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The levelized cost of carbon: a practical, if imperfect, method to compare CO₂ abatement projects*

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ABSTRACT

Calculating the cost effectiveness of projects and policies with respect to reducing carbon emissions provides a simple way for local government agencies to consider the climate impacts of their actions. Yet, defining a metric for cost-effectiveness in relation to climate change is not straightforward for several reasons. In this paper, we focus primarily on dynamics, reflecting the time value of money and how the benefits of reducing carbon emissions may change over time. We define a cost-effectiveness metric called Levelized Cost of Carbon (LCC) that carefully accounts for these dynamics. We also investigate the theoretical and practical implications and limitations of using a cost-effectiveness metric as an approach to rank projects. We apply our metric to a set of transportation projects to illustrate the insights that can be gained by such a process.

Key policy insights:
- Levelized Cost of Carbon (LCC) provides a simple way for local governments to consider climate change mitigation in decision making.
- LCC is a cost-effectiveness metric that carefully accounts for the time value of money and possible changes in the value of reducing emissions through time, thus helping local governments to make better decisions.
- LCC can be used to rank projects, with some caveats, even in the absence of a specific value for the benefits of reducing GHG emissions, thus providing flexibility in the face of uncertainty and political constraints.

1. Introduction

Several tools and analyses exist that can support climate change decision-making at the national and supranational levels. But many, if not most, of the decisions directly affecting behaviour and greenhouse gas emissions (GHG) are made at a local level, by city and regional public agencies (Lutsey & Sperling, 2008). These agencies often do not have the resources to employ sophisticated decision support tools, and they are balancing myriad concerns, among which climate change is only one.

In our collaboration with the Massachusetts Department of Transportation (MassDOT), we found a desire for a simple tool, namely a cost-effectiveness metric, that could be used to evaluate climate change projects alongside the many other issues they need to consider, including safety, congestion, pollution, and political considerations.

Defining a metric for cost-effectiveness in relation to climate change is not straightforward for a number of reasons. In this paper, we focus primarily on dynamics by accounting for time-value of money and time-value of...
emissions reduction. The two most common metrics in the literature (cumulative cost-effectiveness and annualized cost-effectiveness) treat the dynamics differently, providing different guidance in many cases. We define a cost-effectiveness metric that carefully accounts for dynamics and show that the two common metrics are special cases of this one. We then investigate the theoretical and practical implications of using a cost-effectiveness metric to rank projects.

In an ideal world, public agencies would choose GHG-reduction projects to maximize social welfare. There are many theoretical approaches for evaluating projects in terms of social welfare, including cost–benefit analysis (Boardman, Greenberg, Vining, & Weimer, 2017) and robust optimization (Chen, Wang, Wang, He, & Wang, 2014). When the benefits of a project are deeply uncertain (as is the case with climate change), an alternate approach is to choose projects in terms of their cost-effectiveness (Anable, 2008). Cost-effectiveness analysis also has many potential approaches, including empirical estimates (Mansur & Olmstead, 2012), integrated assessment modelling (Bosetti & Tavoni, 2002), and hybrid analyses (Proost et al., 2006). Most of these approaches have been applied to evaluate the cost-effectiveness of high-level climate targets or policies, such as a carbon tax versus an emissions cap. These sophisticated approaches, however, require resources that are beyond the scope of subnational decision-making agencies, such as MassDOT, which we use as a case study. These agencies often do not have the expertise needed for such analyses, nor the budget to support them. A cost-effectiveness metric is a rigorous, intuitive, and yet straightforward approach that may be more amenable to such decision makers. This approach has been used most commonly in the transportation sector; Silva-Send, Anders, and Narwold (2013), for example, provide an example using cost-effectiveness metrics for transportation projects in the city of San Diego.

The contribution of this paper is to (1) define a rigorous metric that can be easily applied by local agencies faced with time and resource constraints; (2) discuss explicitly the assumptions needed for the application to be rigorous, and the compromises that are made when using it in many cases; and (3) apply our metric to a set of transportation projects to illustrate the insights that can be gained by such a process.

2. The Levelized cost of carbon

Cost-effectiveness metrics are simple and intuitive to use and are flexible in the face of uncertainty and political disagreement about the benefits of reducing GHG emissions. That is, the cost-effectiveness metric itself is independent of estimates for the value of reducing GHG; it can be compared to a range of benefit estimates, depending on the current science or the political dictates handed down to local agencies. Our focus here is on defining a cost-effectiveness metric that carefully accounts for the time value of money and the time value of the benefit of reducing emissions.

We propose using a levelized cost per ton of CO₂ avoided (LCC). This is similar to the Levelized Cost of Electricity (LCOE), in that it correctly accounts for discounting to identify the break-even benefit to reducing carbon that is required to make a project worthwhile (see Branker, Pathak, and Pearce (2011) and Short, Packey, and Holt (2005) for discussion of LCOE). This metric is useful because it can be compared to a carbon tax, the price of carbon in a cap and trade market, or the social cost of carbon (SCC), to determine if a project is worth doing. This concept is discussed with more details in section 3.1.1.

The discount rate, the interest rate to determine the present value of future cash flow, needs to play a role in calculating the cost-effectiveness of carbon reduction. For example, consider two projects, both with a one-time initial cost of $1000. One project reduces emissions by 100 tons in 10 years; the other reduces 100 tons immediately. From a cost perspective, we should prefer the second project since we could delay its implementation for 10 years, resulting in a lower cost because of discounting, but still get the same outcome as the first project. A related, but a different issue, is how the climate value of emissions reductions may change over time. We address both below.

Using this logic, we develop the formula for the LCC, which we define as the constant cost per unit of CO₂ avoided that equates the net present value of the benefits and costs of reducing CO₂.
2.1. Derivation of the LCC

The Net Present Value (NPV) of a project $k$ is defined in equation (1):

$$\text{NPV}_k = \sum_{t=0}^{T_k} \frac{1}{(1+i)^t} (\tau_t e^k_t - c^k_t)$$

(1)

Where $e^k_t$ are the emissions avoided and $c^k_t$ are the net social costs of project $k$, in year $t$; $T_k$ is the lifetime of the project. The net social costs would include co-benefits of the project (as a negative cost). The value of reducing emissions in year $t$, $\tau_t$, depends on the context of the decision and the decision maker. For example, the value of reducing emissions might be equal to the emissions price for a firm under a cap and trade policy; it may be equal to the SCC for a public agency. The net benefits, $(\tau_t e^k_t - c^k_t)$ are discounted in each year using discount rate $i$. If the NPV of a project is positive, then it increases social welfare and should be invested in.

We note that there has been much discussion about whether the value of reducing emissions is constant over time, or whether it increases. For example, Bijgaart, Gerlagh, and Liski (2016) argues it increases with output; it is commonly argued to increase with the discount rate (Sathaye, Norgaard, & Makundi, 1993); or with the willingness to pay for avoiding damages (Pearce, 2002). In addition, because damages depend on the atmospheric concentration of emissions, and concentrations are increasing over time, it is argued that the incremental damage from each unit of emissions will increase over time with concentration levels (Pearce, 2002). For simplicity, we assume that the value of reducing a ton of carbon will change at a fixed rate, which we call $\gamma$. That is, assume that $\tau_t = (1+\gamma)^t \tau_0$.

To derive the equation for the LCC$^k_k$ of project $k$, we substitute it for $\tau_0$ in equation (1), set the equation equal to zero and solve for the value of LCC$^k_k$, where we define $b = \frac{1+i}{1+\gamma} - 1$:

$$\text{LCC}_k = \frac{\sum_{t=0}^{T_k} \frac{1}{(1+i)^t} e^k_t}{\sum_{t=0}^{T_k} \frac{1}{(1+\beta)^t} e^k_t}$$

(2)

The LCC for a project is equal to the NPV of the cost of the project divided by an expression for the discounted emissions avoided by the project, where the discount rate for emissions reflects the rate of increase in the value of reducing emissions. Discounting emissions has been criticized, since they are physical and not monetary (see Wang (1997) for a brief discussion). Note, however, that equation (2) does not imply that we are discounting physical emissions in the future. Looking back to equation (1) it is clear that the expression in (2) results from the economic benefits of reducing emissions that are being discounted.

If $\gamma = 0$, $b$ simply equals $i$. If $\gamma$ is positive, $b$ is smaller than $i$, indicating that, as $\gamma$ increases, relatively more weight is put on future emissions reductions. For example, in the literature a value of $\gamma = 2\%$ is suggested (Price, Thornton, & Nelson, 2007; Zenghelis, 2006). If the value of reducing a ton of carbon is expected to increase at a non-constant rate, a more complicated calculation would be required.

2.2. The definition of ‘cost’ and the decision framework

LCC provides flexibility in terms of what type of costs to include in the calculation. The private cost is the cost incurred directly to the agency (Field & Field, 2009); for example, the cost to buy a new fleet of agency vehicles. The social cost is a broader concept and refers to external costs, such as environmental damages, as well as private costs (Field & Field, 2009).

In an ideal world, a public agency would choose projects to maximize net social welfare and would use a net social LCC. In the net social LCC, the costs $c_t$ represent the net social costs of everything except emissions. This LCC would be compared with the appropriate value of reducing carbon, such as the SCC. Several papers, including Wang (1997) and Matute and Chester (2015) in the context of transportation, have discussed the importance of including broader societal benefits into cost-effectiveness analysis.
For many projects, the net social LCC will be negative, meaning the projects have social welfare independent of their impact on emissions. Investing in such a project improves social welfare regardless of emission benefits (Wang, 1997). A few projects may be beneficial entirely on climate grounds, and many projects may be not quite beneficial on their own, but the consideration of GHG benefits pushes them over the top to become worthwhile projects. In an ideal world, these would be the only projects considered under a climate policy.

In some cases, it may be reasonable to consider only direct agency costs (private costs). For example, a Department of Transportation (DOT) may face a constraint on the emissions of agency-owned vehicles that is to be met through technology upgrades; the correct cost metric would be net agency costs. Or, a DOT may face a constraint on transportation sector emissions that it must address through infrastructure investments. If this constraint is not met through its business-as-usual infrastructure investments, then the agency needs to reallocate resources to projects with higher emissions reductions. It may be appropriate in this case for the agency to fill in the emissions gap by prioritizing projects with the lowest agency LCC. In general, if an agency considers only financial costs and ignores broader social welfare impacts, they are getting an indication of whether a project is justified only on the basis of its GHG reduction possibilities.

2.3. Comparison to metrics in the literature

Most of the literature uses one of two metrics, typically called ‘cumulative life-time cost-effectiveness’ and ‘annualized life-time cost-effectiveness’, respectively. In a survey of 33 papers, Kok, Annema, and Wee (2011) found that 42% used the first metric, while 18% used the second; the remaining 27% used more ad-hoc methods, which depend on specific situations and are not generalizable. Other examples include the Working Group III report of the Intergovernmental Panel on Climate Change (IPCC) (Krey et al., 2014), which uses the annualized metric; and Silva-Send et al. (2013) who use a mix of metrics in their analysis of transportation projects, including the annualized life-time cost-effectiveness for most of the projects.

The cumulative life-time cost-effectiveness is calculated by dividing the discounted total costs by undiscounted cumulative emissions reductions. The annualized life-time cost-effectiveness is calculated by dividing the annualized cost by a fixed annual emissions reduction. The LCC encompasses both metrics. If \( \gamma \) is exactly equal to the discount rate, \( i \), then the LCC is equal to the cumulative life-time cost-effectiveness metric. If \( \gamma \) is zero and emissions reductions are equal each year, then the LCC is equal to the annualized life-time cost-effectiveness.

The key point is that cumulative and annualized life-time methods ignore the emissions path. Many real-world projects, however, estimate that annual emissions reductions will increase through time, such as a set of projects from different sectors (energy, agriculture, etc.) provided in a South Carolina climate action report (CECCAC, 2008). For projects like these, ignoring the emissions path causes both the cumulative and the annual metrics to over-estimate the cost-effectiveness.

Our metric is related to the Cost of Reducing one unit of Atmospheric Carbon (CRAC) defined by Sathaye et al. (1993). The CRAC was developed before recent work on defining the SCC, and so was intended to be compared to the shadow price of avoided carbon. Thus, CRAC accounts for the present equivalent of atmospheric carbon. Equation (3) shows the relationship between the CRAC and the LCC.

\[
CRAC = \text{LCC}(i + a) = \frac{\sum_{t=0}^{T} \frac{1}{(1+i)^t}C_t}{\frac{1}{(i+a)} \sum_{t=0}^{T} \frac{1}{(1+\beta)^t}e_t}
\]

where \( a \) is the decay rate of atmospheric carbon. The SCC accounts for the present equivalent of atmospheric carbon; therefore, the correct cost-effectiveness metric to compare with the SCC is the LCC. Thus, the LCC is an updating of the CRAC, accounting for current methodologies.

Similarly, Wang (1997) suggested the need for an LCC-type metric in the context of the life-cycle costs of mobile source emissions. The idea of discounting both costs and emissions is mentioned in this paper, but a rigorous argument is not provided.
3. Applying the LCC: uses and abuses

Cost-effectiveness metrics can be used rigorously under certain conditions. In other cases, they are only heuristics – rules that often give a reasonable answer but are not guaranteed to be optimal. Figure 1 provides an illustration of a decision hierarchy, indicating under what assumptions cost-effectiveness metrics are rigorous.

3.1. Social welfare framework

3.1.1. LCC with social cost of carbon

To use the LCC, we must compare it to a measure of the benefit of reducing carbon. The most commonly used concept to measure this is the SCC. SCC refers to the monetary value of total damages of emitting one ton of carbon dioxide into the atmosphere, for the full lifetime of the emissions. If the LCC of a project is less than or equal to the SCC, then that project is cost-effective; if it is greater, then the project’s costs are higher than its benefits and it should not be adopted.

However, while the SCC is a nice conceptually, there are difficulties in calculating an actual value (Moyer, Woolley, Glotter, & Weisbach, 2014). Moreover, the costs \( c_i \) in the LCC formula would have to account for the entire net social cost of the project, including all social benefits aside from carbon benefits. For example, if the project under consideration were a new traffic roundabout, the estimated costs would need to account for any costs or benefits associated with changes in congestion, safety, other pollutants, and equity. This would be consistent with the broader goals of many local government agencies, which invest in projects for myriad reasons besides targeting GHG emissions. But, the challenges of estimating total net costs may lead to a temptation to use a metric like the LCC to rank projects independent of the value of reducing emissions. The LCC, or any cost-effectiveness metric, however, faces a weakness when used to rank projects. There are cases in which a project that is less cost effective in terms of having a higher LCC will nevertheless be the preferred project with a higher social benefit in terms of NPV. The problem is that there exist projects A and B, and SCC of \( t^* \) such that:

\[
\begin{align*}
\text{LCC}_A &< \text{LCC}_B \\
\text{But} &\quad \text{NPV}_A(t^*) < \text{NPV}_B(t^*)
\end{align*}
\]

Figure 1. Illustration of a decision hierarchy and application of LCC with respect to decision types.
That is, if we used the LCC, we would think that project A was better than project B; however, given an SCC of \( \tau^* \), project B is in fact better.

For example, Figure 2 illustrates four illustrative projects, ranging in size, with project 1 having the lowest cost and emissions avoided, and 4 the highest (see Table A1 in Online Appendix for details). If the LCC was used to prioritize them, then Project 1 would appear to be the best project, followed by 3, 4, and 2. However, we see that project 1 has the highest NPV when the SCC is below 16.5; between 16.5 and 17, project 3 is highest; and project 4 has the highest NPV thereafter.

This is similar to the problem faced when trying to use the internal rate of return (IRR) to compare projects: the IRR implicitly assumes that any additional funds are being reinvested at the IRR, rather than the discount rate. Similarly, LCC (or any other cost per unit of carbon) implicitly assumes that any additional tons of carbon that can be reduced are valued at the LCC rather than the SCC.

This problem does not arise under certain conditions. First, if projects can be linearly scaled to reduce any amount of emissions then the LCC will always compare correctly, regardless of the SCC. Second, if a project is both smaller in terms of NPV of emissions and has a higher LCC, then it will never be preferred under the condition that it has a positive NPV (See the online Appendix for proof). An example of this is project 2 in Figure 2 when compared to projects 3 and 4.

In all other cases, it is not possible to ensure that one project is preferred over another without considering the appropriate SCC. This problem is fundamental to cost-effectiveness metrics: there is no possible metric that can accurately prioritize projects in the absence of the SCC (or other value of reducing emissions), however, current literature discussing cost-effectiveness metrics does not make the point that they cannot be reliably used to compare multiple investments.

### 3.1.2. Pareto analysis

To overcome the proposed challenges, it may be useful to use the LCC in combination with emissions in a Pareto Analysis. This approach helps in ranking projects that have lower LCC but their NPV is not necessarily higher. This allows the decision maker to identify ‘Pareto dominated’ projects and to find a break-even value for the SCC to discriminate between projects. In considering any group of alternatives that are evaluated under multiple metrics, we can identify alternatives that are Pareto-dominated. An alternative is Pareto dominated if it is worse under all metrics than another alternative. In this case, a project is Pareto dominated if it has a higher LCC and lower emissions than another project. For consistency, we apply discounting to the emissions in order to reflect the economic benefits of reducing emissions, as in equation (2). The set of projects that are non-dominated is called the Pareto Frontier.

![Figure 2](image-url)  
**Figure 2.** NPV of 4 illustrative projects as a function of the SCC. Legends report LCC for each project.
We can calculate a break-even point between any two adjacent projects on the Pareto frontier. The break-even SCC is the SCC at which decision makers are just as indifferent between two projects.

The bottom panel of Figure 3 shows how this can be used to communicate with decision makers. If, for example, a project is preferred under the entire plausible range of values for the SCC, then the LCC can be used with confidence in the short term.

3.2. Constrained problems

Public agencies often have a constrained budget for projects, thus they must choose the subset of all possible projects that increase social welfare under the given budget. Or, many agencies are subject to targets for GHG reduction and want to choose the least cost set of projects that will achieve this target. Both problems can be modelled as ‘knapsack’ problems, a class of problems in which a decision maker wants to fill a conceptual ‘knapsack’ with the highest value objects, given a space constraint. In the first case above, the size of the knapsack is the budget, while the value comes from the emissions reductions of possible projects. (Puchinger, Raidl, & Pferschy, 2010).

There is a well-known heuristic for solving knapsack problems: choose projects in terms of cost-effectiveness until the constraint has been satisfied. This heuristic would choose projects by comparing LCCs, in either type of constrained problem. This method is a heuristic that gives a potentially reasonable answer, but it is not guaranteed to give the optimal solution. The solutions become better as the size of the problem grows with respect to the size of the individual projects. Specifically, define the error to be the fractional increase in cost over the

![Figure 3. Marginal abatement cost of Massachusetts projects (Top), Pareto analysis of Massachusetts projects with LCC < $200/t CO₂ (Bottom). The circled projects are non-dominated projects.](image-url)
optimal solution, $\varepsilon = \frac{c - c^*}{c^*}$, where $c$ is the cost of the heuristic solution and $c^*$ is the cost of the optimal solution. Then the worst-case error has the following characteristic (Fisher, 1980):

$$\varepsilon \leq \frac{E_{\text{max}}}{E_{\text{max}} + E}$$

(5)

where $E_{\text{max}}$ is the emissions reduction of the largest candidate project and $E$ is the emissions reduction goal (both applying discounting to reflect the economic benefit of reducing emissions). Equation (5) shows that the worst-case error gets smaller as $E$ increases with respect to $E_{\text{max}}$. For example, we estimated the size of the maximum error for the MassDOT data using the LCC to prioritize the projects. Given the goal for the transportation sector in 2050, this error would be no more than 0.007%. In practice, the error is often much less than the maximum error.

If projects can be scaled down, then this is a ‘fractional’ problem, and the heuristic of choosing projects in order of ascending LCC results in the exact answer (Fréville, 2004). If projects cannot be scaled, however, then a lower LCC is not generally a guarantee that a project is preferred. Moreover, additional constraints, such as requiring specific emissions reductions in specific years, mean that prioritizing in order of ascending LCC is not guaranteed to provide the optimal solution, even if all projects are scalable.

In summary, as depicted in Figure 1, the LCC can be used exactly in some cases, and as an approximation under any of the decision frameworks. It will give the optimal prioritization in cases where the projects are scalable; it is an approximation in other cases and may result in choosing some projects which are suboptimal.

Note, none of the methods suggested here and outlined in Figure 1, except for full cost–benefit analysis, require knowledge of the SCC or any other value of the benefit of reducing carbon emissions. The Pareto Analysis requires the ability to define a plausible range for the SCC.

4. Application to transportation projects

We apply the LCC framework to a set of transportation projects, presenting the range of LCCs and how they are related to different project types.

4.1. Data and assumptions

We apply the framework to two sets of data. The first is from the MassDOT, which contains only agency costs. The second is a set of transportation projects from other US states that were gleaned from publicly available climate change reports. Most of these projects appear to include social benefits, however, this is not always clear.

The dataset from MassDOT includes 295 planned projects with start dates ranging between 2017 and 2021. The provided data include the total project cost to the agency, the GHG reduction amount measured in tons per year, the lifetime, and a cost per ton of emissions as calculated by DOT. Projects are categorized by MassDOT into four types: Traffic Operational Improvement (94 projects); Transit (92); Complete Streets (36); and Pedestrian and Bike Improvement (73). Complete Streets refers to projects that integrate multiple travel modes.

Reported project cost is treated as an investment in the first year of the project. All projects reported a single value for the emissions reduction per year; we assume that this is intended to be a constant annual reduction through the lifetime. MassDOT calculated the cost-effectiveness of each project by dividing the total project cost by the total emissions reduction. The data are summarized in Table A.2 (Online Appendix). Traffic Operational Improvement projects have the lowest median LCC at $1,829 and Bike and Pedestrian projects have the highest at $17,494.

In addition, we collected data on 35 non-Massachusetts transportation projects, from 7 US states (Arkansas, 2008; Colorado, 2007; Florida, 2008; GHGCE, 2010; ICF International, n.d.; Iowa, 2008; New Mexico, 2006; CECCAC, 2008). Of these, five projects include data on annualized costs; 13 projects include the total (non-discounted) cost (which we assumed was equal to an initial investment cost); and 17 provide the NPV of costs. All project consider co-benefits.
In terms of emissions data, 19 projects report a flat emissions reduction per year. This set of reports calculated cost-effectiveness using the annual method. The remaining 16 projects include the total emissions reduction plus values for two specific years. For these projects, we derive an emissions path, assuming it is linear between the two given years. This set of reports calculated cost-effectiveness using the cumulative method.

There are controversies involved in choosing discount rates in the literature (Gollier & Hammitt, 2014). The choice of discount rate in this paper is extracted from state-level reports. For all projects, we assume that $\gamma = 0$. For Massachusetts projects we use the official discount rate of $i = 4\%$. For the other projects, we use 5\%, as indicated in the reports.

### 4.2. Results

Our results are based on the data described above, some of which contain co-benefits and some not. Thus, these results must be interpreted in this context. In the cases where co-benefits are not given, such as for the Massachusetts projects, the results refer to projects that would be done only for CO\textsubscript{2} benefits, ignoring all other benefits to society.

In 70\% of the Massachusetts transportation projects, the value of the LCC differed significantly (by more than 10\%) from the reported cost-effectiveness. This is because the reported values did not include discounting, and many of the projects have lifetimes of 50 years. Similarly, among the non-MA projects that used the cumulative method, 80\% differed significantly. The reports that used the annual method reported cost-effectiveness very close to our LCC.

The top panel of Figure 3 presents the marginal abatement cost curve for the Massachusetts transportation projects. If the value of reducing carbon emissions is set to $200/\text{t CO}_2$, for example, then it would be optimal to invest in the first 10 projects, leading to annual emissions reductions of 9,452 tonnes, or only 0.04\% of the Massachusetts 2050 goal for the transportation sector (CECP, 2015).

Table 1 lists the Massachusetts projects with LCC less than $200 in an ascending order. Most of these projects are Traffic Operations Projects, an indication that these are the most favourable for CO\textsubscript{2} reductions: they make up about one-third of all the projects in the data set, but 80\% of the projects in Table 1. This result is interesting because Traffic Operations Projects are the ‘bread and butter’ of transportation projects and are not aimed primarily at reducing emissions. On the other hand, the projects that are thought of more often as emissions-reducing, such as public transit and cycling projects, do not fare as well.

We compare the LCC to the simple non-discounted metric that MassDOT originally used. The LCC results in a different ranking, with the Cape Bike Shuttle projects being relatively more cost-effective than the last three projects in the Table 1 accounting the time-value of money and time-value of emissions reduction over the life time of the projects (50 years).

The lower panel in Figure 3 illustrates the ten projects in Table 1 in a Pareto analysis. Each project, represented as a dot, is placed so that its LCC is on the vertical axis and emissions avoided are on the horizontal axis.

<table>
<thead>
<tr>
<th>Project title</th>
<th>Projects category</th>
<th>Total project cost ($)</th>
<th>Emissions reduction (tonnes/yr)</th>
<th>Reported cost-effectiveness ($/t CO\textsubscript{2})</th>
<th>LCC ($/t CO\textsubscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oak Bluffs</td>
<td>Traffic Operations</td>
<td>412,370</td>
<td>263</td>
<td>34</td>
<td>73</td>
</tr>
<tr>
<td>West Bridgewater</td>
<td>Traffic Operations</td>
<td>2,805,960</td>
<td>1745</td>
<td>35</td>
<td>75</td>
</tr>
<tr>
<td>Northampton</td>
<td>Traffic Operations</td>
<td>2,106,590</td>
<td>1140</td>
<td>41</td>
<td>86</td>
</tr>
<tr>
<td>Avon</td>
<td>Traffic Operations</td>
<td>3,888,000</td>
<td>1886</td>
<td>45</td>
<td>96</td>
</tr>
<tr>
<td>Worcester</td>
<td>Traffic Operations</td>
<td>2,902,792</td>
<td>1116</td>
<td>57</td>
<td>121</td>
</tr>
<tr>
<td>Easton Signalization &amp; Geometric Improvements</td>
<td>Traffic Operations</td>
<td>1,044,228</td>
<td>359</td>
<td>64</td>
<td>138</td>
</tr>
<tr>
<td>Cape Bike Shuttle</td>
<td>Transit</td>
<td>87,610</td>
<td>68</td>
<td>118</td>
<td>137</td>
</tr>
<tr>
<td>Easton Intersection Improvements</td>
<td>Traffic Operations</td>
<td>1,062,986</td>
<td>359</td>
<td>65</td>
<td>138</td>
</tr>
<tr>
<td>Brockton</td>
<td>Traffic Operations</td>
<td>2,160,432</td>
<td>556</td>
<td>86</td>
<td>181</td>
</tr>
<tr>
<td>Boylston Street</td>
<td>Complete Street Projects</td>
<td>8,214,319</td>
<td>1959</td>
<td>92</td>
<td>195</td>
</tr>
</tbody>
</table>

Table 1. List of Massachusetts transportation projects with LCC < $200/\text{t CO}_2$ in order of ascending LCC.
axis. If projects were chosen in order of ascending LCC, then projects would be chosen from the bottom up. The circled projects are those that are non-dominated: there is no project that is both more cost-effective and has greater emissions savings. The values on the right show the trade-offs between some of the non-dominated projects: the value of the SCC that would justify prioritizing the circled project to the right over the project to the left. Since these values are much higher than current estimates for the SCC (which are between $10 and $212 per metric ton of CO₂ eq (Interagency Working Group on Social Cost of Greenhouse Gases, 2016)), it appears robust to simply prioritize these projects in order of ascending LCC.

Table 2 summarizes the 17 (out of the total of 35) non-Massachusetts projects with LCC less than $200/t CO₂.

Note that these projects include co-benefits, and so these results cannot be compared to the Massachusetts results. Thirteen projects have negative LCCs, indicating that they are beneficial to society even without considering emissions benefits. To put this in perspective, the median and mean LCC among all projects are $474/t CO₂ and $13,923/t CO₂, respectively, clearly indicating a long tail of very expensive projects, with 8 projects having an LCC over $5000/t CO₂.

We assign these projects into four categories: vehicle-based, system-level, traveller-incentive, and outreach. System-level programmes refer to projects involving roadways, networks, and smart growth. All considered MassDOT projects would fall under system-level programmes. We find that vehicle-based programmes make up 59% of the projects in Table 2, but only 40% of the data set, indicating that these types of projects may be the most cost effective, while the systems-level programmes are under-represented. None of the three outreach projects have an LCC less than $200/t CO₂. Note, these projects come from different reports using potentially very different methodologies.

5. Conclusion and policy implications

We have introduced a new metric, the Levelized Cost of Carbon, for calculating the cost-effectiveness of GHG reduction projects. It accounts correctly for the time value of money and for the possibility that the value of reducing GHG changes through time. This definition encompasses the most common definitions in the literature, and makes explicit the assumptions required to use the current cost-effectiveness metrics. The LCC can be compared to the SCC, or any other appropriate value, to determine whether a project should be invested in or not.

It is not generally theoretically valid to use this metric – or any other cost-effectiveness metric – to rank projects. A project that is more cost-effective is not necessarily the project that maximizes social welfare. If the value of reducing emissions is large enough, then it is better to choose a larger, if less cost-effective, project over a smaller, more cost-effective, one.

We outline the assumptions under which it is valid to use LCC to rank projects. If projects can be scaled down linearly, then the LCC provides a correct way to rank projects. More generally, while it is not guaranteed to produce the optimal solution in theory, it often produces very good solutions in practice. Thus, the LCC provides an intuitive way for small agencies to account for climate change in their project selection.

We emphasize that there are several other issues that must be considered when comparing projects. The most important is what is considered among the costs and non-GHG benefits of the project. In many cases, particularly in the transportation sector, the value of reducing GHG is quite small compared to the other social
welfare effects, such as reducing congestion and other pollutants, and increasing safety. Thus, extreme care must be taken when using cost-effectiveness metrics to choose projects.

In transportation, CO₂ is by far the most important GHG, so we focus on that. But in some applications, other GHGs are equally or more important. Incorporating multiple GHGs adds new complexities since different gases have different lifetimes and different warming potentials (Edwards & Trancik, 2014). The most widely adopted methodology is to calculate emissions in terms of CO₂ equivalence.

We illustrate the framework using data on transportation programmes and projects. The data suggest that, when co-benefits are accounted for, vehicle-based programmes, such as adopting stricter GHG standards, may be the most cost-effective way to combat CO₂ emissions. Among current Massachusetts systems-level projects, we found that Traffic Operations Projects were more cost effective than cycling or public transit projects when only agency costs are considered.

The LCC, in accounting for dynamics, encompasses and extends the current metrics in the literature. While it is not perfect from a theoretical perspective, it is a practical way to account for the costs and benefits of prospective GHG-reducing projects, allowing a range of public agencies to move forward with decision-making.

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