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Cost efficiency of municipal green bonds' measures: a marginal abatement cost curves approach

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Abstract

Purpose – With more cities aiming to achieve climate neutrality, identifying the funding to support these plans is essential. The purpose of this paper is to exploit the present of a structured green bonds framework in Sweden to investigate the typology of abatement projects Swedish municipalities invested in and understand their effectiveness.

Design/methodology/approach – Marginal abatement cost curves of the green bond measures are constructed by using the financial and abatement data provided by municipalities on an annual basis.

Findings – The results highlight the economic competitiveness of clean energy production, measured in abatement potential per unit of currency, even when compared to other emerging technologies that have attracted the interest of policymakers. A comparison with previous studies on the cost efficiency of carbon capture storage reveals that clean energy projects, especially wind energy production, can contribute to the reduction of emissions in a more efficient way. The Swedish carbon tax is a good incentive tool for investments in clean energy projects.

Originality/value – The improvement concerning previous applications is twofold: the authors expand the financial considerations to include the whole life-cycle costs, and the authors consider all the greenhouse gases. This research constitutes a prime in using financial and environmental data produced by local governments to assess the effectiveness of their environmental measures.

Keywords Sweden, Municipalities, Green bonds, Marginal abatement cost curves

Paper type Research paper

1. Introduction

Since the signing of the Paris Agreement (UN, 2015), mobilising capital to tackle climate change has become at the forefront of the discussion. Overall, US$5 to 7tn of green and

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sustainable finance will be needed annually until 2030 to meet climate goals (Peake and Ekins, 2017; OECD, The World Bank and UN Environment, 2018). Green finance comprises new financial instruments, including green credits, bonds and loans, green long-term investment accounts, carbon finance, climate finance, green traded stocks and bonds, green bank assurance and green infrastructural finance (Akomea-Frimpong *et al.*, 2022). Green bonds are a particular type whereby proceeds are destined for green purposes (ICMA, 2021). Issuers of green bonds, among others, commit to using the funds for green, climate-related investments and reporting on the annual impact (Nordic Public Sector Issuers, 2020). Independent reviewers provide "second opinions" on the green and sustainability credentials of the green bonds, providing investors with assurance over the sustainability of their investment.

In Sweden, many municipal governments have issued green bonds, following Gothenburg as the first municipality in the world to issue green bonds (García-Lamarca and Ullström, 2022). In 2020, Sweden issued its first sovereign green bond worth SEK 20bn, with an additional SEK 5bn issued by smaller governmental bodies such as regions and municipalities (Sveriges Riksbanken, 2020). As many cities have joined climate neutrality initiatives (European Commission, 2022; Viable Cities, 2020), It is anticipated that governmental actors will issue more green bonds to fund their transition plans (Vanhuyse *et al.*, 2020; Waltré *et al.*, 2022).

This paper aims to investigate the cost-efficiency of the carbon reduction measures financed in Swedish municipalities through the scheme of municipal green bonds using the marginal abatement cost curves (MACCs) methodology. Our research questions are:

RQ1. What actions have been funded by municipal green bonds?

RQ2. What methodology provides a robust estimate of the cost-effectiveness of carbon reduction measures?

To the best of our knowledge, this application represents the first one of its kind to make use of municipal green bonds financial reports to build MACCs.

Our research contributions are twofold.

Firstly, our research provides insight into the methodological approaches used to assess cost-effectiveness. The boom in the green bonds market has led to the development of new impact metrics alongside the more traditional investment decision methods such as cost-benefit analysis (CBA) and return on investment (ROI). MACC, appearing first in the '90s (Jackson, 1991), have gained new popularity as they allow to rank different environmental measures according to cost efficiency (McKinsey, 2009; Vogt-Schilb and Hallegatte, 2014; Jiang *et al.*, 2020; Lozano *et al.*, 2021). This paper critically reviews the latest research on cost-effectiveness measurement and suggests methodological improvements. These include adopting a broader perspective considering all relevant costs, including and beyond initial investments and operational expenditures. Salvage costs (SCs) are often overlooked when assessing the financial needs of the measures, and the difficulties around their estimation are known to the previous literature (Beiron *et al.*, 2022; Borén, 2020; Lindahl *et al.*, 2022; Timilsina *et al.*, 2017). Secondly, we expand the research focus to consider all greenhouse gases (GHG) and not only carbon dioxide, contributing to the small number of papers considering non-CO_2 GHG in the scope of MACCs (Harmsen *et al.*, 2019). Accounting for all GHGs is necessary when evidence suggests that non-CO_2 GHGs may experience a different trajectory than carbon dioxide, producing a result that is far from predictable (Cole and Zhang, 2019; Ustyuzhanina, 2022). The focus on CO_2-eq is also in line with the KPIs Swedish municipalities have selected to monitor their progress under the sustainability-linked bonds framework (Helsingborg Municipality, 2021; ICMA, 2020; Västerås Municipality, 2023).

Secondly, as many municipalities are experiencing limited budgets (see, for example, Vanhuyse *et al.*, 2021, for an overview of municipal finance in Sweden), having insight into which measure contributes the most substantially to meeting climate targets will be essential. There have also been uncertainties about municipal investments' financial and impact reporting (Fenton *et al.*, 2015). Our research supports decision makers to justify investments in projects with high-cost efficiency. In addition, the results of the MACC analysis offer the potential to investigate the adequacy of the current emissions permit prices and the carbon tax. These two instruments can incentivise investing in emissions reduction technologies (Du *et al.*, 2015; Kesicki, 2013; Kesicki and Ekins, 2012; Vogt-Schilb and Hallegatte, 2014).

This paper is organised as follows: Section 2 provides an overview of the different methods for calculating the effectiveness of investments and a discussion on discount rates. Then, in Section 3, we elaborate on the methodology and the data used to calculate the cost curves. Section 4 presents the results, followed by a discussion in Section 5 on the efficiency of these measures compared to other studies, including reflections on GHG emissions in cities. We conclude in Section 6.

2. Methods to assess the effectiveness of investments

2.1 Marginal abatement cost curves

MACCs allow the comparison of different investment options under the measure of currency spent per ton of GHGs avoided, which can be easily compared and cost-efficiency can be easily assessed. Kesicki and Strachan (2011) provide an excellent historical perspective on using MACCs. One of the first appearances the authors mention of a graph that may resemble the one typical of MACC applications is the one found in Meier *et al.* (1982), where the authors investigate the cost efficiency, measured in units of \$/GJ, of energy conservation measures. Using the emissions factor for that specific energy grid, one could quickly turn these figures into MACC. Despite the focus on a slightly different unit of measure, i.e. energy saved rather than avoided or captured emissions, Meier *et al.* (1982) point to the reasoning that guides the evaluation of energy conservation measures and that will also underline that of MACC "a [conservation] measure is economically attractive if its cost of conserved energy is less than the price of the energy that is *saved*" (p. 348). Jackson (1991) represents one of the first examples where this same methodology is applied to the case of carbon abatement.

Table 1 provides an overview of recent research to assess the cost efficiency of different climate solutions across Europe and in different sectors using MACC.

The MACCs methodology can also be applied to regions and cities, as demonstrated by Du *et al.* (2015), who use panel data to carry out an analysis in 30 Chinese provinces; Ibrahim and Kennedy (2016), who constructed MACCs for the city of Toronto, suggesting that numerous measures can be implemented at a negative net present value (NPV); and Garg *et al.* (2014) who investigate the attractiveness of energy efficiency measures in 21 cities of the Indian state of Gujarat.

MACCs are easy to apply and efficiently rank alternative cost-effective options. With MACCS, it is possible to apply the same approach to a whole portfolio of alternatives (Jiang *et al.*, 2020; Huang *et al.*, 2016). However, MACCs analysis has limitations, including an inability to capture long-term dynamics and evaluate non-financial costs such as health costs (Harmsen *et al.*, 2019). The MACC methodology is also affected by the "penny switching" or "razor edge" effect, i.e. the fact that a slight change in the parameters can lead to substantial variations in results (Labriet *et al.*, 2012; Yue *et al.*, 2020). The failure to capture the interactions of the measures in the portfolio is another caveat that should be reflected upon (Kesicki and Strachan, 2011). Market distortions may also significantly

Authors	Focus	Findings
Andersson *et al.* (2018)	The Swedish building sector	Identified cost-neutral measures that can lead to a 15% reduction of the embodied emissions from the building environment. Identified additional cost-effective measures, at about €59/t of CO_2-eq, that can lead to a 18% reduction of CO_2-eq emissions
Beiron *et al.* (2022)	CO_2 capture in Swedish biomass or waste-fired combined heat and power plants	About 10.6–13.6 $MtCO_2$/year are available for capture at a cost, excluding costs for ship transport and storage, smaller than €100/t CO_2
Biermann *et al.* (2022)	Residual heat from existing refineries' boilers	Marginal abatement costs between €35 and €60 for each ton of CO_2
Johnsson *et al.* (2020)	Carbon capture and storage (CCS) measures to curb emissions from the largest manufacturing companies in Sweden	About 50% of the total Swedish emissions from all sectors could be captured at a cost ranging between €40/t CO_2 and €110/t CO_2
Timilsina *et al.* (2017)	The building sector in Georgia and Armenia	Significant emissions reductions from this sector in these countries can be achieved through measures that present a negative net present value (NPV)

Notes: Table 1 lists recent studies that used the MACC methodology, specifying the sector to which the study belongs and reporting the results on the marginal abatement costs of the measures considered there. It is meant to provide an overview of recent methodology trends and show its flexibility to be applied across several sectors
Source: Authors' elaboration

Table 1. Some recent publications on MACC of different climate technologies and in different sectors

demean the results' robustness (Jiang *et al.*, 2020). In conclusion, MACCS should not be considered standalone (Kesicki and Ekins, 2012).

2.2 Comparison of cost-benefit analysis versus marginal abatement cost curves

Pareto efficiency entails reaching an equilibrium when no alternative allocation can increase at least one person's utility without negatively affecting anyone else (Pareto, 1906). As this concept, applied at the community or societal level, has been found unfeasible given the high number of people affected and the incentives for individuals to misrepresent their utilities to steer decisions towards their goals (Manning, 2014), welfare economists relaxed the criteria of Pareto efficiency, introducing the idea of net benefits, understood as the difference between costs and benefits. This concept, the Kaldor–Hicks criterion, constitutes the theoretical foundation of the CBA and justifies the adoption of a specific policy or measure as long as the benefits accrued to the society exceed the costs (Brown, 2022; Little, 1979; Manning, 2014; Mukoyama, 2023; Nash *et al.*, 1975; Nurmi and Ahtiainen, 2018). From a theoretical perspective, all Kaldor–Hicks efficient allocations are Pareto-efficient. However, the reverse is not necessarily true: for an allocation of goods to be Kaldor–Hicks efficient, the aggregated benefits of the society should exceed the costs the society faces. This may imply that a new allocation of goods may harm some elements of the society, therefore, qualifying this new allocation as non-Pareto efficient but still fulfilling the requirements of the Kaldor–Hicks criterion if the net result is positive.

Criticism on CBAs includes that they are affected by:

- distributional issues, mainly when applied in environmental analysis (Joan, 1995);

- ethical issues in the monetisation of environmental impacts (Sunstein, 2005);
- theoretical issues behind the construction of an anthropocentric framework that may fail to properly account for impacts that go beyond those mainly pertaining to human beings (Callicott, 1984); and
- the validity of some of the assumptions it rests on, such as the "ceteris paribus" clause (Vickerman, 2007).

While both MACCs and CBA aim to assess cost-efficiency, there are differences in the methods related to the type of portfolio that can be assessed (single project vs multiple) and the sectors it has been applied to. Firstly, CBAs can be carried out for single investments, whereas MACCs cannot. Using CBA, if the expected benefits exceed the expected costs, given no constraint, it should be reasonable to invest in such a project. MACCs, by contrast, require at least two projects for comparison. This could, for example, be the level of a carbon tax, and a single measure would be considered cost-efficient if the abatement cost is lower than this value. Secondly, CBAs have been performed widely (Pearce, 1998), including in transport (Annema *et al.*, 2017), medicine (Li *et al.*, 2012) and crime (Nagin, 2015). MACCs, in turn, experienced a shift towards predominantly environmental analysis in the early 90s (Mills *et al.*, 1991; Sitnicki *et al.*, 1991), and as they entail an energy-saving component, the application is more restricted, covering, for example, construction (Rosenfeld *et al.*, 1993), renewable energy (Olivier *et al.*, 1983) and fuels (Difglio *et al.*, 1990).

Given our research questions, using MACCs, therefore, is warranted. The section below describes methodological improvements we made in our model and a reflection on the discount rate.

3. Methodology, data and limitations

To construct MACCs, several data points are necessary, including a list of emissions reduction measures and costs. It rests on assumptions whose validity should be analysed to understand the robustness of the conclusions. Assumptions in such applications are mostly related to the measures' costs and the appropriate rate that should be used to discount these (Kesicki and Ekins, 2012).

Below, we describe our sample, followed by the costing method and discount rate.

3.1 The data set

Our data set consists of 109 projects financed under 14 green bonds whose proceedings have been awarded to 59 Swedish municipalities (Table 2). We focus on three of the eight green bonds' framework project categories: clean transportation, renewable energy and green buildings. We do so as these are the categories that report emissions reduction impacts. Using the annual reports from municipalities, we extracted the environmental impacts of the capital investments, expressed in avoided tons of CO_2-equivalents (Nordic Public Sector Issuers, 2020). These investments are reported to avoid about 405 thousand tons of CO_2-eq annually. We note that our data set comprises multiple projects within each category, thereby reducing bias.

Following the computation of the life cycle costs (LCCs) for each of the 109 projects (see below), we extracted each project's annual emission reduction capacities from the investment reports, measured in CO_2 equivalents. We computed the total lifetime emissions reduction capacity using each project's lifetime. Then, the ratio LCCs/total emissions

Category	No. of projects	Examples of use of proceeds (cities)
Clean transportation	3	Tram line extension (Lund), Electric buses (Umeå)
Renewable energy	21	CHP plant (Borås), District heating plant (Östersund), Wind park (Kalmar), Solar park (Gothenburg)
Green buildings	85	Nursing and care homes (Arboga), Office spaces (Hässleholm), Preschool (Lidköping), Residential housing (Timrå)
Total	109	About SEK 21bn were awarded by Kommuninvest for these projects (59 municipalities)

Notes: Table 2 provides an overview of the portfolio this study builds on. The categories are constructed as done by Kommuninvest. Projects in each category are counted, and examples are provided to clarify what type of measures fall into them

Source: Authors' elaboration

Table 2. Overview of our sample

reduction capacity sums up the cost efficiency of the projects funded using the green bonds' proceedings.

3.2 The costing of measures

The whole LCC provides a holistic view of the efficiency in reducing emissions. Municipalities, however, only report the initial capital expenditure for each project. Following an extensive literature review on each measure, we retrieved other input variables from articles dealing with these topics in Sweden to capture specific market features.

3.2.1 Clean transportation. Investments in electric buses are analysed considering the variables found in Borén (2020), which investigates the total costs of ownership of electric buses in the municipality of Gothenburg, Sweden [equation (1)]:

$$CapLCC = CAPEX_0 + \sum_{t=1}^{4}\left[\frac{O\&M_h + O\&M_p + EC}{(1+r)^t}\right] + \left[\frac{O\&M_h + O\&M_p + EC + ExB}{(1+r)^5}\right] + \sum_{t=6}^{10}\left[\frac{O\&M_h + O\&M_p + EC}{(1+r)^t}\right] \tag{1}$$

$O\&M_h$ (SEK/year)	$O\&M_p$ (SEK/year)	EC (SEK/year)	ExB	N (lifetime, years)
75,000	135,000	720,000	750,000	10

Source: Adjusted from Borén (2020)

The battery is assumed to be replaced after five years, halfway through the operational lifetime of the vehicles, generating an "extra-battery" cost (*ExB*). Each vehicle, again following Borén (2020), undergoes operational and maintenance services, which the authors consider either as "planned" ($O\&M_p$) or as "helping" ($O\&M_h$). Energy costs for the electricity on which the buses run are taken from the same paper. An LCC analysis for investments in public buses presents a main challenge given the issues with identifying the end-of-life costs for electric buses. Previous studies investigating LCC for electric buses assumed no residual value or overlooked the problem (Harris *et al.*, 2020; Lajunen, 2014, 2018; Nurhadi *et al.*, 2014; Borén, 2020). The only study we retrieved that provides insight into how to account for these costs, Yusof *et al.* (2021), suggests that the impact of end-of-life costs on total LCC is irrelevant. This could potentially explain the absence that we found in previous studies. We, therefore, compute the LCC for electric buses without considering the end-of-life costs.

To obtain the LCC measure for the expansion of tram lines in Lund municipality, we used a detailed report on this project commissioned by the municipality (Wilhelmsson and Ullberg, 2015). The report also introduces the assumptions and figures for the discount rate and the project's lifespan. As little academic literature is available on the LCC analysis of underground metro lines in Europe, we used these cost figures, calculated per meter of realised track, to evaluate the operational and maintenance costs for expanding Stockholm's metro system to Nacka.

3.2.2 Renewable energy – solar. The analysis of the investments in solar energy production is carried out following the approach by Kan *et al.* (2020) and adding the disposition costs that emerge at the end of the lifetime of the photovoltaic (PV) installations (Lindahl *et al.*, 2022). Initial investment, yearly fixed and yearly variable operation and maintenance costs are included in the computation of the LCC [equation (2)]:

$$LCC = CAPEX_0 + \sum_{t=1}^{N}\left[\frac{(O\&M_f + O\&M_v) * Y}{(1+r)^t}\right] + \frac{RES_C}{(1+r)^N} \tag{2}$$

$O\&M_f$ (SEK/kW/year)	$O\&M_v$ (SEK/kW/year)	Y (capacity)	N (lifetime, years)	Res_c(SEK/KW)
288	0	Project-depending	25	19

Source: Adjusted from Kan *et al.* (2020) and Lindahl *et al.* (2022)

The capacity of the solar energy installations, Y, is assessed using the green bonds reports and other sources made available either by the municipality itself through its website or by the municipality-owned companies that administer the project. The lifetime of the investment, N, reported above, is used as the default input variable value only if no more detailed information on the project's lifetime is provided in the reports. All the monetary variables, the fixed operational and maintenance expenditures, $O\&M_f$, the variable operational and maintenance expenditures, $O\&M_v$ and the residual costs, Res_c, are expressed in SEK, exchanged from the original currency using the rates provided by the Swedish central bank.

3.2.3 Renewable energy – wind. The investment analysis for wind energy production was carried out using a methodology inspired partly by the work of Siyal *et al.* (2016). The formula considers the necessary initial investment, the maintenance costs that emerge during the lifetime of the project and the SC at the end of the lifetime of the windmills [equation (3)].

$$LCC = CAPEX_0 + \sum_{t=1}^{N}\left[\frac{Yp * (O\&M_{wp}/(1000))}{(1+r)^t}\right] + \frac{SC}{(1+r)^N} \qquad (3)$$

$O\&M_{wp}$ (SEK/MWh/Y)	Y_p (production)	N (lifetime, years)	SC (SEK/MWh)
100	Project-depending	20	10% of $CAPEX_0$

Source: Adjusted from Siyal *et al.* (2016)

$O\&M_{wp}$ represent the unitary yearly expenditure in operational and maintenance services, which depends on the wind farm's production. N is the operational lifetime, which is assumed to be 20 years, following Siyal *et al.* (2016). This value is used as a default one, i.e. only in those cases where no operational lifetime estimate is provided in the official documentation produced by the municipalities. Y_p is the yearly energy, production and SC is the salvage cost.

3.2.4 District heating. District heating investments are treated following the approach found in Swing Gustafsson *et al.* (2018), assuming a residual cost of 10% of the initial capital investment [equation (4)], in line with what we found for the other sources of clean energy (solar and wind). This assumption is necessary as we found that residual cost is often overlooked by the literature (Hendricks *et al.*, 2016; Leurent *et al.*, 2018; Moser *et al.*, 2018) but is nonetheless relevant to perform a complete LCC analysis of the projects belonging to this category:

$$LCC = CAPEX_0 + \sum_{t=1}^{N}\left[\frac{O\&M * Y}{(1+r)^t}\right] + \frac{RES_c}{(1+r)^N} \qquad (4)$$

$O\&M$ (SEK/kWh)	Y	N (lifetime, years)	RES_C
0.015	Project-depending	40	10% of $CAPEX_0$

Source: Adjusted from Swing Gustafsson *et al.* (2018)

The approach takes into consideration the thermal output of the plant, Y, its lifetime, N, which is set to 40 years, following our source, as a default value, the operational and maintenance expenditure, $O\&M$, and the residual cost RES_c.

3.2.5 Green buildings. The methodology for an LCC evaluation of green building projects builds on commonly used figures on the LCC of buildings (Li *et al.*, 2020; Islam *et al.*, 2015; Biolek *et al.*, 2019). The end-life costs are estimated at 5% of the total LCC (Vázquez-López *et al.*, 2020), as there is no standard approach on how to treat end-of-life costs in the recent literature (Pernetti *et al.*, 2021; Moncaster and Song, 2012). The significant costs, including the initial investment, water consumption and energy consumption, are accounted for [equation (5)]:

$$LCC = CAPEX_0 + \sum_{t=1}^{N}\left[\frac{(O\&M + E_c * E_p + W_C * W_p) * Y}{(1+r)^t}\right] + \frac{RES_C}{(1+r)^N} \tag{5}$$

$O\&M$ (SEK/m^2)	E_C (KWh/m^2)	E_p (SEK/KWh)	W_p (SEK/m^3)	W_c (m^3/m^2)	Y (m^2)	N (lifetime, years)	RES_C
673	Project-depending	Energy prices	23.6	County-depending	Project depending	50	5% of LCC

Source: Adjusted from Li *et al.* (2020), Islam *et al.* (2015), Biolek and Hanak (2019), Vázquez-López *et al.* (2020)

Costs considered include operational and maintenance costs, which are taken from the analysis performed by SCB through a survey of house owners in Sweden (SCB, 2017); the cost of energy, whose current prices are provided by SCB (SCB, 2020); electricity price forecasts up to 2070 are provided by the Swedish Energy Agency (Energimyndigheten, 2021a), the cost of water (Petrović *et al.*, 2021) and the end-of-life costs; all the other figures depend on the individual projects. Water consumption, which is not reported by the municipalities in their green bonds reports, was estimated using data from SCB with historical series on annual household water consumption and the total size of the dwelling stock. This allows us to obtain the average municipal water consumption per square meter. This result is then used to compute annual water consumption in each building financed through green bonds. We recognise that this represents a conservative approach if one is willing to concede that green buildings, in their being more sustainable, present lower energy and water consumption.

3.3 The discount rate

We applied the discount rates used by different Swedish agencies, mapping each project in Table 2 against an agency and using the corresponding discount rate (Table 3).

We do so as this guarantees geographical appropriateness. From a temporal perspective, recent studies considered these rates valid (Campana *et al.*, 2020; Campana *et al.*, 2021;

Table 3.
Discount rates used by different government agencies in Sweden

Organisation	Main discount rate (%)	Rates for sensitivity analysis (%)
Swedish Environmental Protection Agency (EPA)	4	1, 2
Swedish Geotechnical Institute (SGI)	4	
Swedish Energy Agency	7–12	
Swedish Radiation Safety Authority	2	
Swedish Nuclear Fuel and Waste Management Company	2.5	
Swedish Forest Agency, valuation of forest property	2.5–2.8	
Swedish Forest Agency, cost-benefit analysis		3, 4
Swedish Transport Administration	4	
Swedish National Board of Housing, Building and Planning	4	

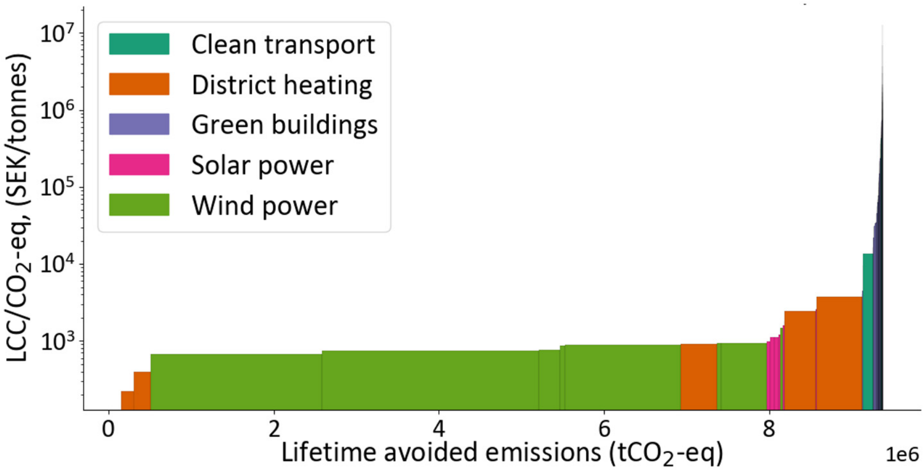
Notes: Table 3 summarises the findings of the research performed by Hansson *et al.* (2016) on the standard practices of Swedish agencies regarding the discount rates they conventionally use
Source: Authors' elaboration based on Hansson *et al.* (2016)

Yan and Salman, 2023). We used the lower bound discount rate for renewable energy projects, i.e. 7%, as it is the most conservative. This corresponds to an approach from the previous literature, i.e. using the carbon tax as a sufficient threshold to measure cost-effectiveness (Almihoub *et al.*, 2013; Hamamoto, 2013; Kesicki and Strachan, 2011; Morris *et al.*, 2012). A carbon tax threshold signals cost-effective measures, i.e. those measures that private and public entities will be willing to invest in because they represent a cheaper alternative to paying the tax (Kesicki and Strachan, 2011). By using a conservative discount rate, measures found to be cost-effective concerning the presence of a carbon tax will still be cost-effective under higher discount rates.

4. Results

Figure 1 shows the results of our analysis, visualised as the typical "stairs" appearance of MACC applications. Each of the rectangles represents a project and is ordered from left to right according to cost-efficiency, here understood as the lifetime costs over the lifetime capacity to reduce or prevent emissions. The X-axis represents the cumulative lifetime avoided emissions. The base of each rectangle is determined by the tons of CO_2-eq that the project will allow to avoid or to reduce over its whole life cycle. The height of the rectangle measures the unitary cost of such a reduction. The area of the rectangle, given by the product of its base, i.e. the lifetime emissions avoidance and of its eight, i.e. the unitary lifetime costs of reduction, returns the lifetime cost of the project.

Two conclusions can be drawn. Firstly, wind power projects have, by far, the most extensive base. That implies they have the largest lifetime capacity to avoid or reduce



Notes: Figure 1 presents the results from the MACC analysis. Every rectangle represents a project, and its measures represent the relevant characteristics for evaluating the cost efficiency and mitigation impact. The base of each rectangle gives the tons of avoided CO2-eq during the whole lifetime of the project. The height of the rectangles represents the cost-efficiency of the project and is measured in lifetime costs over lifetime avoided emissions. The rectangle's area is another measure worth paying attention to: the product of the base times the height of each of the rectangles, i.e. its area, returns the LCC of the projects

Source: Authors' elaboration

Figure 1. Marginal abatement cost curves results (logarithmic scale on the ordinate axis)

emissions. Secondly, wind projects display the most significant areas, i.e. the most expensive projects financed by the Swedish municipalities through the green bonds scheme. Projects in the district heating category also show a large rectangular area, implying significant investments. Green building projects, while representing, by far, the largest share of projects in the portfolio, have a limited impact on emissions. Overall, the two most cost-efficient projects, in terms of LCC per avoided CO_2-eq, belong to the category of district heating, followed by the totality of wind power generation and solar power projects. Clean transport projects are less cost-efficient and green buildings are the least cost-efficient.

We find some heterogeneity in the results (Table 4), with district heating experiencing the most extensive proportional range (ratio of max to min). The two most cost-effective district heating plants have a production strictly limited to heat, while the other three are combined heat and power (CHP) plants. CHP plants are comparable to wind power production projects in terms of cost efficiency. The two most cost-efficient investments in wind energy production coincide with the two largest installed capacities (Mullbergs Vindpark and Hocksjön Vindpark) and the lowest cost efficiency observed in the wind park with the smallest installed capacity (Kalmar). Investments in clean transport solutions are not as competitive. The expansion of Stockholm's metro to Nacka is the most cost-efficient measure in this category, followed by investments in bus electrification. In Sweden, about 77% of the buses in the public transport fleet are classified as Euro 6 buses, the highest possible ranking in the EU scheme for environmental impact assessment of vehicles, and 22% as Euro 5 buses (Svensk Kollektivtrafik, 2022), making the marginal impact of new electric buses, when compared to such a low-carbon fleet, smaller. Green building projects are estimated to be the least cost-efficient abatement measures financed by Swedish municipalities through proceedings of green bonds.

5. Discussion

Compared to previous literature, we do not find substantial regional heterogeneity in the cost-efficiency of the projects (Wu and Ma, 2019), and our findings that clean energy measures rank among the most cost-efficient align with other studies. For instance, new burners in the district heating systems are highly cost-efficient, confirming the work done in Leeds City Region by Gouldson *et al.* (2012).

For wind production, as most of the municipalities in our sample invested in large-scale, out-of-city wind energy parks, the comparison is more difficult as urban installations happen to be on small scales (Gouldson *et al.*, 2012). Compared to the previous literature (Siyal *et al.*, 2016), we do not find any influence of geographical position on the cost-efficiency of wind power projects. Economies of scale and the purchasing agreements (as, for

Cost-efficiency per avoided CO_2-eq overview	Mean	Min	Max
District heating	SEK 1,871/tCO_2-eq	SEK 221/tCO_2-eq	SEK 3,747/tCO_2-eq
Wind power	SEK 771/tCO_2-eq	SEK 674/tCO_2-eq	SEK 1,466/tCO_2-eq
Solar energy	SEK 1,251/tCO_2-eq	SEK 985/tCO_2-eq	SEK 2,602/tCO_2-eq
Clean transportation	SEK 22,460/tCO_2-eq	SEK 13,620/tCO_2-eq	SEK 54,827/tCO_2-eq
Green buildings	SEK 165,621 /tCO_2-eq	SEK 4,076/tCO_2-eq	SEK 12,596,093/tCO_2-eq

Table 4.
Mean, min and max cost-efficiency per avoided CO_2-eq ratio

Notes: Table 4 reports the marginal abatement costs summary statistics, mean, minimum and maximum values, across the project categories
Source: Authors' elaboration

example, found in Schauf and Schwenen, 2021) may explain the results that come from investments in wind energy production: municipalities are allowed to claim ownership of large wind parks that fall outside of their geographic borders and can exploit the capacity and the dimension of these parks to generate economies of scale. We support Lindahl *et al.* (2022) for solar energy production, who question some assumptions concerning this technology's economic ROI. For solar, while it seems that Sweden has a low potential for solar energy production, especially in its northern part (Bódis *et al.*, 2019; Prăvălie *et al.*, 2019; Martinopoulos, 2020), we observe that PV adoption in the country is increasing and will likely continue to do so in the coming years. Its adoption might be motivated by access to spot energy markets and a green certificates market in Sweden (Bódis *et al.*, 2019; Prăvălie *et al.*, 2019; Martinopoulos, 2020; Lindahl *et al.*, 2022). Östersunds Solpark, as an example, is registered as an entity entitled to the issue of green certificates (Energimyndigheten, 2021b), and access to such a market may contribute to making the case of investing in this technology more economically attractive. Household PV uptake could also be motivated by the structure of the incentives scheme and a potential peer effect (Mundaca and Samahita, 2020).

Rail electrification and the construction of new railway stations are the least cost-effective measures among those analysed by Gouldson *et al.* (2012), who focus on an urban setting as we do. In our sample, we found a small number of projects related to rail transportation, as this responsibility is governed at other levels (European Committee of the Regions, 2019). The low cost-efficiency of green buildings could be due to the stringent energy standards set by Boverket, the Swedish National Board of Housing, Building and Planning (Boverket, 2019). In Sweden, standards are about 15% more restrictive than in Norway and Finland for single-family houses and 10% for multi-family buildings (Allard *et al.*, 2021), making them less attractive as the benchmark to be compared is lower than elsewhere. The national standards represent the benchmark the Position Paper on Green Bonds Impact Reporting (Nordic *et al.* Issuers, 2020b) indicates for green bonds issuers. However, the average 2020 energy consumption of single-family houses, apartment buildings and premises was substantially above the standards set by Boverket (Energimyndigheten, 2022a), which could make this category of investments more cost-effective if compared to the current average energy consumption and not to Boverket's regulation. In addition, the GHG emission intensity of electricity production is low in Sweden (Scarlat *et al.*, 2022). It could result in lower emissions savings during the construction and use phase of a green building when energy savings constitute a significant driver of the reduction in emissions. Moreover, environmental impact reporting only considers Scopes 1 and 2 emissions. The use of sustainable materials, fossil-free construction machinery and equipment, sustainable waste management procedures and other initiatives that would help reduce the overall carbon footprint of the buildings are not accounted for by the municipalities when reporting on the emissions impact. While we found green buildings to represent the least cost-effective projects municipalities have invested their proceeds from green bonds into, it must be acknowledged that financial schemes are in place to provide the right incentives to improve the cost-efficiency of green buildings in Europe. Previous research has found regions, municipalities and other local authorities in the EU to be in an excellent position to make the best use of the European structural and research funds to create financial schemes to enhance the process of energy reduction in the real estate sector (Economidou *et al.*, 2023).

Using the Swedish carbon tax at €128 per ton of CO_2-eq as a threshold to define cost efficiency (Andersson *et al.*, 2018), 14 of the renewable energy projects financed by the municipalities would represent convenient alternatives. That is, 14 of the projects represent a reasonable economic alternative to paying the tax: the abatement of the emissions has an LCC cost lower than the cost of paying the carbon tax. In this sense, the current carbon tax price represents a compelling incentive for investments in renewable energy. It does not, however, at the current price, provide the necessary incentive for investments in clean public transportation.

Compared to emerging technologies, such as carbon capture and storage (CCS) and bio-energy carbon capture and storage (BECCS), which has a marginal cost of around €45–€125 (Beiron *et al.*, 2022), wind energy production seems to be cost-competitive, as do three of the measures about district heating and the solar energy projects in Gothenburg, Kristianstad and Östersund. If ship transport and CO_2 storage costs for industrial CCS and BECCS were included, the range of marginal abatement costs for this technology would hover between €80/t CO_2 and €135/t CO_2, meaning that the measures in the energy production, i.e. solar, wind and district heating, are competitive with CCS and BECCS (Beiron *et al.*, 2022; Johnsson *et al.*, 2020). The analysis of MACCs performed by Bauman *et al.* (2008) suggests that this methodology may underestimate the actual costs of production process innovations. Moreover, the future development of costs in the clean energy sector may further hinder the support of CCS or BECCS on economic grounds (Grant *et al.*, 2021). On top of these, an accurate analysis should also consider the biased rhetoric promoted by certain actors (Gunderson *et al.*, 2020).

In sum, the most cost-efficient options found through the proceedings of the green bonds scheme are those involving heat-only district heating systems or CHP generation systems, subject to economic instruments supporting this second typology. Current energy prices do not make CHP competitive enough, and the expected increase in renewable energy production, especially from wind, might further reduce the economic competitiveness of such a means of production (Pääkkönen and Joronen, 2019; Helin *et al.*, 2018; Skytte *et al.*, 2017; Romanchenko *et al.*, 2017). The only way in which CHP can challenge the cost-competitiveness of heat-only boilers is either through the introduction of subsidies for this technology or with energy prices high enough to make it competitive with the levelised cost of electricity that is currently observed in renewable energy production (Haq *et al.*, 2020). While the recent energy crisis in Europe has not left Sweden unaffected, energy prices in the country were, still are and are expected to remain much lower than in the rest of Europe. As the peak in prices was already flattening down in the first week of 2023 compared to the maximum of 2022, it is unlikely that such a momentary stimulus may make investments in the least cost-effective district heating energy production more attractive (Energimyndigheten, 2023). District heating is a market that mainly pertains to the Nordics, with Sweden, Finland and Denmark constituting the core of the European market (Bertelsen and Vad Mathiesen, 2020). However, the financial obstacles, mainly in capital-intensive upfront investments, are often found across the continent (Colmenar-Santos *et al.*, 2016). To account for these financial issues, recognising that current investments in district heating infrastructure in Sweden are not optimised, the Swedish Energy Agency has developed a platform to help business better manage their investment decisions in this sector (Energimyndigheten, 2022b).

The results we present here on the cost-efficiency of several abatement measures also highlight a dilemma that was already recognised long ago in the literature: decreasing marginal benefits from environmental policies (Schöb, 1996). As an economy becomes less carbon-intensive, future investments become less cost-efficient as marginal benefits decrease. For instance, as the public transport fleet gets cleaner with new investments, the purchase of additional electric buses does little to reduce the emissions from public transport further. In low-carbon societies, this type of investment might be hard to justify. Such a reflection should also warn against the external validity of the findings from this paper.

Overall, the figures produced here cannot be used alone to understand the relevance of investing in the measures. One missing aspect of using MACCs is the dynamic interaction and the level of dependence among the funded measures. Currently, in most Swedish cities, emissions from transport are a substantial contributor to overall GHG emissions (Naturvårdsverket, 2022). Focusing solely on clean energy production and not on the less cost-efficient public transport buses would not aid cities in achieving climate neutrality targets. It is also to be noticed that some of the policies expected to significantly contribute to reducing emissions from the transport sector may be market-based, such as taxes, and present no need for capital investments from the municipalities (Tikoudis and Oueslati, 2023). These initiatives would then fall outside of the list of those funded by municipal governments. Focusing on one single set of measures may also pose the risks of unexpected reactions by some industry sectors and generate dynamics that hinder the achievement of the emissions reduction goals (Ustyuzhanina, 2022). In addition, the EU legislation has already encouraged local authorities to increase their focus on specific sectors such as sustainable public transport (European Parliament and The Council of the European Union, 2014). Increased pressure on this matter can be expected with the recent provisional deal to review the fit for 55 packages (Council of the European Union, 2023). Such pressure from the overarching authorities may limit the freedom of local governments to decide on what measures to prioritise. And the attractiveness of less cost-efficient measures may be increased by the adoption of a portfolio approach (Drake and Fabozzi, 2010).

MACC graphs also constitute an efficient tool for policymaking: decision makers can set a cost-efficiency threshold and then identify those measures that can be financed within its limit and use the figures produced here. This threshold can be identified through discussion with stakeholders or using the carbon tax or other cost-efficiency criteria as a reference point. All those measures whose abatement costs are lower than that would then be deemed cost-efficient under such an approach. A visualisation of this idea is provided in Figure 2: as we set a price of about SEK 800 per ton of CO_2-eq, we identify district heating and wind power projects to be the ones to focus on. It is evident that such an approach only relies on financial considerations and fails to account for other aspects that may be relevant in the decision-making process. Alternatively, a municipal government could map the emissions generated in the city, identify the connections between different areas (e.g. transport and energy production) and bundle measures that are deemed less cost-efficient with the more cost-efficient ones to attract investors to the portfolio (see, e.g. Amighini *et al.*, 2022 on portfolio management of the green climate fund).

6. Conclusion

We constructed MACCs using the green bonds' reports produced by Swedish municipalities and Kommuninvest, the voluntary financial vehicle of Swedish municipalities and regions, to investigate the cost efficiencies of 109 projects funded under 14 green bonds issued by 59 municipalities. Identifying mitigation project lifecycle costs and emissions will help municipalities make better financial allocation decisions. It will help those who make sustainability-linked bonds a part of their climate strategy with finance budgeting. We find investments in clean energy production, i.e. large-scale wind, solar and district heating, to be the most cost-efficient as measured in LCC per ton of avoided CO_2-eq. These measures are also found to constitute attractive alternatives to other options such as CCS and BECCS. The Swedish carbon tax at its current level provides the right incentive to invest in these projects and transition away from fossil fuels in the energy industry. Clean transport, i.e. electric

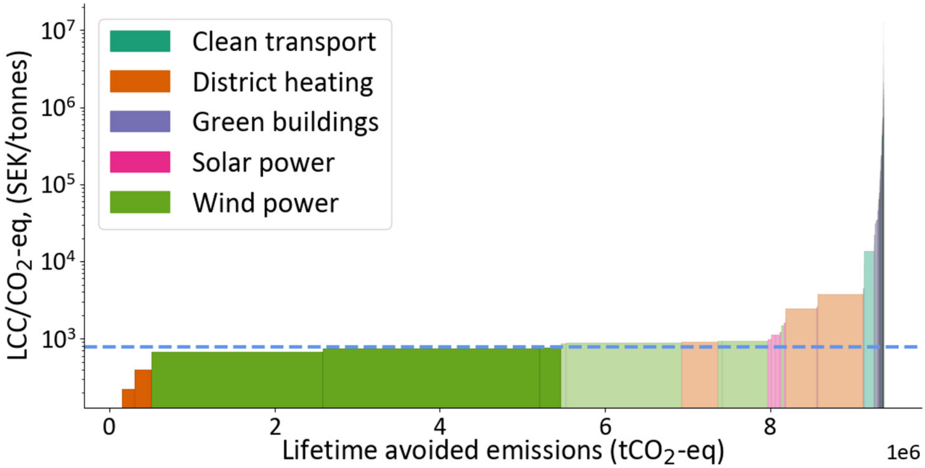


Figure 2.
Graphic identification of cost-effective measures

Notes: Figure 2 represents a potential policy use of the MACC methodology. By adjusting the carbon tax, whose level is represented here by the dashed lines, the government can influence the cost-efficiency considerations around implementing the measures. The projects with a marginal cost higher than the carbon tax, here represented in shadowed colours, are not cost-efficient in the sense that the payment of the carbon tax would represent a cheaper option
Source: Authors' elaboration

buses, expansion of the metro lines in Stockholm and the expansion of the tram service in Lund are found to be less cost-efficient, and so are green buildings investments.

Our conclusions on some of the measures, such as solar energy, question the effectiveness of such investments in Sweden and identified green certificate markets as a possible explanation thanks to the possibility of generating profits. However, to become climate-neutral in cities, municipalities should tackle emissions in all sectors, warranting less cost-effective measures to be funded. Such a necessity would then call on the understanding that while each project is presented and reported individually, its impact will also affect other projects. Bundling different projects into a portfolio could allow them to attract investors and generate a return that financial investors may be willing to accept.

In our analysis, a limitation is that municipalities only report on Scopes 1 and 2 emissions (Nordic Public Sector Issuers, 2020). Further research will be needed to investigate to what extent the inclusion of direct and indirect emissions in the impact reporting may change the narrative of the results presented here. A holistic approach that considers all the GHGs, all the emissions across Scopes 1, 2 and 3 and the entire LCC of the projects would represent the most complete analysis to understand their cost-efficiency.

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