as well as design flaws in policies promoting cleaner options.
Social	Limited acceptance/awareness of benefits from the clean alternatives as well as a shortage of awareness raising mechanisms/stakeholder engagement mechanisms.

example, there are ongoing efforts to acquire carbon finance from voluntary carbon markets for high-efficiency wood burning Kuniokoa cookstoves in rural communities in Thailand. Those efforts, which will be revisited later in the paper, demonstrate the national and international relevance of this intervention (CQuest Capital 2021).

The second reason for selecting these options is they can deliver significant co-benefits (CCAC 2023). For instance, inspection and maintenance programme could lead to sizable reductions in GHGs and air pollutants from the transport sector, including SLCPs. This potential is significant because such programmes target high-emitting (malfunctioning, tampering) vehicles accounting for more than half of the sector's entire emissions (Hausker 2004, Li 2017). In addition, clean stoves and fuels not only help limiting emissions but can have positive effects on the health of women and children (Rosenthal *et al* 2018). Controls on open burning, meanwhile, can curb pollution and promise more sustainable agricultural yields (Oanh *et al* 2018).

The third reason for selecting these options is that achieving their co-benefits is difficult. Several studies have noted that inspection and maintenance of vehicles is challenging, especially in developing countries (Dasgupta *et al* 2001, Hausker 2004, Li and Crawford-Brown 2011, Clean Air Asia 2016, Dandapat *et al* 2020). Similarly, barriers such as low levels of social acceptance, a lack of information, or misplaced government support often stand in the way of clean cookstoves and fuels (Limmechokchai and Chawana 2007, Chalise *et al* 2018, Thoday *et al* 2018). Efforts to curb open burning of biomass have also easier to demonstrate on paper than achieve in practice (Kanokkanjana and Bridhikitti 2007, Chalise *et al* 2018, Bhuvaneshwari *et al* 2019, Sharma and Jain 2019). In sum, many of the options confront barriers that are not typically quantified in co-benefits modelling (see also figure 2 for an illustration of problems, barriers and solutions).

4. Methods

4.1. Estimating the size of barriers

One of the keys to estimating how much technological, economic, social, and institutional feasibility affect implementation is quantifying their effects on diffusion. This section describes the estimated size of the barriers belonging to the categories in table 2.

To arrive at these estimates, the study went through five steps illustrated in greater detail in figure 3.

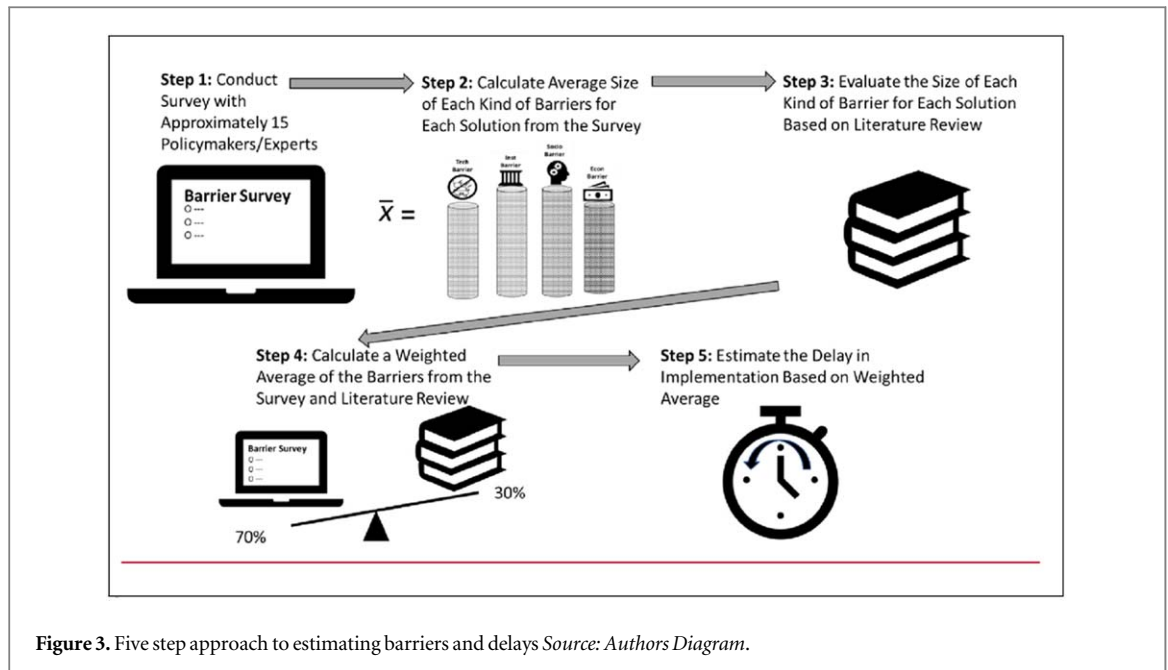


Figure 3. Five step approach to estimating barriers and delays Source: Authors Diagram.

Box 1. Magnitude of Barriers

The following approach was used to assess the size of barriers for each solution:

- 0% when a response was 'no effect'
- 5% (halfway between 1% to 10%) for 'small'
- 15% (halfway between 11% to 20%) for 'moderate'

First, a barriers survey was distributed to approximately 30 researchers, policymakers and development specialists in mostly Thailand as well as a few additional countries in Southeast Asia. There were three types of surveys: one for transport, one for open burning, and one for residential energy/cookstoves. The respondents were selected based on their deep knowledge of the solution (controls on burning of biomass) or because they worked for a government agency responsible for implementing that solution (regulating mobile source emissions). Most of the respondents were researchers but policymakers accounted for between 10 to 30 percent of the respondents in all three survey areas. The selection of respondents was determined based on consultations with recognized institutions with an extensive network and context-appropriate knowledge of the issue area in Thailand. Survey respondents were told that their titles and positions but not their names would be shared (see appendix for a listing of the backgrounds for each of the survey respondents). The survey asked respondents to assess the size of the influence on the barrier in table 2 on the diffusion of the solutions in table 1; the assumptions in Box 1 were used to code the size of effects.

Second, once the approximately 30 responses were received for each type of solution, an average size was calculated for each type of barriers for each solution. For example, an average barrier size was calculated for the technical, economic, social, and institutional barriers for 'promoting evehicles' based on the survey responses from the transport survey. See equation (1) for the relevant notation.

$$\bar{x}_{k,j} = \frac{\sum_{i=1}^n \bar{s}_{k,j,i}}{n} \quad (1)$$

Where

i : each expert survey response

j : type of barrier (i.e. technological, economic, social and institutional barriers)

k : mitigation option shown in table 1

n : the total number of responses to expert survey

$\bar{x}_{k,j}$: average magnitude of barrier type j for mitigation option k based on the expert survey, which $\bar{x}_{k,j} \leq 25\%$

$\bar{s}_{k,j,i}$: the size of effects of barrier type j for mitigation option k from each expert survey response i , which $\bar{s}_{k,j,i} \leq 25\%$

Third, the study then complemented the evaluation of the barriers from the surveys with an assessment of relevant literature. The literature review drew from studies concentrating on key sectors and solutions. To the

Table 3. Barrier assessment criteria.

Indicator	Description
No effect	The literature does not mention the barrier.
Small	The literature refers to barriers indirectly and/or briefly though not as a major issue. Moreover, when mentioned, their impact on a solution's diffusion is limited. For example, in the case of a 'institutional' barrier, the literature refers to the need to strengthen implementation capacities, but does not go into depth beyond making this point.
Moderate	The literature refers to the barrier directly, but the impact seems modest. For example, in the case of a 'social' barrier, the literature mentions why a stakeholder engagement mechanism is needed to strengthen support for a solution.
Significant	The literature refers directly and frequently to the barrier, while its impact seems significant. For example, in the case of 'technological' barriers, the literature concentrates on the critical role of enabling technologies to support transitions to cleaner options.

greatest extent possible, the literature was taken from work in Thailand and Southeast Asia (see [appendix](#) for list of studies); however, this was not always possible since the research on these solutions in Thailand and Southeast Asia was limited. To translate the literature review into quantitative data, the authors determined if each kind of barrier was 'small,' 'moderate,' or 'significant' for each article based on the criteria presented in table 3. The results of that determination were first entered into table in the [appendix](#) to help offer a visual map of the feasibility landscape. The authors then reviewed that landscape to arrive a single 'no barrier,' 'small,' 'moderate,' or 'significant' score for each type of barrier for each solution (equation (2)). Note that the final score for literature review assessment was based on the authors' determination of the overall size of barrier as opposed to a numerical average for the reviewed studies. The decision to use a single overarching score as opposed to an average reflected the difficulties of arriving at a justifiable scheme for weighting studies from different countries, years and disciplines.

$$x_{k,j} = S_{k,j} \quad (2)$$

where

$x_{k,j}$: the size of barrier type j for mitigation option k based on the literature review, which $x_{k,j} \leq 25\%$
 $s_{k,j}$: the size of barrier type j for mitigation option k based on the literature review i , which $s_{k,j,i} \leq 25\%$

Fourth, the study then synthesized the data from the expert survey and literature review barrier scores to come up with a final barrier score for each kind of barrier and solution. To construct that overall score, a weighted average that placed greater weight on the survey than the literature was used: the expert survey was accorded the weight of 0.7; the literature review assessment was accorded a weight of 0.3 (see equation (3)). The decision to give more weight to the survey reflected the belief expert survey offered a more accurate and recent assessment of the influence of the barrier in question. This determination was based on the fact that the questions in the survey were directly related to the issues and challenges in this study. In contrast, most of the literature was not focused on barriers but covered a broader range of sector specific technical issues. In addition, while every effort was made to use recent literature, the surveyed studies were a little more than six years old on average. However, to safeguard against criticism that the 0.3 to .0.7 ratio may skew results to the survey, a sensitivity analysis was also conducted. That sensitivity analysis assigned weight ratios of 0.6 to 0.4 and 0.8 to 0.2 to the surveys and literature reviews. The results of that sensitivity analysis are illustrated in the error bars in figure 3; the difference in weighting schemes did not significantly alter the results of the barrier analysis.

$$b_{k,j} = 0.7 \times \bar{x}_{k,j} + 0.3 \times x_{k,j} \quad (3)$$

$$B_k = \sum_j b_{k,j} \quad (4)$$

where

$b_{k,j}$: the magnitude of barrier type j for mitigation option k combined with the expert survey and the literature review, which $b_{k,j} \leq 25\%$

B_k : the total magnitude of barriers for mitigation option k combined with the expert survey and the literature review, which $B_k \leq 100\%$

Fifth, the study focused on how much the different types of barriers slowed diffusion of a particular solution. To make that determination, converting the composite assessment of the magnitude of the barriers into changes in how quickly a technology diffused is important. The approach to 'slowing diffusion' is described below.

4.2. Translating barriers into delays

The approach used herein involves interpreting magnitude of barriers as a delay over a 15- year period—that is, a 'delay' before an option was adopted or 'started to diffuse.' The assumption of a 15-year period is set as a default

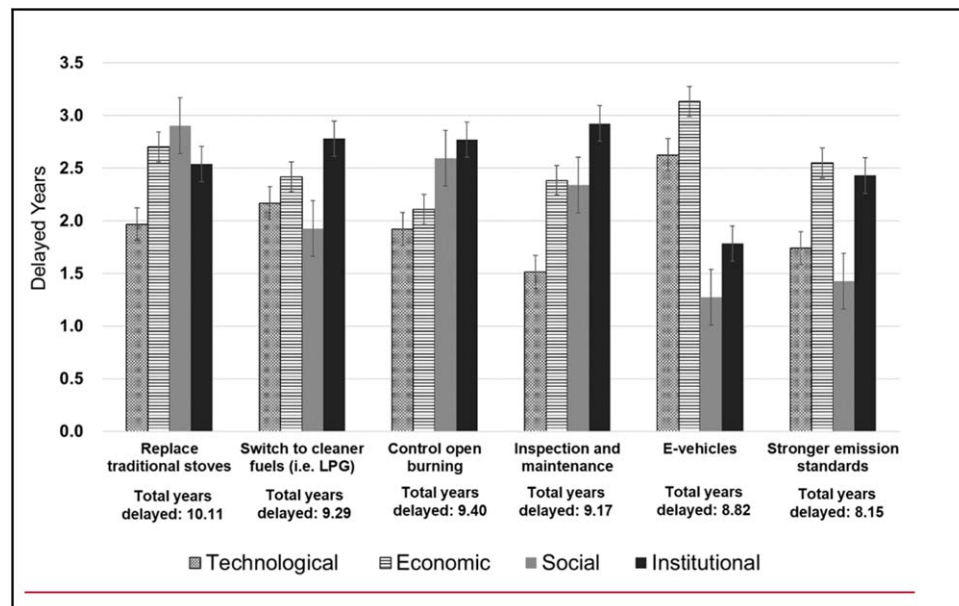


Figure 4. Estimated delays.

value. The selection of this interval is based on studies that show transitions to sustainable technologies can be between ‘1 and 16 years’ (Lund 2006, Sovacool 2016)—though some views that transitions can be lengthier contested processes (Grubler 2012). It nevertheless merits highlighting that the possible period for solutions may vary greatly across different technological and social changes and across different stages of innovation processes (Bento and Wilson 2016). Further, a possible drawback of making these assumptions is that Thailand have demonstrated at least modest levels of uptake and effectiveness for the different technologies or solutions that could influence whether the length of the assumed delay.

Despite these limitations, the delay in the adoption approach has the advantage of being relatively easy to interpret and incorporate into modelling scenarios. It is also likely that using an expert survey will help to account for starting points and the level of barriers at any given point in time. To illustrate both of these advantages, if the estimated reduction in diffusion rate was 22% over the assumed 15-year period, this would translate into a delay of slightly more than approximately 3 years (i.e., $0.22 \times 365 \text{ days} \times 15 \text{ years} = 1204 \text{ days} = 3 \text{ year}, 3 \text{ months and } 19.5 \text{ days}$), as shown in equation (5). Taking this calculation further, if both the institutional and social barriers were slowing the diffusion, this would involve a sum of the percentages associated for each type of barrier and then multiplying that sum by the overall time period as shown in equation (6). The results of this approach are presented in figure 4 below.

$$t_{k,j} = T \times b_{k,j} \quad (5)$$

$$t_k = \sum_j T \times b_{k,j} \quad (6)$$

Where

$b_{k,j}$: the magnitude of barrier type j for mitigation option k as a delay rate (reduced rate) in the speed of diffusion, which $b_{k,j} \leq 25\%$

T : the maximum delayed period (i.e. 15 years)

$t_{k,j}$: the time delayed for diffusion of mitigation option k due to of barrier type j

t_k : the total time delayed for mitigation option k due to barriers, which $t_k \leq 15 \text{ years}$

The results presented in figure 4 are illuminating for several reasons. First, the results suggest the combined impacts of the barriers are significant. In many cases, those impacts are estimated to be delays of eight or more years in total. This would be enough to undermine the prospects of achieving the full benefits of the proposed solutions. Second, the magnitude of the types of barriers vary across solutions. The technical and economic barriers are greater for the electric vehicles and emissions standards; however, the institutional and social barriers are greater than the technological and economic barriers for the other four solutions. The relatively greater magnitude of these barriers is important because these are the types of hurdles that are not explicitly factored into co-benefits modelling. Third, the lack of explicit consideration of institutional and social barriers may also lead to a discounting of the kinds of reforms needed to support the adoption and spread of a solution.

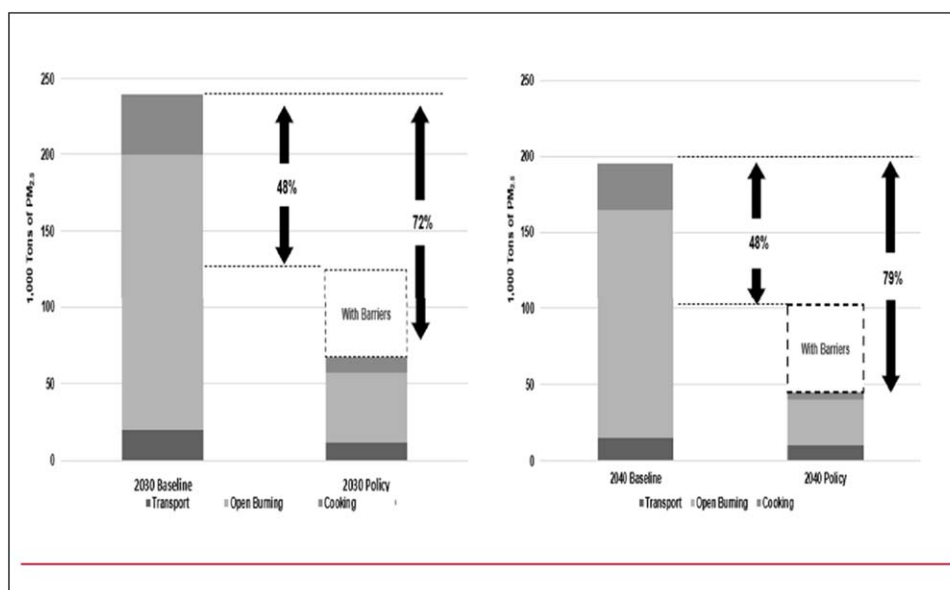


Figure 5. Indicative illustration of impacts from $PM_{2.5}$ of barriers to implementing transport, cooking and open burning solution in 2030 and 2040.

4.3. Applying the feasibility assessment to policies

One reason the results from this approach can prove illuminating is it is relatively easy to see their effects on policies. Figure 5 demonstrates those effects for policies in Thailand's $PM_{2.5}$ Action Plan for fine particulate emissions (the key interventions are listed in table 3).

Figure 4 depicts the emission levels for three scenarios. The first baseline scenarios demonstrate $PM_{2.5}$ emissions without any policies. The second policy scenario demonstrates emissions of $PM_{2.5}$ with perfect implementation of policies. The dotted box on top of the policy scenario labeled 'with barriers' suggests the size of the effects of the barriers on the actual reductions—that is, those amounts would be actually emitted but not be reduced due to delayed implementation considering barriers shown in figure 4.

As suggested in figure 4, the effects of the barriers are significant; the levels of emissions for all of the sectors in the with-barriers scenario is about 24% (in 2030) to 31% (in 2040) greater than would be achieved in the no-barriers effective implementation scenario. Further, the effects are most notable for open burning from agricultural residue and, to a lesser extent, clean cooking. The results underline assuming effective implementation might lead to unrealistic assumptions of what can be achieved. It also implies a need to think carefully about the enabling environment to bring estimated results in line with actual implementation conditions.

4.4. Overcoming implementation barriers at the policy level in Thailand

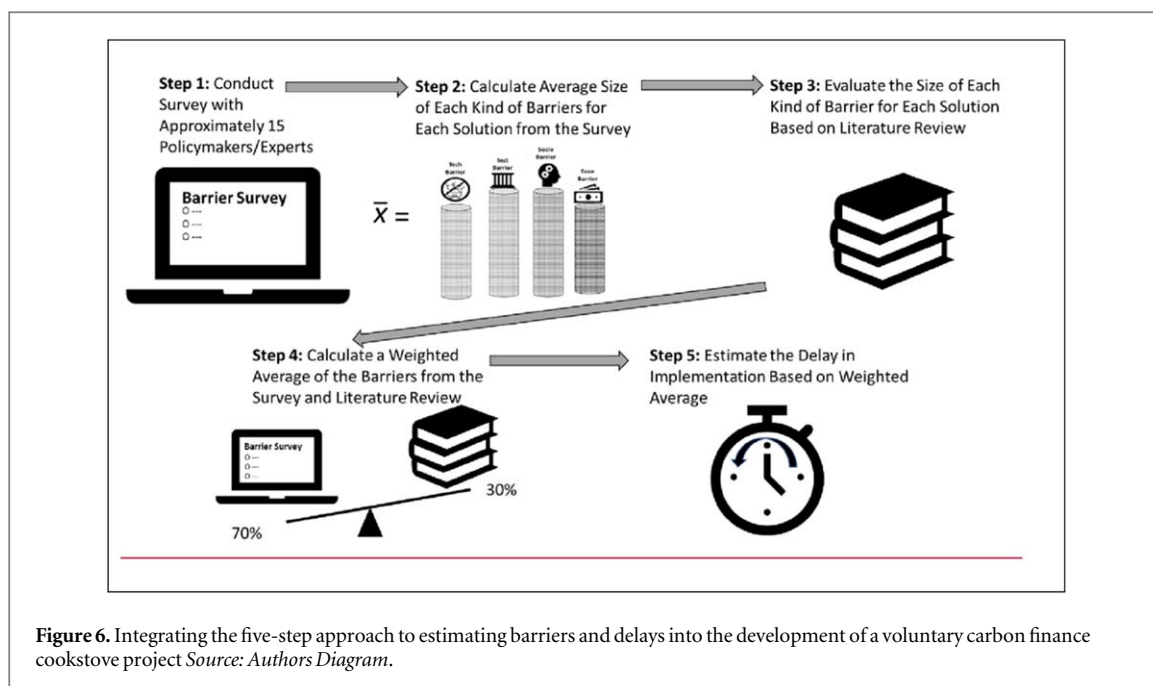
There may also be potential enabling reforms that could help overcome key barriers. The section provides an overview of proposed reforms in Thailand divided into the transport, residential energy, and agricultural sectors. More detailed descriptions of enablers are presented in table 4.

For the transport sector, there is a clear need to strengthen the integration between the proposed reforms and transport, climate, air quality and health planning. This is occurring to some extent as the work on e-vehicles features in Thailand's Nationally Determined Contribution and other climate plans, and efforts to strengthen inspection and maintenance and vehicle standards are part of the $PM_{2.5}$ Action Plan. Strengthening institutional coordination could break siloes, boost capacities and reduce redundancies in implementing solutions. In addition, enhancing institutional coordination would also shed light on the effects of e-vehicles on air quality, while illustrating how tighter standards and inspection and maintenance on air pollution, health, and climate change. Beyond these institutional reforms, policy signals that make clear the long-term goal of transitioning to e-vehicles, commitments to financial incentives for the purchase of these vehicles, and efforts to expand charging station networks would reduce private sector and consumer uncertainties. In addition, strengthening oversight and funding for inspection and maintenance and platforms for dialogues with vehicles manufacturers and refineries on vehicles standards would be helpful. The latter set of reforms are important since proposed attempts to tighten standards can be delayed due to challenges of switching to lower sulfur fuels.

Table 4. Specific solutions and enabling reforms.

Sectors	Solutions	Relevant policies	Enabling reforms
Transport	Implementing Euro 5 and 6 emission standards in 2025 and 2027, respectively and fuel quality with sulphur not more than 10 ppm	<i>Thailand PM2.5 National Action Plan</i> Euro 5 Emission Standards for new vehicles	<ul style="list-style-type: none"> •Mechanism to coordinate with climate, air pollution, transport, energy, and industrial agencies on fuel quality improvements and tighter emission standards
		Euro 6 Emission Standards for new vehicles	<ul style="list-style-type: none"> •Awareness raising on the benefits of better fuel quality and tighter emission standards
		Fuel Quality with sulphur not more than 10 ppm <i>Thailand PM_{2.5}</i>	<ul style="list-style-type: none"> •Programme to assess policy effectiveness •Financial support for refineries to switch to produce low sulphur fuels (reallocation of fossil fuel subsidies) and for automotive industry to switch to produce tighter emission standard vehicles.
Residential Energy	Promotion of EVs	<i>National Action Plan</i>	<ul style="list-style-type: none"> •Mechanism to coordinate with climate, air pollution, transport, energy, and industrial agencies
		Targets as follows:	<ul style="list-style-type: none"> •Financial support for purchasing e- vehicles
		<ul style="list-style-type: none"> •motorcycles 650,000 •light passenger car 440,000 •buses 33,000 •trucks 34,000 •1,450 charging stations with 12,000 charging ports. 	<ul style="list-style-type: none"> •Financial support for charging stations •Awareness raising on the benefits of e- vehicles
Residential Energy	Inspection and maintenance	Gradual phase out of older vehicles	<ul style="list-style-type: none"> •Financial support for vehicles users to finance retrofits
		More efficient or cleaner stoves	<ul style="list-style-type: none"> •Based on recent efforts from the Ministry of Energy to promote clean cookstoves, marking a return to approach used from 2008 through 2011 •Financial support for more efficient stove producers
Agricultural and forest fire control	Zero agricultural residue burning	<i>Thailand PM2.5 National Action Plan</i> 90% reduction in agricultural residue burning	<ul style="list-style-type: none"> •Financial support for shifting to liquid petroleum gas and biogas •Dissemination of cleaner stoves •Awareness raising on the benefits of cleaner stoves
			<ul style="list-style-type: none"> •Increased enforcement capacity for regulatory agencies •Strategic use of monitoring technologies (including satellites and low-cost sensors) •Incentives to purchase baling machines, mulching equipment and other management technologies •Creation of sustainable value chains to manage and convert residue into products •Awareness raising on the benefits of non-burning agricultural practices and improved air quality

For residential energy, there is also a need to enhance integration across relevant sectoral remits and administrative portfolios. More explicit inclusion of residential energy in Nationally Determined Contributions and climate policy discussions and mechanisms facilitating planning across key divisions would help in this regard. It also may be useful to raise the profile of those issues and consider a 10-year program that works with



universities and civil society partners to identify and promote alternatives that work in different contexts in Thailand. This could help build a reliable market for cleaner stoves, cleaner fuels and alternative technologies such as biodigesters and off-grid renewable applications. It would further help boost awareness levels and trigger demonstration effects that can help shift markets and mindsets on these issues. In all cases, there could also be a greater emphasis on follow-up and review and monitoring of impacts.

For the open burning of agricultural residue, there has been some recent progress due to growing political commitments and related push from top leadership. However, open burning and forest fires remain persistent problems in Thailand due, in part, to the challenges of enforcing outright bans on the practice (Kim Oanh 2013a). In this case, it might also be helpful to build stronger horizontal links across the environmental, agricultural and health agencies as well as vertical links between national and subnational governments. These links could help bring more funding to resource-constrained governments and increase investments in awareness of the impacts of alternatives such as mushroom or production of rice straw derived pellets (though depends on the mixture and composition of biomass (Kim Oanh 2013b); on-site microbial degradation or a mechanical rice straw (RS); or baling machine to collect ground biomass for off-site uses (Kanokkanjana and Bridhikitti 2007). Greater reflection on how to create markets for sustainable biomass use with circular economy models in, for example, furniture manufacturing might also gain traction.

4.5. Applying the feasibility assessment to carbon finance projects

One of the strengths of the approach presented in this article is that can apply to interventions at different scales. For example, a slightly modified version of the steps in section 4.1 could assess the feasibility of implementing the aforementioned climate finance cookstove project in section 2. More concretely, one could conduct a survey of users and local experts to estimate the effects of different barriers. This could then be combined with a review of field studies and other literature on the same barriers. The estimated size of the barriers could further be converted into delays over the anticipated project lifetime. Those delays could be incorporated into an assessment of emissions reductions and their associated co-benefits under 'perfect implementation' and 'with barriers' scenarios. In an additional sixth step, project developers can work with local decision makers and affected communities to determine how barriers can be overcome.

Figure 6 illustrates how the proposed now six-step approach could be integrated into the process for the aforementioned cookstove voluntary carbon project in section 2. Note that a few modifications, underlined on the revised figure, are suggested in downscaling. These include an even greater weight on the barrier survey as relevant field studies and literature are likely to be more limited in number and scope. As also suggested in figure 6, most of the adapted project level approach is likely fit in part 4 on sensitization of a typical voluntary carbon finance project development process; an additional step might be checking the estimated delays against actual part 7 on implementation.

Applying the feasibility assessment on smaller scale could be useful for a few reasons. Most notably, examining barriers for a community level project is likely to offer a context-rich understanding of how much

issues such as social acceptance influence implementation. This is particularly important because social acceptance is likely to vary not only across a country but communities. Applying the approach at the project level might also facilitate closer communication with affected stakeholders and project developers. This could, in turn, boost ownership of enabling reforms such as awareness raising programmes. Finally, efforts to downscale could also complement tools that have been used for analyzing factors influencing acceptance of new practices in areas such as agriculture (Kuehne *et al* 2017).

While there are advantages of downscaling from national policies to local projects, obtaining survey responses and locating relevant literature may take time and resources. For instance, administering a survey to those with sufficient expertise to comment on multiple dimensions of feasibility for a specific project may require a strong local network and investing in awareness raising activities. Yet, it may be possible to reduce that time and resources by mainstreaming the approach into existing sensitization materials. It may also be possible to integrate these efforts to longstanding efforts to bring more systematic assessments of sustainable development benefits and the feasibility of achieving them into carbon finance mechanisms. Discussions are ongoing of using a more systematic assessment of SDG benefits to evaluate activities funded under Article 6.4 of the Paris Agreement (UNFCCC 2023).

5. Conclusion

This study has argued multiple dimensions of feasibility deserve more attention in research on co-benefits. It then developed a novel approach for incorporating different dimensions of feasibility into co-benefit modelling. Making these links is useful because integrated assessment models often assume different packages of policies correspond with different emission pathways. The framework presented herein suggests that movement along emissions pathways depends on the package of policies and reforms enabling their implementation. Reflecting on enabling reforms should therefore receive more attention in the modelling of how policies affect emissions. This added attention is particularly important for actions that require enabling support to drive behavioural and social changes.

While this study's main results therefore can help refine co-benefits modeling, they also raise questions about the broader application of its findings. This section outlines similar methods to those in this study could be extended to other contexts.

One extension would be conducting a barriers analysis in other countries. Building a barriers database that contributes to a more general feasibility framework could help generate average lengths of implementation delays. It would then be possible to extrapolate results to countries with similar conditions and validate the results with stakeholder consultations. This could also be complemented by updated literature reviews and weighting schemes. Making sure assumptions and methods used to make these assessments and weighting are transparent will be critical.

Another extension involves making the link between the feasibility assessment and work on technological diffusion. Studies of different diffusion functions for innovation have made significant headway in modelling factors that impact the spread of solutions. For instance, the Bass diffusion model (Bass 1969, Norton and Bass 1987, Brown 2011, Radomes and Arango 2015) is a model that presents how two factors—innovation and imitation—influence technological diffusion. This work could be more explicitly linked to modelling scenarios. There are indeed already extensions of the Bass model that bring integrate technology prices from government policies that suggest potential synergies with the approach demonstrated in the paper (Bitencourt *et al* 2021).

A related extension involves connecting the feasibility assessment to the costs of enabling reforms. In this case, there is sizable literature on transaction costs that can offer insights into the costs of creating and running public programs under different institutional conditions (Falconer 2000, Falconer and Saunders 2002, Vatn *et al* 2001, Rorstad *et al* 2007, Kuperan *et al* 2008, Mettepenningen *et al* 2009). This kind of cost information could be fed into modelling frameworks to understand the resources needed to lower non-economic and non-technological barriers. It could also offer an interesting complement to some of the work that has focused on how enabling policies such as subsidies or carbon taxes alter selections of different technologies.

Another extension involves systemic changes that can overcome barriers. In this case, though barriers appear significant for some of the solutions, changing within and across socioeconomic systems may help break them down. For example, the transition to cleaner stoves and fuels may move forward as with more market access for cleaner options and lower energy prices. The proposed transition may nonetheless be difficult due to resistance from existing resource-intensive systems. One way to drive systemic change is to identify leverage points with the greatest potential at different scales. In fact, one of the core insights of work transitions is that complementing larger landscape changes with small scale niches can lead the way to systemic changes. Future studies could use surveys to identify where it is feasible to complement small-scale cooking projects with institutional reforms that support air quality plans to drive transformative change.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Appendix. List of survey respondents and surveyed literature cookstoves

Country	Profession	Affiliation
Thailand	Researcher/academic	Asian Institute of Technology
Thailand	NGO	Center for Creativity and Sustainability
Thailand	Researcher/academic	Lampang Rajabhat University
Thailand	Researcher/academic	Ubon Ratchathani University
Thailand	Researcher/academic	Center for Clean Air Solutions
Thailand	Lecturer	Pibulsongkram Rajabhat University
Thailand	Researcher/academic	Srinakharinwirot University
Thailand	Researcher/academic	Science & Industrial Tech. PSU Surat
Thailand	Government official/ policymaker	Department of Alternative Energy Development and Efficiency
Thailand	Government official/ policymaker	Department of Alternative Energy Development and Efficiency
Thailand	Researcher/academic	King Mongkut's University of Technology North Bangkok
Thailand	Researcher/academic	Royal Forest Department, BKK
Thailand	Government official/ policymaker	Department of Alternative Energy
Thailand	Private sector/business	Ratchaburi province
Thailand	Government official/ policymaker	National Research Council of Thailand
Thailand	Private sector/business	Representative of the community enterprise group, manufacturer and distributor of high efficiency charcoal cooking stoves
Thailand	Government official/ policymaker	Provincial energy office of Chiang Mai.
Thailand	teacher and entrepreneur	Chiang Mai Rajabhat University/Lanna Technology
Thailand	Government official/ policymaker	Royal Forest Department
Thailand	Researcher/academic	Expert center of innovative clean energy and environment TISTR
Vietnam	NGO	Vietnam Clean Air Partnership (VCAP)
Cambodia	Government official/ policymaker	Phnom Penh, Cambodia
Philippines	NGO	Clean Air Asia
Germany	Private sector/business	GIZ
Vietnam	Project developer	SNV Vietnam
Vietnam	Government official/ policymaker	Hanoi Environmental Protection Agency
Singapore	Government official/ policymaker	National Environment Agency Singapore

5.1. Open burning

Country	Profession	Affiliation
Cambodia	Researcher/academic	Royal University of Phnom Penh
Indonesia	Researcher/academic	Itenas Bandung Indonesia
Malaysia	Researcher/academic	Universiti Kebangsaan Malaysia
Myanmar	Private sector/business	Environmental Quality Management Co., Ltd, Yangon, Myanmar
NA	Retired Government Official	Before my retirement I worked at the Environmental Research and Training Center, Department of Environmental Quality Promotion
Philippine	Researcher/academic	Manila Observatory and Ateneo de Manila University (Department of Physics)
Philippine	Researcher/academic	Manila Observatory
Philippine	NGO	Clean Air Asia
Philippine	Researcher/academic	Clean Air Asia
Singapore	Researcher/academic	University
Thailand	Government official/ policymaker	Air Quality and Noise Management Bureau, Pollution Control Department, Bangkok, Thailand

(Continued.)

Country	Profession	Affiliation
Thailand	Researcher/academic	King Mongkut's Institute of TechnologyLadkrabang
Thailand	Researcher/academic	National Astronomical Research Instituteof Thailand (NARIT)
Thailand	Researcher/academic	Thammasat University
Thailand	Researcher/academic	Thammasat University
Thailand	Researcher/academic	Asian Institute of Technology
Thailand	Government official/ policymaker	Pollution Control Department, Ministry ofNatural Resources and Environment
Thailand	Researcher/academic	Valaya Alongkorn Rajabhat Universityunder the Royal Patronage
Thailand	Researcher/academic	King Mongkut's University of TechnologyThonburi (KMUTT)
Thailand	Researcher/academic	Chiang Mai University
Thailand	Researcher/academic	Department of Agronomy, Faculty ofAgriculture, Kasetsart University
Thailand	Researcher/academic	Chiang Mai University
Thailand	Researcher/academic	Asian Institute of Technology, Thailand
Thailand	Researcher/academic	Faculty of Public Health, ThammasatUniversity, Thailand
Thailand	Researcher/academic	Asian Institute of Technology
Vietnam	Researcher/academic	Institute for Agricultural Environment, HaNoi, Viet Nam
Vietnam	Researcher/academic	Hanoi University of Science andTechnology, Hanoi, Vietnam
Vietnam	Researcher/academic	Hanoi, Vietnam
Vietnam	Researcher/academic	Vietnam Clean Air Partnership (VCAP)
Vietnam	Researcher/academic	Faculty of Environment, University of Science, VNUHCM, VietnamNational University Ho Chi Minh City

5.2. Transport

Country	Profession	Affiliation
Myanmar	Researcher/academic	Private sector
Thailand	Researcher/academic	King Mongkut's Institute of Technology Ladkrabang
Thailand	Researcher/academic	Siam University, Bangkok
Thailand	Researcher/academic	KMUTT
NA	Researcher/academic	University
NA	Government official/policymaker	Environmentalist
Thailand	Researcher/academic	King Mongkut's University of Technology Thonburi (KMUTT)
Thailand	Researcher/academic	Ayutthaya, Thailand
NA	Government official/policymaker	Department of Land Transport
Thailand	Researcher/academic	Transportation Institute, Chulalongkorn University
Thailand	Researcher/academic	King Mongkut's University of Technology Thonburi
NA	Private sector/business	Grutter Consulting
Thailand	Researcher/academic	Asian Institute of Technology
Thailand	Researcher/academic	Chulalongkorn University
Vietnam	Researcher/academic	Hanoi University of Science and Technology, Hanoi, Vietnam
Indonesia	Researcher/academic	Itenas Bandung
Thailand	Researcher/academic	The Joint Graduate School of Energy and Environment
NA	Researcher/academic	KU
Thailand	Researcher/academic	ENTEC NSTDA
Thailand	Researcher/academic	Thammasat University
Thailand	Researcher/academic	Lecturer
Thailand	Government official/policymaker	TISI
Thailand	Private sector/business	Thailand Ayutthaya, HATC-MA
Thailand	Researcher/academic	Center for Clean Air Solutions
Thailand	Government official/policymaker	Pollution Control Department (Thailand)
Thailand	Environmental Consultant	United Nations Industrial Development Organization
Thailand	Researcher/academic	PTT Public Company Limited
Thailand	Researcher/academic	Asian Institute of Technology, Thailand
Thailand	Researcher/academic	Faculty of Public Health, Thammasat University
Thailand	Development organization	UNEP
Thailand	Researcher/academic	Asian Institute of Technology
Thailand	Engineer	Honda Automobile(Thailand)
Thailand	Government official/policymaker	Thailand
Germany	International cooperation company	GIZ

(Continued.)

Country	Profession	Affiliation
NA	Government official/policymaker	Department of Land Transport
Australia	Researcher/academic	Australian Embassy Bangkok
Thailand	Researcher/academic	Department of Environment, Air Quality and Noise Management Division
Thailand	Researcher/academic	Nakhon Ratchasima, Thailand

No barrier/insignificant information Source	+ Location/Years	Small Summary	++ Tech	Moderate Econ	+++ Social	Significant Inst
Li and Crawford-Brown 2011	Bangkok Metropolitan Area, 2000–2010	This study finds that the benefits clearly outweigh the costs of an I/M programme in Bangkok.		+		
Li 2017	Bangkok Metropolitan Area, 2010–2015	This study argues that the design and the implementation of I/M programme influences their effectiveness.				+++
Dandapat <i>et al</i> 2020	Kolkata and Howrah, India, 2015–2020	This study assesses the performance of I/M programme in Kolkata and Howrah, India.				+++
Kholod and Evans 2016	Russia, 2010–2015 (note that this applies to all diesel emissions)	This study assesses Russia's approach to controlling diesel emissions by looking at of I/M programmes, noting the lack of training and the inspecting center, perverse incentives in programme design, and limited government oversight.				+++
Baptista Ventura <i>et al</i> 2020	Brazil, 2015–2020	This study evaluates the impacts of a poorly implemented I/M programme as well as the need for improvements in public transport in Rio De Janeiro, Brazil.	++			+++
Tungsuwan <i>et al</i> 2021	Thailand, 2020–2030	The article focuses on the policies that Thailand has adopted to promote e-vehicles, raising questions about the policies and supportive technologies that needed by 2030 to create a market for e-vehicles.	++	++		++
Thananusak <i>et al</i> 2017	Thailand, 2020–2030	This study examines factors affecting acceptance of e-vehicles in Thailand, contending consumer perceptions of performance of the e-vehicle is critical.	+++		+++	
Vongurai 2020	Thailand, 2020–2030	This study evaluates factors affecting willingness to purchase e-vehicles in Thailand, suggesting a need for greater awareness of environmental benefits and technological advances (i.e. fuel efficiency).	++		++	
Bakker 2018	ASEAN, 2020–2030	This study employs the Avoid-Shift-Improve framework to organize policies in ASEAN countries, concluding that enforcement is often lacking.				+++
The National 2020	Thailand, 2020–2030	This study examines stringent emissions standards in Thailand and complaints from the electric vehicle industry.				+++
Subramanian <i>et al</i> 2009	Thailand, 2010–2020	This study employs a technical/atmospheric analysis of the Developing Integrated Emissions Strategies for Existing Land Transport (DIESEL) project, finding that emissions reductions in PM _{2.5} are significant only for heavy not light duty vehicles for tighter Euro standards on PM emission rates.	++			

(Continued.)

No barrier/insignificant information Source	+ Location/Years	Small Summary	++ Tech	Moderate Econ	+++ Social	Significant Inst
Cheewaphongphan <i>et al</i> 2020	Thailand, 2020–2050	This study assesses the mitigation potential for the transport sector in Thailand, underlining delays in the tightening of emission standards and that institutional and policy factors are responsible for the delays.				+++
Zhang <i>et al</i> 2018	Global, 2005–2100	The study uses integrated assessment/computable general equilibrium model to illuminate relationship between the transport sector and the macroeconomy, noting that technological transformations in the transport sector are possible but require stronger linkages with climate/development policies.	++	++		
Sharma and Jain 2019	India	This study concentrates on the costs of household cooking fuels and impediments slowing the choice of clean household energy in India's Indo-Gangetic India.	++	++	+++	+++
Vigolo <i>et al</i> 2018	Global	This article suggests that more than access/affordability are needed to promote improved cookstoves ICS.	++	+++	+++	+++
Thoday <i>et al</i> 2018	Indonesia	This study concentrates the impressive transition in the Zero-Kero program in Indonesia.	++	+++	++	+++
Dendup and Arimura 2019	Bhutan	This study concentrates on how the provision of information facilitating the uptake of clean cooking fuel in Bhutan—with some variation depending on education levels etc	++	+++	++	+++
Chalise <i>et al</i> 2018	India	The study concentrates on the challenges to biogas and other clean cooking interventions in India, noting that the accumulation of technical knowledge helps to curb resistance to clean cooking interventions.	+++	++	+++	++
Kshirsagar and Kalamkar 2014	Global	This study reviews literature on barriers to improved cookstove programmes, underlining the key role of institutional infrastructure.				+++
Kanokkanjana and Garivait 2013	Thailand	This study calls for alternative straw management practices in Thailand in an estimation of carbon content loss from burning of rice straw.		+++	+++	
Pearson <i>et al</i> 2016	Global	This report focuses on opportunities and challenges to curbing open burning in the Himalayas with an emphasis on India, it also suggests that cultural factors and lack of awareness of soil properties make resolving the problem difficult.		+++	+++	
Bhuvaneshwari <i>et al</i> 2019	India	This study concentrates on difficulties with limiting burning in India, and underlines a lack of institutional mechanism to manage crop residue is a major hurdle.		+++	+++	+++

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References

- Ackerman F, DeCanio S J, Howarth R B and Sheeran K 2009 Limitations of integrated assessment models of climate change *Clim. Change* **95** 297–315
- Aunan K, Fang J, Vennemo H, Oye K and Seip H M 2004 Co-benefits of climate policy—lessons learned from a study in shanxi, China *Energy Policy* **32** 567–81
- Ayres R and Walter J 1991 The greenhouse effect: damages, costs and abatement *Environmental and Resource Economics* **1** 237–70
- Backlund S, Thollander P, Palm J and Ottosson M 2012 Extending the energy efficiency gap *Energy Policy* **51** 392–6
- Bakker S 2018 Shifting to low-carbon transport in ASEAN: Policy development in a rapidly motorising region University of Twente https://researchgate.net/profile/Stefan_Bakker/publication/324106229_Shifting_to_low-carbon_transport_in_ASEAN_Policy_development_in_a_rapidly_motorising_region/links/5acde19eaca2723a334098de/Shifting-to-low-carbon-transport-in-ASEAN-Policy-development
- Baptista Ventura L M, de Oliveira Pinto F, Gioda A and de Almeida D'Agosto M á 2020 Inspection and maintenance programs for in-service vehicles: an important air pollution control tool *Sustainable Cities and Society* **53** 101956
- Bass F M 1969 A new product growth for model consumer durables *Manage. Sci.* 215–27
- Bento N and Wilson C 2016 Measuring the duration of formative phases for energy technologies *Environmental Innovation and Societal Transitions* **21** 95–112
- Bertram C et al 2024 Feasibility of peak temperature targets in light of institutional constraints *Nat. Clim. Change* **14** 954–60
- Bhuvaneshwari S, Hettiarachchi H and Meegoda J N 2019 Crop residue burning in India: policy challenges and potential solutions *International Journal of Environmental Research and Public Health* **16** 832
- Bitencourt L, Abud T, Santos R and Borba B 2021 Bass diffusion model adaptation considering public policies to improve electric vehicle sales—a Brazilian case study *Energies* **14** 5435
- Bollen J, Guay B, Jamet S and Corfee-Morlot J 2009 Co-benefits of climate change mitigation policies. economic department working papers no. 693. Paris: organisation for economic cooperation and development OECD
- Bond T C et al 2013 Bounding the role of black carbon in the climate system: a scientific assessment *Journal of Geophysical Research: Atmospheres* **118** 5380–552
- Brown D, Seymour F and Peskett L 2008 How do we achieve REDD co-benefits and avoid doing harm? *Moving Ahead with REDD* 109–56 (CIFOR)
- Brown H C P 2011 Gender, climate change and REDD + in the Congo Basin forests of Central Africa *International Forestry* **13** 163–76
- Brutschin E, Pianta S, Tavoni M, Riahi K, Bosetti V, Marangoni G and Van Ruijven B J 2021 A multidimensional feasibility evaluation of low-carbon scenarios *Environ. Res. Lett.* **16** 064069
- Bussolo M and O'Connor D 2001 Clearing the Air in India: the economics of climate policy with ancillary benefits *OECD working paper No. 182* <https://www.cleanairworld.org/dataoecd/24/7/2697158.pdf>
- Cai Q, Zusman E and Meng G 2023 The shift to synergies in China's climate planning: aligning goals with policies and institutions *Climate* **11** 234
- CCAC 2023 Clean air and climate change solutions in Southeast Asia (UNEP. CCAC and UNEP) 2018 *Short-Lived Climate Pollutants Short-Lived Climate Pollutants in Latin America*
- Chalise N, Kumar P, Priyadarshini P and Yadama G N 2018 Dynamics of sustained use and abandonment of clean cooking systems: lessons from rural India *Environ. Res. Lett.* **13** 035010
- Challcharoenwattana A and Pharino C 2015 Co-benefits of household waste recycling for local community's sustainable waste management in Thailand *Sustainability* **7** 7417–37
- Cheewaphongphan P, Hanaoka T and Chatani S 2020 Long-term trend of regional passenger road transport demand and emission estimation under exhaust emission regulation scenario in Thailand *Environ. Res. Commun.* **2** 051009
- Clean Air Asia 2016 Vehicle inspection & maintenance in Asia: status and challenges 2016 Clean Air Asia
- CQuest Capital 2021 Local stakeholder consultation for installation of high efficiency wood burning cookstoves in Thailand, https://cdn.shopify.com/s/files/1/2153/6027/files/Local_Stakeholder_Consultation_Deck_Thailand.pdf?v=1615297857
- Dandapat S, Ghosh T, Shankar U, Maitra S and Maitra B 2020 A relook at the pollution certification of in-use vehicles in india and a way forward *Asian Transport Studies* **6** 100020
- Dasgupta S, Laplante B, Mamingi N and Wang H 2001 Inspections, pollution prices, and environmental performance: evidence from China *Ecol. Econ.* **36** 487–98
- Dendup N and Arimura T H 2019 Information leverage: the adoption of clean cooking fuel in bhutan *Energy Policy* **125** 181–95
- Dhar S, Pathak M and Shukla P R 2017 Electric vehicles and india's low carbon passenger transport: a long-term co-benefits assessment *J. Clean. Prod.* **146** 139–48
- Dhar S and Shukla P R 2015 Low carbon scenarios for transport in india: co-benefits analysis *Energy Policy* **81** 186–98
- Dubash N K, Raghunandan D, Sant G and Sreenivas A 2013 Indian climate change policy: exploring a co-benefits based approach *Economic and Political Weekly* **48** 47–61
- Elkins P 1996 How large a carbon tax is justified by the secondary benefits of CO₂ abatement? *Environmental and Resource Economics* **18** 161–87
- Falconer K 2000 Farm-level constraints on agri-environmental scheme participation: a transactional perspective *Journal of Rural Studies* **16** 379–94
- Falconer K and Saunders C 2002 Transaction costs for SSSIs and policy design *Land Use Policy* **19** 157–66
- Farzaneh H, Zusman E and Chae Y (ed) 2021 *Aligning Climate Change and Sustainable Development Policies in Asia* (Springer)
- Glomsrød S, Vennemo H, Johnsen T and Glomsrød S 1992 Stabilization of emissions of CO₂ : a computable general equilibrium assessment *The Scandinavian Journal of Economics* **94** 53
- Grubler A 2012 Energy transitions research: insights and cautionary tales *Energy Policy* **50** 8–16
- Haines A, Amann M, Borgford-Parnell N, Leonard S, Kuylenstierna J and Shindell D 2017 Short-lived climate pollutant mitigation and the sustainable development goals *Nat. Clim. Change* **7** 863–9
- Hannah C, Giroux S, Krell N, Lopus S E, McCann L E, Zimmer A, Caylor K K and Evans T P 2021 Has the vision of a gender quota rule been realized for community-based water management committees in Kenya? *World Development* **137** 105154
- Hausker K 2004 Vehicle inspection and maintenance programs: international experience and best practices US Office of Energy and Information Technology
- Hickmann T, Bertram C, Biermann F, Brutschin E, Kriegler E, Livingston J E, Pianta S, Riahi K, Van Ruijven B and Van Vuuren D 2022 Exploring global climate policy futures and their representation in integrated assessment models *Politics and Governance* **10** 171–85

- Hoffmann B et al 2021 WHO air quality guidelines 2021—aiming for healthier air for all: a joint statement by medical, public health, scientific societies and patient representative organisations *International Journal of Public Health* **66** 2019–22
- IPCC 2018 Summary for policymakers. Global warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the World Meteorological Organization
- IPCC 2022 *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK and New York, NY, USA* ed P R Shukla et al (Cambridge University Press) (<https://doi.org/10.1017/978100915792>)
- Jiang P, Xu B, Geng Y, Dong W, Chen Y and Xue B 2016 Assessing the environmental sustainability with a co-benefits approach: a study of industrial sector in baoshan district in Shanghai *J. Clean. Prod.* **114** 114–23
- Kanokkanjana K and Bridhikitti A 2007 Sustainable rice straw management for urban air pollution reduction in Bangbuathong, Nonthaburi province, Thailand Asian Institute of Technology
- Kanokkanjana K and Garivait S 2013 Alternative rice straw management practices to reduce field open burning in Thailand *International Journal of Environmental Science and Development* **4** 119–23
- Karlsson M, Alfredsson E and Westling N 2020 Climate policy co-benefits: a review *Climate Policy* **20** 292–316
- Karlsson M, Westling N and Lindgren O 2023 Climate-related co-benefits and the case of Swedish policy *Climate* **11** 40
- Kholod N and Evans M 2016 Reducing black carbon emissions from diesel vehicles in Russia: an assessment and policy recommendations *Environmental Science and Policy* **56** 1–8
- Kim Oanh N T 2013a Integrated approach to rice straw management for reduction of field-burning activity (Chapter 13) *Integrated Air Quality Management, Asian Case Studies* (CRC Press)
- Kim Oanh N T 2013b Integrated approach to rice straw management for reduction of field-burning activity *Integrated Air Quality Management, Asian Case Studies* (CRC Press)
- Kriegler E, Brian C O'N, Hallegatte S, Kram T, Lempert R J, Moss R H and Wilbanks T 2012 The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways *Global Environ. Change* **22** 807–22
- Krupnick A, Burtraw D and Markandya A 2000 The ancillary benefits and costs of climate change mitigation: a conceptual framework *Paper Presented at the IPCC Gas, Expert Workshop on Assessing the Ancillary Benefits and Costs of Greenhouse Mitigation Policies*
- Kshirsagar M P and Kalamkar V R 2014 A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design *Renew. Sustain. Energy Rev.* **30** 580–603
- Kuehne G, Llewellyn R, Pannell D J, Wilkinson R, Dolling P, Ouzman J and Ewing M 2017 Predicting farmer uptake of new agricultural practices: a tool for research, extension and policy *Agric. Syst.* **156** 115–25
- Kuperan K, Abdullah N M R, Pomeroy R S, Genio E L and Salamanca A M 2008 Measuring transaction costs of fisheries co-management *Coastal Management* **36** 225–40
- Kuylenstierna J C I et al 2020 Development of the low emissions analysis platform—integrated benefits calculator (LEAP-IBC) tool to assess air quality and climate co-benefits: application for bangladesh *Environ. Int.* **145** 106155
- Li M, Zhang D, Li C T, Mulvaney K M, Selin N E and Karplus V J 2018 Air quality co-benefits of carbon pricing in China *Nat. Clim. Change* **8** 398–403
- Li Y 2017 Evaluating and improving the effectiveness of vehicle inspection and maintenance programs: a cost-benefit analysis framework *Journal of Environmental Protection* **08** 1541–66
- Li Y and Crawford-Brown D J 2011 Assessing the Co-benefits of greenhouse gas reduction: health benefits of particulate matter related inspection and maintenance programs in Bangkok, Thailand *Sci. Total Environ.* **409** 1774–85
- Limmechokchai B and Chawana S 2007 Sustainable energy development strategies in the rural Thailand: the case of the improved cooking stove and the small biogas digester *Renew. Sustain. Energy Rev.* **11** 818–37
- Liu Z, Adams M, Cote R P, Geng Y, Ren J, Chen Q, Liu W and Zhu X 2018 Co-benefits accounting for the implementation of eco-industrial development strategies in the scale of industrial park based on emergy analysis *Renew. Sustain. Energy Rev.* **81** 1522–9
- Lund P 2006 Market penetration rates of new energy technologies *Energy Policy* **34** 3317–26
- Majone G 1975a On the notion of political feasibility *European Journal of Political Research* **3** 259–74
- Majone G 1975b The feasibility of social policies *Policy Sciences* **6** 49–69
- Malley C S et al 2022 Air pollution mitigation assessment to inform Cambodia's first clean air plan *SSRN Electronic Journal* **220** 115230
- Mathias J D et al 2020 Grounding social foundations for integrated assessment models of climate change *Earth's Future* **8** e2020EF001573
- Mayrhofer J and Gupta J 2015 The science and politics of co-benefits in climate policy *Environmental Science and Policy* **57** 22–30
- McMichael A J 1997 Integrated assessment of potential health impact of global environmental change: prospects and limitations *Environ. Model. Assess.* **2** 129–37
- Menikpura S N M, Sang-Arun J and Bengtsson M 2013 Integrated solid waste management: an approach for enhancing climate co-benefits through resource recovery *J. Clean. Prod.* **58** 34–42
- Mettepenningen E, Verspecht A and Van Huylbroeck G 2009 Measuring private transaction costs of European agri-environmental schemes *Journal of Environmental Planning and Management* **52** 649–67
- Morgenstern R, Krupnick A and Zhang X 2004 The ancillary carbon benefits of SO₂ reductions from a small-boiler policy in taiyuan, PRC *Journal of Environment and Development* **13** 140–55
- Nemet G F, Holloway T and Meier P 2010 Implications of incorporating air-quality co-benefits into climate change policymaking *Environ. Res. Lett.* **5** 014007
- Nielsen K S et al 2020 Improving climate change mitigation analysis: a framework for examining feasibility *One Earth* **3** 325–36
- Nielsen K S et al 2020 Perspective improving climate change mitigation analysis: a framework for examining feasibility *One Earth* **3** 325–36
- Norgaard R B and Baer P 2005 Collectively seeing climate change: the limits of formal models *BioScience* **55** 961–6
- Norton J A and Bass F M 1987 A diffusion theory model of adoption and substitution for successive generations of high-technology products *Management Science* **33** 1069–86
- Oanh N T K et al 2018 Assessment of co-benefits of using rice straw derived solid fuel for cooking to reduce emissions of agro-residue open burning in selected GMS countries *Development and Climate Change in the Mekong Region Case Studies* 143–68(SEI)
- Pathak M and Shukla P R 2016 Co-benefits of low carbon passenger transport actions in Indian Cities: case study of Ahmedabad *Transportation Research Part D: Transport and Environment* **44** 303–16
- Pearce D 2000 Policy frameworks for the ancillary benefits of climate change policies Centre for Social and Economic Research on the Global Environment
- Pearce D 2000 Policy frameworks for the ancillary benefits of climate policies CSERGE Working paper GEC 2000-11
- Pearce D W 1992 The secondary benefits of greenhouse gas control CSERGE Working paper 92-12(CSERGE, University College London)

- Pearson P, Bodin S, Gittelsohn A, Stephanie K, McCarty J, Stevenson G and Albertengo J 2016 Fire in the fields: moving beyond the damage of open agricultural burning on communities, soil, and the cryosphere CCAC https://breathelife2030.org/wp-content/uploads/2016/09/Fire-in-the-Fields-OB-ReportA4-Final_22nov2015.pdf
- Pollution Control Department 2019 PM2.5 control plan
- Radomes A A, and Arango S 2015 Renewable energy technology diffusion: an analysis of photovoltaic-system support schemes in medellin, Colombia *J. Clean. Prod.* **92** 152–61
- Ramanathan V, Chung C, Kim D, Bettge T, Buja L, Kiehl J T, Washington W M, Fu Q, Sikka D R and Wild M 2005 Atmospheric brown clouds: impacts on South Asian climate and hydrological cycle *PNAS* **102** 5326–33
- Roggero M, Gotgfelf A and Eisenack K 2023 Co-benefits as a rationale and co-benefits as a factor for urban climate action: linking air quality and emission reductions in Moscow, Paris, and Montreal *Clim. Change* **176** 179
- Rosenthal J, Quinn A, Grieshop A P, Pillarisetti A and Glass R I 2018 Clean cooking and the SDGs: integrated analytical approaches to guide energy interventions for health and environment goals *Energy for Sustainable Development* **42** 152–9
- Rørstad P K, Vatn A and Kvakkestad V 2007 Why do transaction costs of agricultural policies vary? *Agricultural Economics* **36** 1–11
- Schneider S H 1989 The greenhouse effect: science and policy *Science* **243** 771–81
- Schneider S H 1997 Integrated assessment modeling of global climate change: transparent rational tool for policy making or opaque screen hiding value-laden assumptions? *Environ. Model. Assess.* **2** 229–49
- Sharma D and Jain S 2019 Impact of intervention of biomass cookstove technologies and kitchen characteristics on indoor air quality and human exposure in rural settings of india *Environ. Int.* **123** 240–55
- Shi Q et al 2022 Co-benefits of CO₂ emission reduction from China's clean air actions between 2013–2020 *Nat. Commun.* **13** 1–8
- Shindell D, Borgford-Parnell N, Brauer M, Haines A, Kuylenstierna J C I, Leonard S A, Ramanathan V, Ravishankara A, Amann M and Srivastava L 2017 A climate policy pathway for near- and long-term benefits *Science* **356** 493–4
- Sorrell S, Mallett A and Nye S 2011 Barriers to industrial energy efficiency: a literature review *United Nations Industrial Development Organisation Working paper*:98
- Sovacool B K 2009 The importance of comprehensiveness in renewable electricity and energy-efficiency policy *Energy Policy* **37** 1529–41
- Sovacool B K 2016 How long will it take? conceptualizing the temporal dynamics of energy transitions *Energy Research and Social Science* **13** 202–15
- Staub-Kaminski B I, Zimmer A, Jakob M and Marschinski R 2014 Climate policy in practice: a typology of obstacles and implications for integrated assessment modeling *Climate Change Economics (CCE)* (World Scientific Publishing Co. Pte. Ltd)
- Steg L et al 2022 A method to identify barriers to and enablers of implementing climate change mitigation options *One Earth* **5** 1216–27
- Subramanian R, Winijkul E, Bond T C, Thiansathit W, Oanh N T K, Paw-Armart I and Duleep K G 2009 Climate-relevant properties of diesel particulate emissions: results from a piggyback study in Bangkok, Thailand *Environ. Sci. Technol.* **43** 4213–8
- Takemura T 2020 Return to different climate states by reducing sulphate aerosols under future CO₂ concentrations *Sci. Rep.* **10** 21748
- Thananusak T, Rakthin S, Tavewatanaphan T and Punnakitikashem P 2017 Factors affecting the intention to buy electric vehicles: empirical evidence from Thailand *Int. J. Electr. Hybrid Veh.* **9** 361–81
- The National 2020 The National 2020 Carmakers' move to delay emissions cap angers thai e-vehicle industry (The National), <https://nationthailand.com/in-focus/30392608>
- Thoday K, Benjamin P, Gan M and Puzzolo E 2018 The mega conversion program from kerosene to LPG in Indonesia: lessons learned and recommendations for future clean cooking energy expansion *Energy for Sustainable Development* **46** 71–81
- Tungsuwan S, Sakamoto N, Yong B and Kittichungchit V 2021 Thailand: electric vehicles - a new automotive world order BakerMckenzie <https://insightplus.bakermckenzie.com/bm/industrials-manufacturing-transportation/thailand-electric-vehicles-a-new-automotive-world-order>
- Uchida T and Zusman E 2008 Reconciling local sustainable development benefits and global greenhouse gas mitigation in Asia: research trends and needs: regional policy research *Studies of Regional Policy* **11** 57–73
- UNEP and CCAC 2016 Integrated Assessment of Short-Lived Climate Pollutants for Latin America and the Caribbean: improving air quality while mitigating climate change. Nairobi: UNEP
- UNEP APCAP and CCAC 2019 Air pollution in asia and the pacific: science-based solutions. united nations environment programme UNEP <http://ccacoalition.org/en/resources/air-pollution-asia-and-pacific-science-based-solutions>
- UNEP/WMO 2011a Opportunities to Limit Near Term Climate Change: An Integrated Assessment of Black Carbon and Tropospheric Ozone and Its Precursors. Nairobi: UNEP/WMO
- UNEP/WMO 2011b Integrated assessment of black carbon and tropospheric ozone: summary for decision makers UNEP
- UNFCCC 2023 Concept note: development of a sustainable development tool for article 6.4 of the Paris agreement-version 2.0 <https://unfccc.int/sites/default/files/resource/a64-sb007-aa-a07.pdf>
- Ürge-Vorsatz D, Tirado-Herrero S, Dubash N and Lecocq F 2014 'Measuring the Co-benefits of climate change mitigation *Annual Review of Environment and Resources* **39** 549–82
- Vatn A 2001 Transaction costs and multifunctionality *OECD Workshop on multifunctionality* vol 2, p 2001
- Ven D-J van de et al 2023 A multimodel analysis of post-glasgow climate targets and feasibility challenges *Nat. Clim. Change* **13** 570–8
- Vigolo V, Sallaku R and Testa F 2018 Drivers and barriers to clean cooking: a systematic literature review from a consumer behavior perspective *Sustainability* **10** 4322
- Vongurai R 2020 Factors affecting customer brand preference toward electric vehicle in bangkok, Thailand *Journal of Asian Finance, Economics and Business* **7** 383–93
- Walker T 2024 Is Thailand's 'clean air act' enough to end pollution? *Deutsche Welle* **2024**
- Warszawski L et al 2021 All options, not silver bullets, needed to limit global warming to 1.5 °C: a scenario appraisal *Environ. Res. Lett.* **16** 064037
- WHO 2014 7 million premature deaths annually linked to air pollution 2014 <http://who.int/mediacentre/news/releases/2014/air-pollution/en/>
- Zhang R, Fujimori S and Hanaoka T 2018 The contribution of transport policies to the mitigation potential and cost of 2 °C and 1.5 °C goals *Environ. Res. Lett.* **13** 054008
- Zusman E 2008 Recognising and rewarding co-benefits in the post-2012 climate regime : implications for developing asia *The Climate Regime Beyond 2012* (IGES)