Summer 2020

Electrification and Decarbonization for Mid-sized Municipalities: A Case-study Marginal Abatement Cost Analysis

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By

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Accepted in Partial Completion
of the Requirements for the Degree
Master of Arts

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Electrification and Decarbonization for Mid-sized Municipalities:
A Case-study Marginal Abatement Cost Analysis

A Field Project
Presented to
The Faculty of
Western Washington University

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August 2020

Abstract

This project provides a marginal abatement cost curve analysis for the City of Bellingham, based upon the recommendations provided by the City's Climate Action Plan Task Force. A bottom-up methodology for performing the marginal abatement cost analysis is provided, including the relevant data and assumptions used in the analysis. The results show the massive potential emissions impacts of electrification and driving down the electric grid emissions intensity. The shortcomings and improvements of the resultant cost curves are discussed, and advice on future iterations is given. This project offers a pathway for Bellingham and other mid-sized municipalities to develop marginal abatement costs analyses as they pursue climate action and decarbonization in their communities.

Acknowledgments

First, I would like to acknowledge my committee members, Charlie Barnhart and Joel Swisher, who offered their invaluable depth of expertise, and willingness to learn alongside me as this project developed.

I would also like to acknowledge the Bellingham Climate Action Plan Task Force 2018-2019 Members: Christine Grant, Derek Long, Don Goldberg, Erin McDade, Jill MacIntyre Witt, Lynn Murphy, Mark Schofield, and Rick Nicholson. This work would not exist if not for this group of dedicated individuals who offered countless volunteer hours to the Bellingham community and provided an example of how bold climate and energy policy is accomplished at a local level.

I also want to acknowledge the City of Bellingham staff that supported the task force; Renee LaCroix, Mark Gardner, and Clare Fogelsong, and the Kulshan Services team; David Roberts, Allison Roberts, and Nathan Rice. Not only did they help to support the Task Force but also myself as I leaned on their expertise and resources.

Finally, I want to thank all of the faculty and staff of the Institute for Energy Studies at WWU. Without them, I would not have the skills or passion to pursue a project like this.

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List of Acronyms

MAC – Marginal Abatement Cost

GHG – Greenhouse Gas

CAP – Climate Action Plan

CATF – Climate Action Task Force

CO_2e – Carbon Dioxide Equivalents

kWh – Kilowatt-hour

MWh – Megawatt-hour

VMT – Vehicle Miles Travelled

EV – Electric Vehicle

CRF – Capital Recovery Factor

CAPEX – Capital Expenditure

OPEX – Operational Expenditure

CSE – Cost of Saved Energy

LCOE – Levelized Cost of Electricity

IOU – Investor Owned Utility

PSE – Puget Sound Energy

Introduction

This project, in collaboration with the City of Bellingham (COB) Climate Action Plan Task Force, provides a Marginal Abatement Cost (MAC) Curve analysis for several proposed climate action and greenhouse gas (GHG) mitigation measures. The MAC curves and analysis are intended to inform Bellingham policymakers, guiding action to help achieve the City's climate action goals. Marginal abatement cost curves compare low-carbon technologies' or strategies' abilities to mitigate GHG emissions and their associated economic costs for avoiding additional units of GHG emissions. MAC curve analyses from cities similar in scope to this project were used to inspire the bottom-up methodology that was developed. The main components include calculating the costs and emissions abatement potentials of the climate action measures compared to the chosen reference scenario. This report presents the methods for constructing MAC curves and develops a guide for other local jurisdictions to follow in providing a MAC analysis for municipal climate action. The curve produced in this project is specific to Bellingham's climate action goals, however, it is not unlike others in the literature and elsewhere, and can be readily applied in other locations.

Marginal Abatement Cost Curves

Multiple analyses have applied MAC curves at a variety of scales, including global (Per-Anders Enkvist et al., 2007), national (Chen, 2005), city (Ibrahim & Kennedy, 2016), and even specific sectors of an economy (Peng et al., 2018). Currently, there is limited academic literature that focuses on the use of MAC curves at the small-to-midsize city scale, however, the general methodologies can still apply. Through this review of the literature, the applicability, limitations, and considerations for methods development of MAC curves are discussed, which were used to best inform the development of this project.

Applicability

Marginal Abatement Cost Curves have been widely used to inform climate and energy policy, as they show both the cost and the total abatement potential for GHG mitigation efforts. MAC curves are a visually informative tool that show the potential costs, and savings, of implementing a low-carbon strategy compared to the business-as-usual scenario. Typically, MAC curves are developed for entire countries, specific economic sectors, or used to show the effects of placing a price on emissions or emissions trading schemes (Moran et al., 2011; Per-Anders Enkvist et al., 2007; Shukla, 1995). Although academic literature and other case-studies on MAC curves produced for local scales are lacking, work is emerging aligning with the notion that cities can help lead the charge on climate policy and save money whilst pursuing low-carbon pathways (Kousky & Schneider, 2003). In developing a reliable MAC curve, Huang et al. (2016) recommend working alongside stakeholder groups to help limit the use and misuse of assumptions and improve the transparency and acceptance of the results (Huang et al., 2016). In the development of this project, I worked alongside the Bellingham Climate Action Task Force, and the workgroups connected to it, including local energy utilities, companies, consultants, and government departments. These relationships helped to garner much of the necessary data needed to produce a reliable MAC curve and further refine the strategies analyzed.

Limitations

Given the complex nature of how marginal abatement cost curves can be produced, and the variety of different measures, sectors, and stakeholder groups involved, there have been some criticisms of how they are presented in the literature. Fischer & Morgenstern (2006) investigated the wide range of estimates that arise when comparing MAC curves to others, noting that the significant variation in results from similar mitigation measures can draw concern. There are recurring critiques of MAC curves in the literature that include issues relating to the assumptions used, lack of transparency, practicality, and the considerations of external costs (Kesicki & Ekins, 2012). Since MAC Curves rely on time-dependent data, they can only tell the story of the years represented in the curve, based on data available at the time they were constructed. They cannot accurately reflect future scenarios unless they are refined and updated as time goes on. In order to combat this shortcoming of MAC curves, (Ibrahim & Kennedy, 2016) suggest updating MAC curves alongside that of government greenhouse gas inventories to keep them relevant and successfully informative. This project intends to offer a pathway for Bellingham and other communities to be able to re-apply and refine this methodology to construct MAC curves as they develop their climate action policies and planning into the future.

MAC curves are also sensitive to discount rates, along with electric and fuel prices. The latter can fluctuate significantly with time, so the best practice is to clearly identify which prices are being used in the calculations and from when they were recorded. Further, MAC curves do not directly include external costs or ancillary benefits, such as the costs of continued environmental damage, energy security, or health effects. Assessing the emissions abatement potentials of measures depends upon the model used for greenhouse gas emissions forecasting. To overcome these limitations, (Kesicki, 2011) recommended including ancillary benefits when and where possible, and clearly representing any of the uncertainties in doing so. As such, where relevant, this project intends to report on ancillary costs and benefits associated with the mitigation measures not represented in the MAC analysis.

As with other economic tools, MAC curves have their shortcomings; however, these can be lessened by clear identification and explanations of the assumptions and methods used to derive the cost curve. This research project aims to be clear in what the MAC curve does and does not represent and be explicit in describing the methods that were used to develop the curve. As such, a supplementary information document has been included to fully list data sources, assumptions, and other details behind the development of the curve, beyond what is found in the methods section.

Considerations in Methods Development

The literature provides a look into the many different approaches for constructing MAC curves, and the limitations associated with these different methods. There are some important things to consider when building a methodology for creating a MAC curve, and here these elements are investigated, including; data, calculations, reliability, and the use of assumptions.

Due to the fact that MAC curves rely upon estimations of future scenarios and cover wide economic sectors, estimated and assumed points of data are often necessary for performing calculations and constructing models. Ahmed Ali Almihoub et al., (2013) mention that the use of actual data instead of relying heavily on estimations can go a long way in helping to make the resulting MAC curve more reliable. For the sake of this project, the smaller-scale made reliability more manageable in terms of the gross amount of data that needed to be collected and analyzed. Further, as Ibrahim & Kennedy (2016) did with their Toronto case study, it has been made clear where the data and inputs came from and whether it is available publically. Some of the mitigation measures in this analysis benefitted from having more available data draw on than others, making some more reliable than others.

In addition to data clarity, this project intended to include Scope 3, or Life Cycle Assessment (LCA), emissions data into the calculations for building Bellingham's MAC curve, when and where appropriate. LCA data was not available for each measure, but there are national studies that were used for some common technologies, like solar photovoltaics and wind turbines. Stokes et al. (2014) used LCA data in the MAC Curve they developed for water-saving technologies. Currently, there is a lack of consideration for LCA data in MAC curves and other climate policy as it can be complex and difficult to factor in. When considering the life-cycle costs and impacts, a different prioritization mix can result in the MAC curve, which can shed light on some potential hidden associated emissions of implementing some measures. By including this element in the development of the methods this project hopes to further bolster the reliability of the resulting MAC curve and future developments of this kind of analysis. Through considering the data used, LCA factors, and adequate accounting of the methods for deriving the MAC curve for this project, the hope is that some of the common criticisms of MAC curves can be overcome to avoid this work being considered unreliable and that these considerations be applied in future iterations of this kind of analysis.

Conclusion

To summarize, MAC curves make for informative policy tools, especially when it is clear in how they were developed. The literature on the subject provides many cautions in terms of how MAC curves are derived and how they are used. This project has aimed to be considerate of these cautions and form a transparent methodology to best avoid the limitations and reliability issues of MAC curves. In developing a MAC curve for Bellingham, this project has built upon existing literature and tailored methods to city-focused climate action in general and to the City of Bellingham in particular.

Background

The Bellingham Climate Protection Action Plan

In 2007, the City of Bellingham passed resolution 2007-10 which adopted greenhouse gas reduction targets and set to develop its first Climate Protection Action Plan to achieve those targets (City of Bellingham, 2007). This document has since been updated several times and guided the City's climate action efforts. The Climate Action Protection Plan includes a greenhouse gas inventory and a collection of mitigation measures to reduce the city's emissions divided between municipal and community-wide measures. The measures are separated into six main categories: Energy Efficiency and Conservation, Transportation, Renewable Energy, Green Building, Land Use, and Waste Reduction. The latest iteration of the Plan was updated in 2018 and served as the starting point for the Task Force work, and as a data resource for the development of this project.

COB Resolution 2018-06-01

In May of 2018, the Bellingham City Council passed Resolution No. 2018-06 which adopted new targets for renewable energy and formed the Climate Action Plan Task Force to recommend measures to help meet the new goals. As stated in the resolution, the greenhouse gas reduction ambitions are as follows:

- “100% renewable energy for municipal facilities (electricity, heating, transportation) by 2030.”
- “100% renewable energy use for the Bellingham community’s electricity supply by 2030.”
- “100% renewable energy for community heating and transportation by 2035.”

As per the Resolution, a limited-term Community and Staff Climate Action Plan Task Force was formed with the following directives:

- “Adopt a triple bottom line plus technology philosophy.”
- “Determine feasibility, costs and impacts of the 100% renewable energy ambitions.”
- “Develop 100% renewable energy targets.”
- “Identify funding mechanisms and develop a plan to achieve the Task Force’s recommended 100% renewable targets.”
- “Develop accelerated greenhouse gas emissions targets for the Council to consider for adoption.”
- “Identify policy considerations to attain accelerated targets.”

The Task Force was to consist of no more than 12 members appointed by the Mayor and confirmed by the City Council, including up to six community members with background or expertise in relevant fields. One member was to represent the energy utilities, one member to represent public transportation, and up to six representing City departments. Finally, the Resolution stated that the City Council would consider adopting the Task Force recommendations in the 4th quarter for 2019, including policies to accelerate the Climate Action Plan greenhouse gas reduction targets and 100% renewable energy targets (City of Bellingham, 2018).

Targeted Sectors

Despite the ambitions of the City Council resolution and the goals of the Task Force, the Task Force was not able to devote enough time and expertise to tackle all sectors of Bellingham's economy in full. Early-on in their process, the Task Force decided to focus on the sectors that they could most effectively make sound recommendations for, and that included proven commercially available technological options to pair with many of the measures. The residential and commercial sectors were in the focus of the Task Force and therefore the scope of this MAC analysis project. This included measures directed towards residential and commercial building efficiency and electrification, and transportation electrification within city limits. City land-use measures were also an area that was explored, although only to a limited extent. The energy supply serving Bellingham was also addressed, although the recommendations did not fully address electrification outside of residential and commercial buildings. The main sectors that fell out of the scope of the Task Force's purview included recommendations to decarbonize industrial buildings and operations and aviation from the local airport.

Methods in Detail

Climate mitigation measures are unique in several aspects: capital costs, financing (*e.g.* discount rates and capital recovery factors), operation and maintenance costs, variable fuel costs, fuel sources, emission factors, efficiencies, lifetimes, and more. This leads to myriad formulations that are specific to each measure. The following is an effort to generalize calculating the marginal abatement costs and emissions reduction for any given measure and provides a framework for doing so. More specific details about the calculations for any particular measure analyzed in this project can be found in the Supplementary Information tables within the appendix.

Equation (1)

The equation to calculate the abatement potential of a measure is found in equation (1).

$$GHG\ Abatement = \frac{Emissions\ Reductions}{Lifetime} \times Target\ \times Unit\ \times Pop \tag{1}$$

Target: Number of years to reach the climate target.

Unit: Measure units in the population.

Pop: Applicable proportion of the population to which the measure is applied.

Equation (2) will result in the cumulative abatement potential of all of the measures plotted on the curve.

$$GHG\ Cumulative = \sum_{MM=1}^{N} GHG\ Abatement_{Measure} \qquad (2)$$

N: Number of measures to reach the target

MM: Mitigation Measure

Equation (3)

To derive the cost-effectiveness of a measure, equation (3) and the following intermediate calculations need to be performed.

$$\frac{\$}{CO2e} = \frac{\Delta\ Cost}{\Delta\ GHG} \qquad (3)$$

Δ Cost: Change in costs from the mitigation measure to baseline scenario (measure – baseline).

Δ GHG: Change in emissions from the mitigation measure to baseline scenario (baseline – measure).

The numerator in equation (3) can be derived through equation (4).

Equation (4)

$$\Delta\ Cost = Incremental\ Captal\ Cost_{Measure} + \sum_{t=0}^{L} Incremental\ Benefits_{Measure}\ (t) \qquad (4)$$

L: Lifetime of the measure or technology, in years.

t: Year.

Equation (5) will result in the incremental (or marginal) capital cost of the measure.

$$Incremental\ Capital\ Cost = Capital\ Cost\ of\ Measure - Capital\ Cost\ of\ Reference \quad (5)$$

Equation (6) yields the incremental (or marginal) benefits, with discounting included.

$$Incremental\ Benefits = \sum_{t=0}^{L} \big(Operating\ Costs(t) - Savings(t)\big) \times \frac{(1+i)^L - 1}{i(1+i)^L} \quad (6)$$

i: Discount rate.

Equation (7) finds the difference in the operating costs from the measure to the baseline scenario.

$$Operating\ Costs = \left[Operating\ Costs_{Measure}(t) - Operating\ Costs_{Reference}(t)\right] \quad (7)$$

Equation (8) finds the savings result from reduced energy consumption or fuel switching of a measure.

$$Savings = [EC_{BE,Reference}(t) - EC_{BE,Measure}(t)] \times P_{BE} - EC_{AE,Measure}(t) \times P_{AE} \quad (8)$$

ECBE: Energy consumption of baseline energy

ECAE: Energy consumption of alternate energy

PBE: Price of baseline energy

PAE: Price of alternate energy

Finally, equation (9) gives the denominator for equation (3), by comparing the energy consumption and associated emissions factors for the measure and baseline scenario.

Equation (9)

$$\Delta\, GHG = \left[\left(\left(EC_{BE,Reference} - EC_{BE,Measure}\right) \times EF_{BE}\right) - \left(EC_{AE,Measure} \times EF_{AE}\right)\right] \times L \qquad (9)$$

EFBE: Emissions factor of baseline energy

EFAE: Emissions factor of alternate energy

Data

The table below includes some of the major inputs and assumptions used for many of the MAC calculations presented. The following section goes into additional detail on each of the plotted measures. More information covering the inputs and assumptions can be found in the Supplementary Information tables within the appendix.

Variable	Value	Units
Residential Electric Rate	\$0.09	\$/kWh
Residential Natural Gas Rate	\$1.00	\$/therm
Gasoline Price	\$3.00	\$/gallon
Bellingham Population	89,405	people
Population Growth Rate	1.44%	percent
Vehicle Miles Travelled	600,231,185	miles per year
Grid Emissions Intensity	258.6	Kg CO_2e/MWh

Table 1: Global Data and Assumptions

Mitigation Measures Data and Assumptions

This section outlines each Task Force recommendation that was analyzed in this MAC project, and the major assumptions used for each. Additional information on the data, assumptions, and intermediate results can be found in the Supplementary Information tables within the appendix. For all of the Building and Transportation measures below, two scenarios were calculated: the effects of the measure with the 2018 electricity grid emissions intensity and the effects of the measure with a 100% renewable grid. Unless specified otherwise, all dollars are in USD and a 5% discount rate is used.

Building Measures

The following two measures were divided into space and water heating respectively, with the sectors, residential and commercial, combined and averaged together.

Measure B4/B5 from Climate Action Task Force Final Report

Electrifying Space Heating in Residential and Commercial Buildings

The main assumptions used for calculating the MAC for these measure's scenarios were fuel prices of both natural gas and electricity (found in Table 1), and the efficiencies of the two different technologies. For the baseline case natural gas furnace, 95% efficiency factor was used and for the mitigation measure heat pump technology, 340% was used. The capital recovery factor for this calculation was based on the lifetime of the two heating technologies as referenced by the warrantied life of the products.

This MAC doesn't take into account the additional benefit of also having air conditioning available from the heat pump or the additional costs of natural gas pipe infrastructure for new construction. Also left out of the financial analysis is the health benefits associated with not combusting natural gas in the home (Singer et al., 2017).

Measure B4/B5 from Climate Action Task Force Final Report

Electrifying Water Heating in Residential and Commercial Buildings

As with space heating, the main assumptions for this measure were fuel prices and the efficiencies of the two technologies. A 68% efficiency was used for the natural gas water heater and 355% for the heat pump water heater. As with space heating, the CRF was calculated based on the warrantied lifetime of the products. Once again, health benefits and gas pipeline infrastructure costs are not included.

Measure B6 from Climate Action Task Force Final Report (See Energy Supply Below)

On-site renewable energy generation or participation

The renewable energy measures within the building section of the Climate Action Task Force Final Report were not analyzed separately from the Energy Supply measures. To avoid risks of double-counting and other uncertainties, the MAC analysis for these measures is represented in the analysis for the Energy Supply section measures focused on increasing renewable energy capacity.

General Lighting Efficiency

LED Lighting Upgrades

This measure was not directly included in the Climate Action Task Force Final Report, it is however similar to measures found within the 2018 Climate Action Plan. It was included as a proven and common technology within building efficiency and can act as a calibration to reference against the other measures.

The key assumptions for this mitigation technology were that lighting needs would be equivalent and that the electricity costs would be the same. The capital costs and efficiencies were derived from current market references. It was assumed that there were negligible rebound effects that would result in increased consumption by switching to the more efficient technology. The capital recovery factor was again derived based on the lifetime of the two technologies.

Measure B1/B2 from Climate Action Task Force Final Report

Residential Building Efficiency

These measures were combined into an average building efficiency MAC analysis covering both owner-occupied and rental occupied housing. From a policy perspective, the differences in addressing energy efficiency in these two categories are significant, however, these discrepancies were too nuanced to capture in the MAC analysis, hence them being combined and averaged here for the entire residential sector.

For this analysis, the average incremental costs and energy savings assumptions were based on data from 500 Bellingham weatherization projects completed through the Community

Energy Challenge, as reported in the Final Task Force Report (City of Bellingham, 2019). Energy savings are represented in kilowatt-hours, although likely also include energy saved from reduced natural gas usage. The incremental costs also include the average savings from available rebates and incentives from the Community Energy Challenge and the local energy utilities, Puget Sound Energy and Cascade Natural Gas Corporation. For the city-wide scenario, it was assumed that these average efficiency savings could be applied to 50% of the 2018 building stock by the year 2035. The capital recovery factor for this measure was derived assuming the rates from a home equity line of credit (HELOC) loan at 5% for 10 years.

Transportation Measures

The first eight measures from the Transportation section of the Climate Action Task Force Final Report were summarized in the MAC analysis as a general vehicle electrification measure for the entire city community since the eight measures are designed to ultimately set the city on a path to meet resolution targets through supporting vehicle electrification.

Measure T1-T8 from Climate Action Task Force Final Report

Electrifying Transportation

An increase in VMT was assumed based on projected population growth (Whatcom County, 2015), then EV adoption was assumed to reach nearly 100% in 15 years. For average electric vehicle efficiency, 0.3mi/kWh was used and for internal combustion engine (ICE) vehicles an average efficiency of 22mpg was used, with $3/gallon as the baseline case gasoline price. The incremental costs for a new EV over a new ICE vehicle also took into account currently available federal tax credits.

The following two measures focused on supporting transportation mode shifting to bicycling, with the aim of increasing bicycle mode share from the current 4% to 12% by the resolution target of 2035.

Measure T9-T10 from Climate Action Task Force Final Report

Increase Bicycle Share of VMT

It was assumed that through these measures 12% of projected VMT in 2035 would be replaced with bicycle travel, a mode shift increase of 8% from the current 4%. It was assumed that this increase in mode shift would be made possible in part by the proposed increase in bicycle-friendly infrastructure, such as protected bike lanes, as suggested in the recommendation. For the incremental costs of these measures, $19,512/mile of protected lane was used for an increase of 100 miles of infrastructure in the city by 2035 (City of Bellingham, 2019). It was assumed that a bike would account for 1000 miles per year replaced from the 10,000 miles per year average traveled per car. Therefore, the baseline case vehicle costs only represented a tenth of what was used in reference to the costs for the bike. No embodied emissions were accounted for either the baseline or mitigation measure.

Energy Supply Measures

Measure E1 from Climate Action Task Force Final Report

Community Green Direct (Utility-A)

Here it was assumed that the City of Bellingham could opt into a city-wide version of this program at a similar rate to other institutions that have participated in the PSE Green Direct program at an average of about $0.05/kWh. The baseline rate was assumed as the current commercial rate of $0.06/kWh as that is more akin to the rate structure of Green Direct rather than comparing to the residential tariff. It is unknown if this kind of program would be possible to be offered at all through the utility, and whether it could be offered at the current rates. If this option is pursued in the future, it may come with additional unknown costs.

<u>Measure E3 from Climate Action Task Force Final Report</u>

Green Power Participation (Utility-C)

This measure assumes an increase in program participation to cover nearly all Bellingham customers and no additional incremental costs beyond the cost of opting into the program, which is a $0.01/kWh increase (Puget Sound Energy, 2019a). This analysis also assumed the emissions values presented on the Green Power website, which likely don't account for embodied emissions for the power mix supplied through opting in to the program, which has been accounted for in some of the other Energy Supply MAC analyses. To achieve full program participation by all residents would require extensive outreach, and those uncertain costs have not been accounted for here.

<u>Measures E4-E6, E10-E13, B6 from Climate Action Task Force Final Report</u>

Increased Solar PV Installations

For these measures that focus on increasing access to installing solar PV, a residential solar installation case study was used. This data included the average installation cost, system wattage, estimated annual energy output, and available rebates and incentives.

Measure E6 from Climate Action Task Force Final Report

City-Owned Renewable Energy (Muni-C)

This measure focused on the City of Bellingham government procuring its own renewable energy generation projects. This analysis assumed incremental operating costs based on the projected levelized cost of electricity rates from local installers for both wind and solar generation. Additional unknown administrative costs for procuring these energy resources are not included in the MAC analysis.

Measure E15 from Climate Action Task Force Final Report

Municipal Utility District (Muni-A, Muni-B)

This measure seeks to create a Municipal Utility for the city in place of being served by the local investor-owned utility. The MAC analyses for this option used projected 2025 LCOE rates for renewable energy projects (U.S. Energy Information Administration, 2020) and the rates from Jefferson County, Washington which underwent a similar municipalization process. Not included in this analysis are the unknown legal and administrative fees associated with pursuing this option, which is important to take note of since they could be significant.

Measure E1/E3 from Climate Action Task Force Final Report

Utility Partnership (Utility-B)

This measure is based on a possible partnership between the local utility and the City to procure additional renewable energy in order to get on track to meet the resolution goals. The assumptions for this MAC analysis came from the values found within a presentation on this kind of option presented by the local electric utility, Puget Sound Energy (Puget Sound Energy, 2019).

Results

Bellingham Marginal Abatement Cost Curves

Figure 1 shows the MAC curve for Bellingham based on the recommendations from the Climate Action Task Force Final Report, using the 2018 utility grid electricity mix serving the city. As shown in the figure, the measure with the most abatement potential and therefore largest impact on emissions reduction is electrifying all vehicle miles traveled within Bellingham. This result does not come as too much of a surprise given that transportation makes up the large majority of Bellingham's emissions in 2015, at 32% of community emissions, according to the GHG inventory in the Climate Action Plan (Rice, 2018). The bicycle mode-shift measure has a measurable amount of emissions reduction potential, and interestingly offers the most savings, even when taking into account the increased infrastructure costs deemed necessary to make the goal possible. It is important to note that this measure is assuming a very aggressive amount of mode-shifting to bicycling at about 1000 miles annually per capita, an average of about 2.8 miles traveled per day instead of driving. Electrifying the city's vehicle fleet represents only a portion of the entire community VMT, but can still be achieved at overall cost savings. The building measures represent net savings, except for electrifying space heating, however that measure alone nearly accounts for the abatement potential of all the other building measures combined. Despite the increased marginal costs for this measure based on the data in this analysis, it is imperative that it be paired with the other building measures, and be prioritized for all new construction to avoid costly retrofitting and to further avoid locking in emissions.

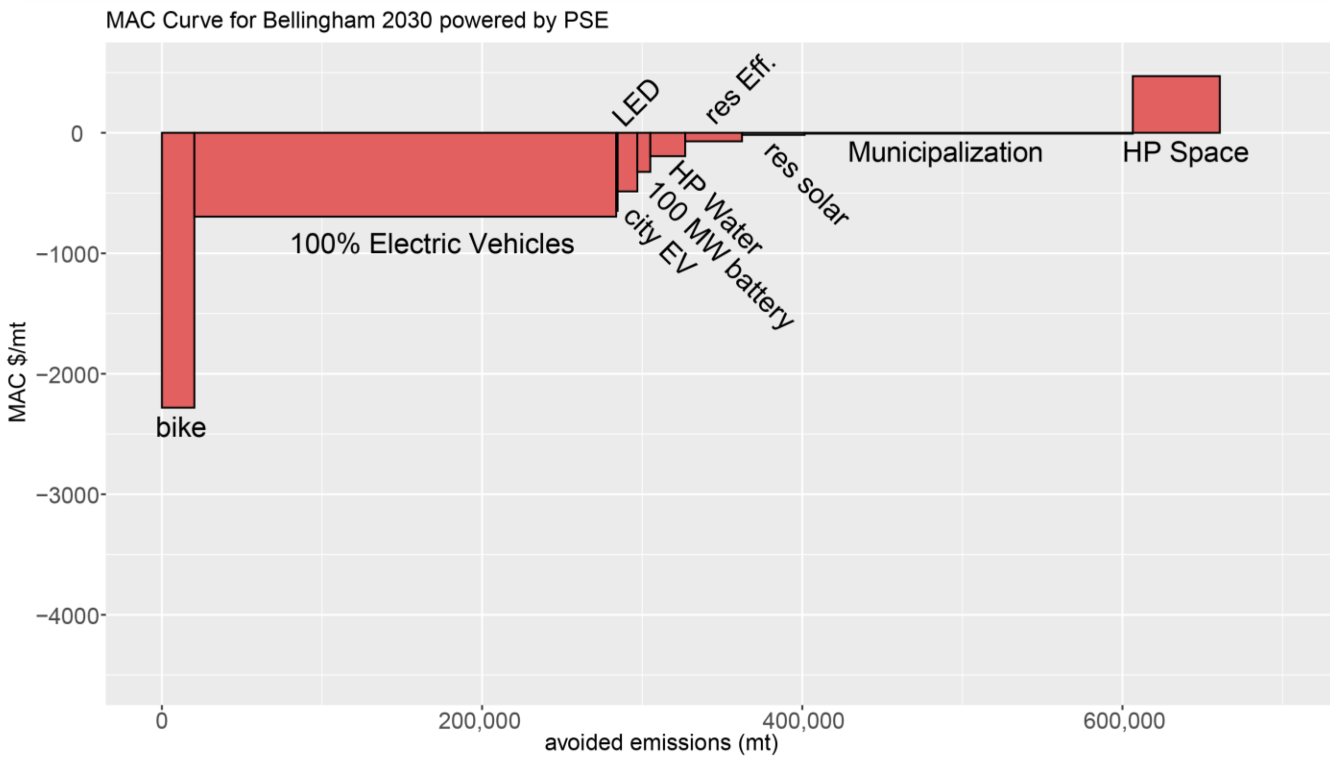

Figure 1: Bellingham MAC Curve - PSE Grid

Finally, the energy supply measures have the second-largest abatement potential, as this is assuming going from the 2018 local utility grid mix of about 250 kg/MWh to nearly zero, at 30 kg/MWh when accounting for the life-cycle emissions of wind and solar technologies. This measure is incredibly impactful in achieving the goals of the City Council’s resolution, however, there are many uncertainties and complications with accounting for the costs and logistics of how it could be implemented. It can represent net savings over time, as plotted on the curve in Figure

1. However, it is also possible for it to have a higher marginal cost, taking into account the many uncertainties in taking on such a large task as municipalizing from the local IOU.

Figure 2 plots the same building and transportation measures, with the effect of a renewable grid supplied with a 66% solar 33% wind mix. This hypothetical future scenario impacts the abatement potential and the denominator of the MAC function. The result, therefore, increases the amount of avoided emissions compared to the baseline since any additional kWh of added electric load is now drastically emitting less. This scenario helps to highlight how contingent the impact of the energy supply is on many of the other mitigation measures, especially electrification measures. The marginal abatement costs for some measures come down under this scenario since the denominator is larger, although the change in costs from the baseline case to the mitigation measure are the same as they were in the previous scenario in Figure 1.

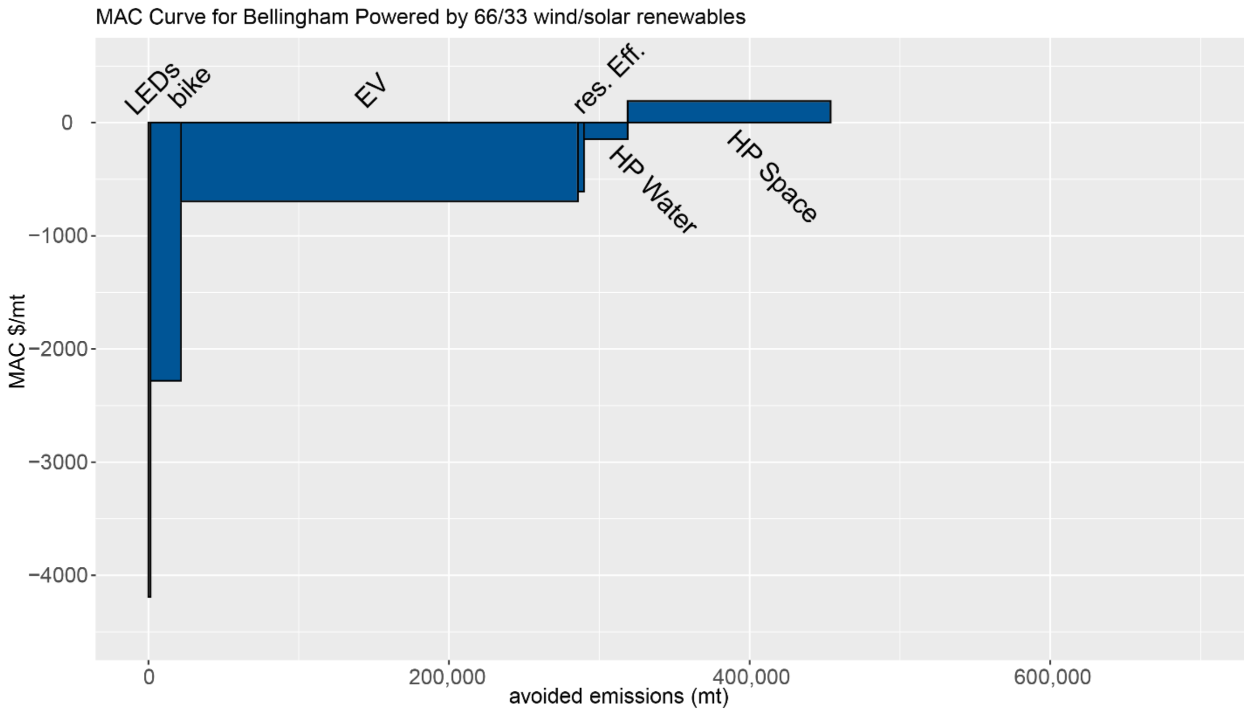

Figure 2: Bellingham MAC Curve - Renewable Grid

Individual Marginal Abatement Cost Curves

Figure 3 is a MAC curve that plots the same measures as the city-wide MAC curves shown above but is only analyzing the cost-effectiveness and abatement potentials for an individual undergoing the proposed actions and changes from the Climate Action Task Force measures. The results for these analyses are very similar to the above as one would expect since it is mostly a change in the ratio of costs and emissions abatement. Similar to Figure 2, Figure 4 is an individual MAC curve with the electricity supply being 100% renewable. In this scenario, electrification measures have an even greater impact, especially space heating, as the difference between the natural gas baseline and a clean electricity source is significant. Similarly, vehicle electrification also ends up having a larger impact in the renewable scenario since it is now being fueled by a cleaner electricity supply.

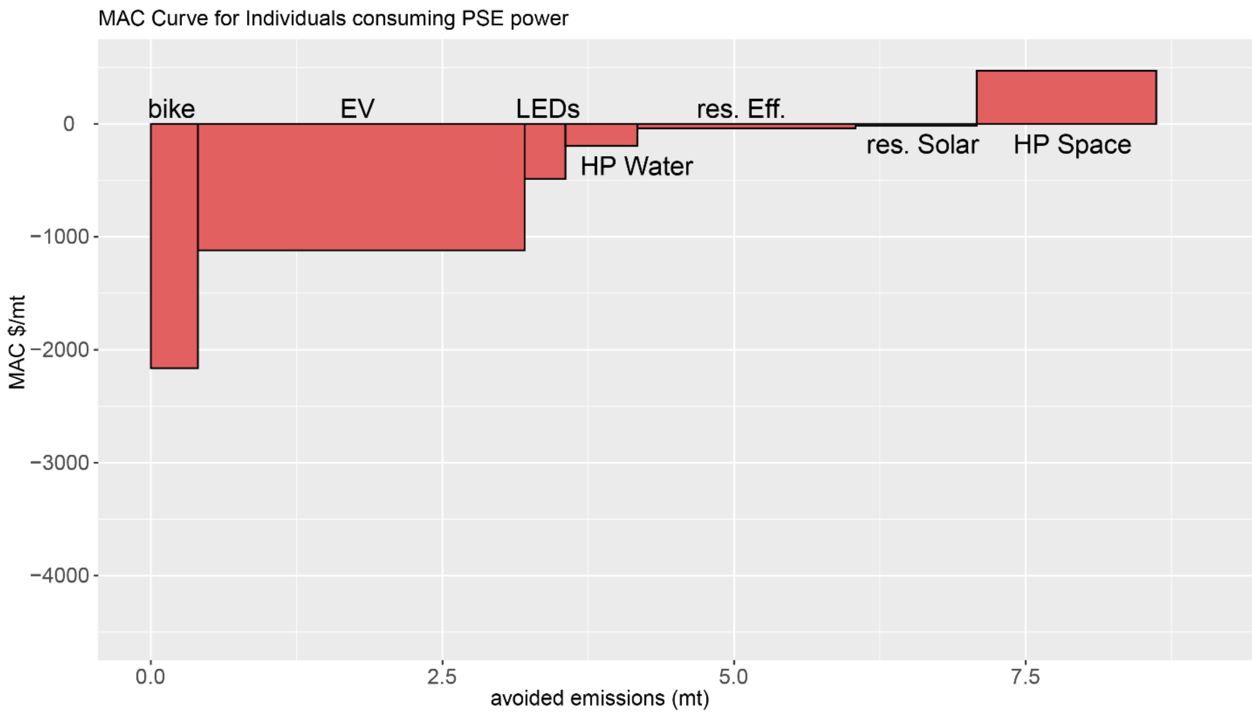

Figure 3: Individual MAC Curve - PSE Grid

These individual MAC curves are supplementary to the ones that focus on Bellingham's climate action as a whole but are helpful for citizens in understanding the impacts and savings of the recommended actions and policies that may be implemented in some form in the future. During the work of the Climate Action Task Force, there was opposition from a variety of interest groups and companies, and there were attempts to stir a rival conversation based on inflated, high-bound numbers of some of the proposed changes to discourage local homeowners from supporting the Task Force recommendations. These individual MAC analyses can help to combat disinformation campaigns, and these methods could be applied in the future to help with informing the public accurately about costs and savings as policies are developed based on the recommendations.

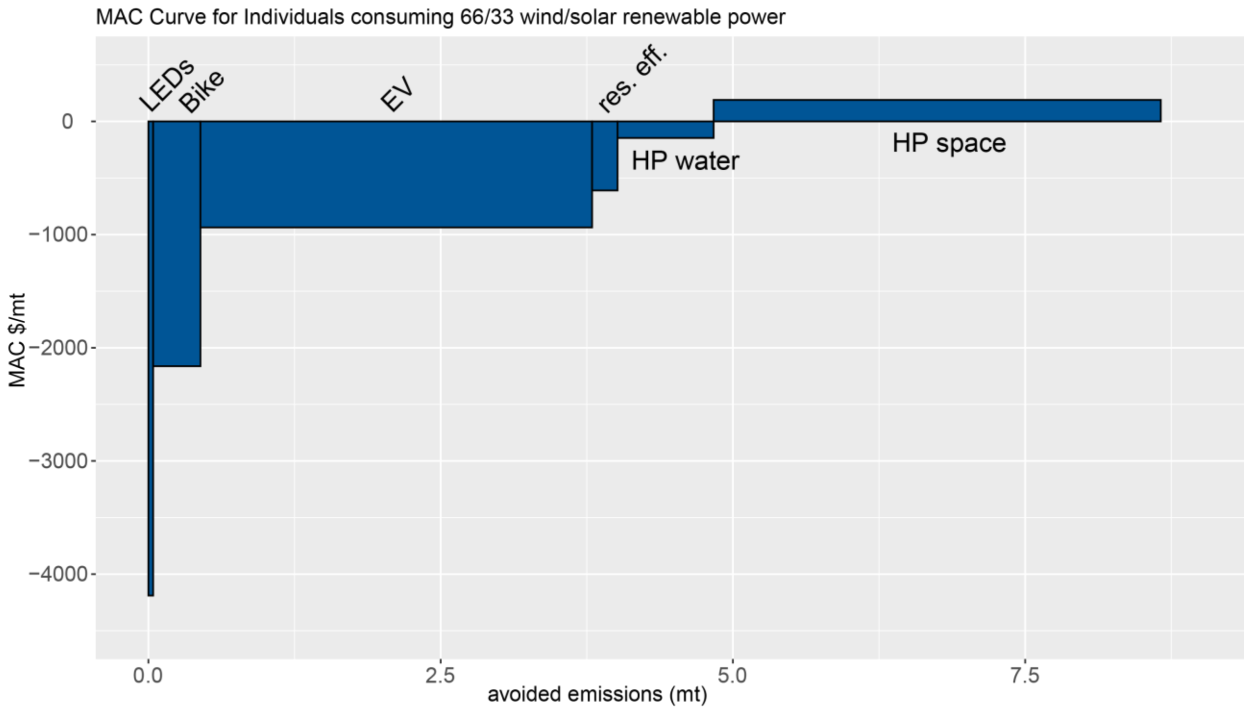

Figure 4: Individual MAC Curve - Renewable Grid

Energy Supply MAC Curve

Finally, Figure 5 plots different energy supply possibilities for the City going forward as it attempts to reach the goals of the resolution. The scenarios plotted are described in the Energy Supply Data and Assumptions section above. It is important to note here, that the abatement potentials along the axis of the chart are not cumulative, as there is overlap between the possible options and therefore explicit double counting when adding along the X-axis of the chart. Assessing the options based on their width, or just their abatement potential values is still viable here, so the curve is still useful in that regard. Based on the analysis, many of the options can offer net savings overtime whilst pursuing a cleaner electricity supply for the City. Some options do have net marginal costs over the existing baseline scenario, however, they are relatively low-cost. This chart also pairs well with Figures 2 & 4 which plot the Task Force recommendations under the scenario of achieving a 100% renewable electricity grid.

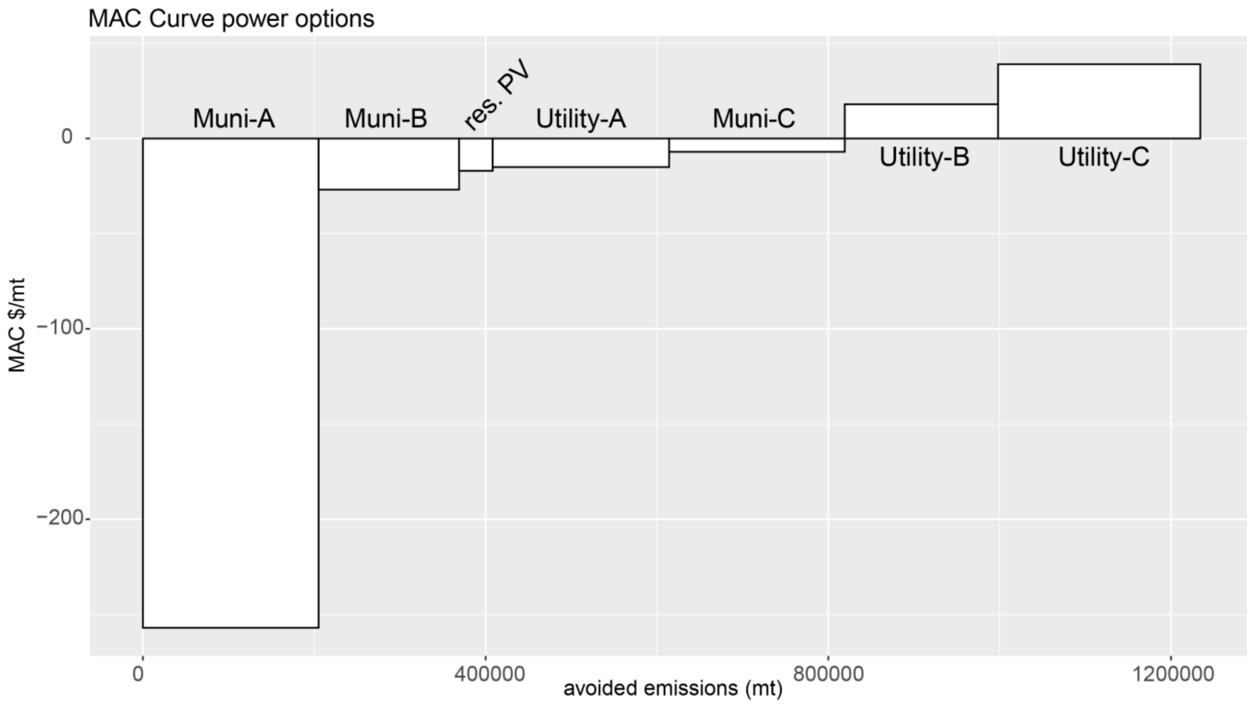

Figure 5: Electricity Supply Options MAC Curve.

Muni-A: Municipal Utility District (EIA), Muni-B: Municipal Utility District (Local Example), Muni-C: City-Owned Renewable Generation, Utility-A: Community Green Direct, Utility-B: Utility-City Partnership, Utility-C: Green Power Participation.

Discussion

As emphasized in the recommendations put forth by the Climate Action Task Force and reinforced by the results of this MAC analysis, electrification is a key strategy in decarbonizing Bellingham and achieving the ambitions of the resolution. Equally important is driving down the emissions intensity of the electric supply serving the City. This aligns with the popular notion in climate policy of being increasingly energy-efficient, fuel switching to electricity, and ensuring that said electricity is on the path to be decarbonized. The results of this MAC study would also imply that over 50% of Bellingham’s emissions can be reduced at overall net cost savings. This helps to further drive home the point that pursuing climate action does not necessarily yield a costlier pathway compared to business-as-usual.

This MAC analysis is a bit more speculative than other MAC studies in that the mitigation measures analyzed are designed with a very aggressive target in mind with a relatively short timeline. Given this, many of the measures in this MAC analysis are trying to set a path to nearly completely decarbonize certain sectors of the local economy. They have very ambitious underlying assumptions that the proposed recommendations from the Task Force will put Bellingham on the path to achieve the targets. In reality, there will certainly be more actions needed to achieve the targets as time goes on, especially as costs come down and technology improves.

Something not clearly captured by the MAC analysis is the high upfront costs associated with many of these mitigation measures. Equity and affordability are not inherently clear in the analysis. The MAC curve provides a great visual representation of the cost competitiveness of different climate action strategies, however, it is important to note that these costs or savings are realized over time. Many of the options presented still have very burdensome upfront capital costs and investments needed to achieve those savings down the road. This is especially important to highlight and consider when developing an equitable policy, as for low-income households some of these upfront burdens are simply not possible to bear without the proper funding mechanisms and support. Many options are identified in the recommendations of the Climate Action Plan Task Force Final Report, including; clean energy funds, promotion of financing systems, virtual net-metering, and property assessed clean energy (PACE) financing.

Improvements and Future Work

It could be interesting and beneficial to perform a similar MAC analysis for the recommendations from the Climate Action Task Force that do end up becoming a more developed policy, as currently, these are all just policy recommendations that have yet to be fully designed. In this case, there would likely be firmer definitions and goals outlined which would create a path for a more concrete, robust, and accurate analysis since fewer assumptions about the measures would need to be made. It would be also worthwhile to continue to evolve and reanalyze measures using this MAC framework into the future as work on local climate action continues in order to provide a relevant and up-to-date analysis.

Other studies have performed sensitivity analyses on some of the key assumptions in MAC curve projects, such as the selected discount rate or fuel prices. This additional analysis can help to add some more clarity to the resulting MAC curve and ensure further reliability, it is recommended to pursue this for future iterations of this framework.

Conclusion

To conclude, the marginal abatement cost curve analysis presented in this report offers an additional tool for Bellingham policymakers to add to their process of local climate action and decarbonization. The methods and framework can be applied to produce additional MAC analyses in the future and offers a pathway to other cities to follow suit. This project finds that Bellingham can pursue the recommendations of the Climate Action Task Force at net savings compared to inaction, and further emphasizes electrification as a key decarbonization strategy. Numerous improvements can be added to this kind of MAC analysis and it is incredibly important to consider the elements of the suggested climate action strategies that are not successfully captured here. Regardless, the marginal abatement cost curve analysis can add great value to the City of Bellingham and others as they continue down the path of decarbonization and climate action.

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Appendix

Supplementary Information Tables

The tables below list the marginal abatement costs and emissions reductions for each measure in the analysis, as plotted on the MAC curve figures in the Results section. Additionally, these tables include further information on the data and assumptions that were used as inputs for the MAC analysis calculations. The background price and emissions data used in the MAC calculations are as follows:

- Price of Residential Electricity: $0.09/kWh
- Price of Commercial Electricity: $0.06/kWh
- Price of Residential Natural Gas: $1.00/therm
- Price of Gasoline: $3.00/gallon
- Emissions Intensity of Electricity: 258.6 kg CO_2e/MWh
- Emissions Intensity of Natural Gas: 5.307 kg CO_2e/therm
- Emissions Intensity of Gasoline: 8.89 kg CO_2e/gallon

Measure	Marginal Abatement Cost ($/mt)	Emissions Avoided (mt CO2e)	Baseline Scenario	Baseline Data & Assumptions	Climate Action Measure	Measure Data & Assumptions	References
MB4/5: Electrifying Space Heating				$4300 (CAPEX)		$10500 (CAPEX)	
City-Wide 2018 Grid	$471	54,356		$632 (OPEX)		$517 (OPEX)	
City-Wide Renewable Grid	$190	135,007	Natural Gas Furnace	95% Efficiency	Ducted/Ductless Heat Pump	340% Efficiency	[1, 2, 3]
Individual 2018 Grid	$471	1.54		10 year lifetime		10 year lifetime	
Individual Renewable Grid	$190	3.83		Annual Heating Load: 6.00E+07 BTU		Annual Heating Load: 6.00E+07 BTU	
				CRF: 0.13		CRF: 0.13	
MB4/5: Electrifying Water Heating				$1059 (CAPEX)		$1300 (CAPEX)	
City-Wide 2018 Grid	-$194	21,778		$160 (OPEX)		$90 (OPEX)	
City-Wide Renewable Grid	-$146	29,015	Natural Gas Water Heater	68% Efficiency	Heat Pump Water Heater	355% Efficiency	[4, 5]
Individual 2018 Grid	-$194	0.62		6 year lifetime		10 year lifetime	
Individual Renewable Grid	-$146	0.82		Annual Heating Load: 1.72E+07 BTU		Annual Heating Load: 1.72E+07 BTU	
				CRF: 0.20		CRF 0.13	
LED Lighting Upgrades				$1.50 (CAPEX)		$1.00 (CAPEX)	
City-Wide 2018 Grid	-$486	12,353		$6.57 (OPEX)		$0.93 (OPEX)	
City-Wide Renewable Grid	-$4,189	1433		60 Watts		8.5 Watts	
Individual 2018 Grid	-$486	0.35	Incandescent Lighting	1095 Annual Lighting Hours	LED Lighting	1095 Lighting Hours	[6, 7]
Individual Renewable Grid	-$4,189	0.04		24 Lighting units per home		24 Lighting Units per home	
				1 year lifetime		10 year lifetime	
				CRF: 1.05		CRF: 0.13	
MB1/2: Building Efficiency				No change to energy consumption		$7290 (CAPEX)	
City-Wide 2018 Grid	-$71	35500				$4563 (CAPEX after rebates)	
City-Wide Renewable Grid	-$610	4123	No Additional Efficiency		Increased Energy Efficiency	$723 (CSE)	[1]
Individual 2018 Grid	-$39	1.87				7233 annual kWh avoided	
Individual Renewable Grid	-$610	0.217				CRF: 0.13	
						50% of 2018 homes by target year	

T1-T8: Electrifying Transportation				$40750 (CAPEX)		$32500 (CAPEX)	
City-Wide 2018 Grid	-$696	263,508	Internal Combustion Engine Vehicle	$1902 (OPEX)	Battery Electric Vehicle	$519 (OPEX)	[8, 9]
City-Wide Renewable Grid	-$574	307,755		26 miles per gallon		0.24 kWh/mi	
Individual 2018 Grid	-$1,120	2.80		10,000 miles per year		10,000 miles per year	
Individual Renewable Grid	-$937	3.35		CRF: 0.21		CRF: 0.21	
				5 year loan, 02% rate		5 year loan, 02% rate	
T9-T10: Increase Bicycle Share of VMT				$3895 (CAPEX)		$1000 (CAPEX Bike)	
City-Wide 2018 Grid	-$2,281	20,269		$1468 (OPEX)		$100 (OPEX Bike)	
City-Wide Renewable Grid	-$2,281	20,269	Internal Combustion Engine Vehicle	22 miles per gallon	Increased Bicycle Trips and Infrastructure	$2,000,000 (CAPEX Infrastructure)	[1, 10]
Individual 2018 Grid	-$2,163	0.404		1000 miles per year		1000 miles per year	
Individual Renewable Grid	-$2,163	0.404		CRF: 0.23		CRF: 0.10	
				5 year lifetime		15 year lifetime	

Measure	**Marginal Abatement Cost ($/mt)**	**Emissions Avoided (mt CO2e)**	**Climate Action Measure**	**Measure Data & Assumptions**	**References**
E1: Community Green Direct Utility-A	-$15	205,911	Green Direct for City Electricity Supply	$0.05/kWh (OPEX) Administrative costs not included 30.6 kg CO2e/MWh Assuming a rate similar to existing, even at a larger scale	[11, 12]
E3: Green Power Participation Utility-C	$39	236,480	Green Power Program	$0.01 (Added OPEX) 0.034 kg CO2e/MWh Assuming full participation No assumed costs for achieving full participation	[13]

E4-E6, E10-E13, B6: Solar PV	-$17	39,103	Residential/Commercial Solar PV	$2.11/Watt Federal tax credit included 44 kg CO2e/MWh (Scope 3) CRF: 0.057 30 year lifetime Added home value excluded	[14]
E6: City-Owned Renewable Energy Muni-C	-$7	205,413	Locally Owned Renewable Generation	$0.085 30.6 kg CO2e/MWh Not including additional project costs	[12,15]
E15: Municipal Utility District Muni-A	-$257	205,413	Municipal Utility 2025 EIA LCOE	Assumes EIA LCOE values (reference 16) 30.6 kg CO2e/MWh Assumes EIA rates available Not including additional administrative costs	[12, 16]
E15: Municipal Utility District Muni-B	-$27	163,613	Municipal Utility Local Example	$0.085/kWh 79.7 kg CO2e/MWh Not including administrative and legal costs	[17]
E1/E3: Utility Partnership Utility-B	$18	179,169	Utility & City Renewable Partnership	Assuming incremental costs from reference Assuming emissions avoided from reference	[18]

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