Final Report

Marginal Abatement Cost Curve for Assessment of Natural Gas Utilities' Cap and Trade Activities (EB-2016-0359)

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Table of Contents

List of Exhibits **3**
List of Tables **3**
Executive Summary **5**
1. Introduction 16
2. Customer Abatement 22
3. Renewable Natural Gas 45
4. Facility Abatement 58
5. Summary MACCs 60
6. Recommendations 67

Appendix A Air Source Heat Pumps **A-1**
Appendix B RNG Results Disaggregated by Feedstock Cost Category **B-1**

List of Exhibits

Exhibit 1 Summary MACC Including Customer Conservation Measures and RNG Potential for Minimum LTCPF 10
Exhibit 2 Summary MACC Including Customer Conservation Measures and RNG Potential for Maximum LTCPF 12
Exhibit 3 Summary MACC Including Customer Conservation Measures and RNG Potential for Mid-Range LTCPF 14
Exhibit 4 Ontario Carbon Price Forecast Scenario Results Expressed in Real 2017 CAD \$/tCO_2e 20
Exhibit 5 Industrial MACC for Minimum LTCPF 27
Exhibit 6 Industrial MACC for Maximum LTCPF 28
Exhibit 7 Industrial MACC for Mid-Range LTCPF 29
Exhibit 8 Commercial MACC for Minimum LTCPF 33
Exhibit 9 Commercial MACC for Maximum LTCPF 34
Exhibit 10 Commercial MACC for Mid-Range LTCPF 35
Exhibit 11 Residential MACC for Minimum LTCPF 39
Exhibit 12 Residential MACC for Maximum LTCPF 40
Exhibit 13 Residential MACC for Mid-Range LTCPF 41
Exhibit 14 Illustrative S-Curve Representing Assumed Deployment of RNG Facilities for One Feedstock Type from 2018-2028 49
Exhibit 15 RNG MACC for Minimum and Mid-Range LTCPF 56
Exhibit 16 RNG MACC for Maximum LTCPF 57
Exhibit 17 Summary MACC Including Customer Conservation Measures and RNG Potential for Minimum LTCPF 61
Exhibit 18 Summary MACC Including Customer Conservation Measures and RNG Potential for Maximum LTCPF 63
Exhibit 19 Summary MACC Including Customer Conservation Measures and RNG Potential for Mid-Range LTCPF 65
Exhibit 20 Canadian RNG Potential by 2020 ....B-1
Exhibit 21 Canadian RNG Potential by 2028 ....B-2

List of Tables

Table 1 Summary MACC Including Customer Conservation Measures and RNG Potential for Minimum LTCPF, Average Cost and Abatement Results 11
Table 2 Summary MACC Including Customer Conservation Measures and RNG Potential for Maximum LTCPF, Average Cost and Abatement Results 13
Table 3 Summary MACC Including Customer Conservation Measures and RNG Potential for Mid-Range LTCPF, Average Cost and Abatement Results 15
Table 4 Industrial MACC for Minimum LTCPF, Average Cost and Abatement Results 27
Table 5 Industrial MACC for Maximum LTCPF, Average Cost and Abatement Results 28
Table 6 Industrial MACC for Mid-Range LTCPF, Average Cost and Abatement Results 29

Table 7 Industrial Measure-Level Marginal Abatement Cost Data (Ranges) for 2018-2020 Timeframe....30
Table 8 Commercial MACC for Minimum LTCPF, Average Cost and Abatement Results....33
Table 9 Commercial MACC for Maximum LTCPF, Average Cost and Abatement Results....34
Table 10 Commercial MACC for Mid-Range LTCPF, Average Cost and Abatement Results....35
Table 11 Commercial Measure-Level Marginal Abatement Cost Data (Ranges) for 2018-2020 Timeframe....36
Table 12 Residential MACC for Minimum LTCPF, Average Cost and Abatement Results....39
Table 13 Residential MACC for Maximum LTCPF, Average Cost and Abatement Results....40
Table 14 Residential MACC for Mid-Range LTCPF, Average Cost and Abatement Results....41
Table 15 Residential Measure-Level Marginal Abatement Cost Data (Ranges) for 2018-2020 Timeframe....42
Table 16 RNG Feedstocks....46
Table 17 RNG Resource Potential in 2028 for Canada and Ontario....47
Table 18 LFG Facility Assumptions by Facility Size (from smallest to largest landfill)....50
Table 19 WWT Facility Assumptions by Facility Size (from smallest to largest WWT facility)....50
Table 20 Livestock Farm Assumptions by Farm Size (from smallest to largest farm facility)....51
Table 21 Agricultural Residue Assumptions by Varying Yield and Feedstock Price....52
Table 22 Summary of the National and Ontario Provincial RNG Potential in 2028 by Feedstock....54
Table 23 RNG MACC for Minimum and Mid-Range LTCPF, Average Cost and Abatement Results....56
Table 24 RNG MACC for Maximum LTCPF, Average Cost and Abatement Results....57
Table 25 Summary MACC Including Customer Conservation Measures and RNG Potential for Minimum LTCPF, Average Cost and Abatement Results....62
Table 26 Summary MACC Including Customer Conservation Measures and RNG Potential for Maximum LTCPF, Average Cost and Abatement Results....64
Table 27 Summary MACC Including Customer Conservation Measures and RNG Potential for Mid-Range LTCPF, Average Cost and Abatement Results....66
Table 28 Assessment of Abatement Cost Associated with Residential ASHPs – Capital Cost Assumptions....A-2
Table 29 Assessment of Abatement Cost Associated with Residential ASHPs – Annual Performance Assumptions....A-3
Table 30 Assessment of Abatement Cost Associated with Residential ASHPs – The Existing Home....A-4
Table 31 Assessment of Abatement Cost Associated with Residential ASHPs – The New Home....A-5
Table 32 Canadian RNG Potential by 2020, LCOE and Potential Results....B-1
Table 33 Canadian RNG Potential by 2028, LCOE and Potential Results....B-2

Executive Summary

Background and Objectives

Ontario's cap and trade program is a regulatory instrument aimed at meeting the provincial government's greenhouse gas (GHG) emissions reduction targets. Beginning in January 2017, the cap and trade program and resulting price on carbon will impact the price end users pay for transportation fuels, natural gas and other fossil fuels.

Under Ontario's cap and trade program, the natural gas utilities, including Enbridge Gas Distribution Inc., Union Gas Limited and Natural Resource Gas Ltd. (the utilities) have the following compliance obligations:

- Facility-related obligations for facilities owned or operated by the utilities; and,
- Customer-related obligations for natural gas-fired electricity generators, and residential, commercial and industrial customers who are not independently covered under the cap and trade program (i.e., that are not Large Final Emitters (LFEs) or voluntary participants).

The utilities are required to purchase and remit emissions units (allowances or offset credits) for both sources of emissions over the 2017-2020 timeframe (the first compliance period). Utilities may also choose to reduce the amount of customer- and facility-related GHGs emitted in any given period (i.e., GHG abatement). GHG abatement activities reduce the number of emissions units a utility would be required to purchase in order to comply with the cap and trade program.

The costs associated with all cap and trade activities, including purchasing emissions units and GHG abatement, will be recovered from customers. As the Ontario natural gas and electricity sector regulator, the Ontario Energy Board (OEB) has a new role in assessing the cost consequences of the natural gas utilities' cap and trade activities for the purpose of approving cost recovery in rates.

The objective of this study is to provide the OEB with its first province-wide marginal abatement cost curve (MACC) to inform the utilities in the development of their Compliance Plans. The MACC illustrates a range greenhouse gas reduction (abatement) options that could be implemented during the first compliance period (2017-2020).The abatement options included on the MACC are related to customer activities and renewable natural gas (RNG). Facility abatement activities were considered for the MACC but excluded due to lack of data.

The study focuses on costs to the utilities, rather than costs to society or to customers. The reason for focusing on costs to the utility is that the MACC is intended to inform the development of utilities' Compliance Plans and to assist the OEB in evaluating the cost consequences of those Plans. The utilities' Compliance Plans will identify costs to be recovered from ratepayers through the lens of the utility, and as such this study has developed a MACC that uses the same cost lens.

Key Methodological Features

The OEB's MACC varies from traditional MACCs because it was developed for the specific purpose of informing and evaluating the gas utilities' Compliance Plans. As a result, there are several important considerations defined below aimed at providing context to the results provided herein:

- Conservation-related abatement activities described in Section 2, Customer Abatement, may involve the need for a customer to purchase new equipment or pay fuel/energy costs – these costs are not included in the MACC analysis. As discussed, this study focuses on costs to the utilities rather than costs to customers or society.
- The benefits of avoided carbon costs (i.e., lower overall compliance obligation resulting in fewer emissions units needing to be purchased) are included in the cost metric. This is intended take into account the fact that an abatement activity results in avoided carbon costs (avoided costs from purchasing emissions units) over its lifetime. Abatement activities with long lives, such as providing an incentive to a customer to buy an efficient furnace that may last 25 years, will avoid more carbon costs than an abatement activity that is shorter-lived.
- The MACCs represent a “menu of options” which includes existing DSM savings and activities as well as potential future cap and trade-incented abatement activities.
- Abatement costs are “average” rather than “marginal” – depending on where / how an abatement activity is implemented, or whether it is already included in a DSM program, the costs may differ. Natural gas DSM activity is fairly mature in Ontario and there is typically a non-linear relationship between spending and savings in DSM.
- The MACC was modelled using costs and adoption curves developed in the 2016 Conservation Potential Study (2016 CPS, see section 1.4.4) which reflect business-as-usual (BAU) incentive levels. The results do not represent the maximum possible abatement that could be achieved through customer abatement, nor the maximum possible costs.
- The MACC cost metric is based on a net present value of lifetime costs and benefits, and does not consider the distribution of those cost streams over time. Many abatement activities are characterized by frontloaded costs and backloaded benefits.

Customer Abatement Methodology and Assumptions

In order to answer the question of how much natural gas abatement can be achieved, and how much is cost effective under three different carbon price scenarios, ICF leveraged all of the data inputs and assumptions from utilities and stakeholders that were used to develop the proprietary Conservation Potential Study (CPS) model, and incorporated the long-term carbon pricing forecasts (LTCPF), see Section 1.4.2 for an explanation of carbon pricing inputs.

The CPS model is populated with inputs and assumptions that were subject to rigorous review through extensive consultation with the OEB, the two major utilities and other natural gas sector stakeholders before being used for the 2016 CPS. The following data and assumptions were used to develop the MACC and remain unchanged from the CPS:

- Lists of conservation measures for industrial, commercial and residential sectors and the associated measure-level assumptions/parameters including:
    - natural gas savings
    - electricity savings (or increases)
    - effective useful life, and
    - measure applicability

- Adoption rates for BAU case incentive levels
- End use classification (e.g., industrial HVAC, commercial space heating, etc.)
- Utility program and incentive costs
- Treatment of conservation measure interactions
- All economic and market assumptions (including 4% discount rate)

The same caveats and limitations apply to this study as are documented in the 2016 CPS report, including that the model does not consider factors such as infrastructure requirements or lead time to implement abatement programs.

Cost Metric

The cost metric used in this study was developed to quantify the cost effectiveness of natural gas customer conservation abatement options under different carbon pricing assumptions from a utility perspective. The cost metric includes:

Benefits (avoided costs):

- Natural gas avoided costs, comprising commodity costs, upstream capacity costs and downstream distribution system costs[1]
- Avoided cost of carbon, based on the three LTCPF scenarios (see Section 1.4.2)

Costs:

- Utility incentive costs
- Utility program delivery costs

The data and assumptions for all cost and avoided cost components listed above remain unchanged from the 2016 CPS[2], with the exception of the carbon price which is based on the LTCPF Report. The three MACC study scenarios – based on the minimum, maximum and mid-range carbon price forecast – were developed by varying the LTCPF used in the cost metric.

Capped and Uncapped Participants

Estimates of natural gas consumption volumes representing ‘capped’ participants under Ontario’s cap and trade program were developed through consultation with the utilities, and their associated natural gas volumes were removed from the modelling exercise[3]. Facilities directly covered under the program are excluded from the utilities’ compliance obligations, so the associated abatement potential was excluded from the MACCs.

Heat Pumps

Heat pumps were assessed through an analysis separate from the CPS model exercise (refer to Appendix A).

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[1] For a detailed description of avoided costs, see chapter 3 of the 2016 CPS Report.
[2] While cost data and assumptions from the CPS were used for this analysis, the definition of the cost metric in this study is *not* the same as the cost metric in the CPS. The main driver behind the differences in what costs and benefits are included is that the CPS was based on a societal cost perspective, whereas this study’s objective is to evaluate costs from a utility perspective.
[3] Refer to Section 6.2 for recommendation to develop market penetration rates that might be more reflective of non-LFEs in future studies.

RNG Methodology and Assumptions

To estimate the resource potential for RNG across Canada and in Ontario within the study scope and timeline, ICF completed a desk-based literature review of publicly available documents. RNG production estimates for five feedstocks including landfill gas (LFG), wastewater treatment gas, animal manure, source separated organics (SSO) and agricultural residue from the Canadian Biogas Study were used to develop the abatement potential estimates through 2028 via two conversion technologies: anaerobic digestion or thermal gasification. ICF made the simplifying assumption that RNG production from LFG, wastewater treatment plants, animal manure, and SSO would occur via anaerobic digestion. It was also assumed that agricultural residue would be converted to RNG via thermal gasification.

The main cost components considered in ICF's analysis include:

- Collection - This refers to a variety of cost elements, including the capture of gas from landfills or wastewater treatment plants or the collection of a feedstock.
- Upgrading biogas for injection - Broadly speaking, raw biogas needs to upgraded and scrubbed of contaminants prior to injection into a transmission pipeline. The primary cost components for upgrading biogas that ICF included in the analysis are: conditioning the biogas, compression of the biogas, sulfur removal, and a nitrogen rejection system.
- Other equipment expenditures - This refers to other capital expenditures including digesters, thermal gasification equipment, etc.
- Pipeline interconnect - Pipeline interconnect represents the combination of the point of receipt from the customer pipeline and the pipeline extension to the utility pipeline. These costs vary by project size, complexity, and distance from common carrier pipeline.
- Construction and engineering - The deployment of biogas projects requires significant investments in construction and engineering, including site design, labour to install equipment, etc.
- Operations and maintenance - ICF includes the costs of operating and maintaining the biogas production facility - including collection, conditioning, compression, and injection. These costs are generally expressed as a percentage of the capital expenditures, and range from 5-15%.

In all scenarios, ICF assumed an s-curve of deployment of RNG production facilities. The underlying principle of this assumption is that the initial investments will be modest over the first 5-7 years (2018-2024), but that deployment in the out-years ramps up. ICF's deployment curves should not be considered a forecast; rather, they are meant to capture plausible investment in RNG production considering the barriers to financing, permitting a project, and completing it (typically with an 18-36 month timeframe between project financing and coming online).

For each feedstock, ICF calculated the levelized cost of energy (LCOE)[4] in dollars per cubic metre ($\$/m^3$) by incorporating the capital expenditures from equipment, operations and maintenance (O&M), and a discount rate of 4% for our calculations.

[4] LCOE is similar to the cost components of the MACC cost metric but is not equivalent because it only includes positive costs – it does not incorporate the commodity cost of fossil-derived natural gas and the forecasted price of allowances (avoided costs or benefits in the MACC cost metric).

Summary MACC Results

Exhibit 1, Exhibit 2 and Exhibit 3 and supporting Table 1, Table 2, and Table 3 presented in this section are compilations of the customer abatement MACCs presented in Section 2 and the RNG MACCs presented in Section 3 for the 2018-2020 study period. Each summary MACC – one MACC presented for each of three carbon pricing scenarios – illustrates the estimated achievable potential savings[5] in tonnes CO_2e and cubic metres of natural gas, for natural gas abatement through customer conservation measures and RNG abatement.

How to Read the MACC

The summary MACCs should be interpreted in the same manner as the MACCs in Sections 2 and 3 of this report. The MACC diagrams illustrate cost and abatement in m^3 and tonnes CO_2e.

The zero dollars line (x-axis) represents the "cost-effective" threshold, which includes the price of an allowance. Bars below the zero-line represent activities that are less costly than an allowance on a lifetime basis. Bars above the zero-line represent activities that are more expensive than an allowance on a lifetime basis.

Each bar on the MACC represents either a group of measures[6] (grouped by end use, e.g., residential space heating) or an RNG activity by feedstock (e.g., RNG from LFG). The height of the bars represents average costs per tonne of CO_2e abated for each end use.

The labels associated with each bar on the MACCs indicate the sum of the marginal abatement, in tCO_2e, for all bars to the left of the label line[7].

The width of the bars represents the abatement potential in tonnes of CO_2e, including both cost effective and non-cost effective measures. Estimates of the proportion of the customer abatement potential that is associated with cost effective measures for each individual bar as well as RNG abatement potential are provided in the tables that follow each exhibit. Also included in the supporting tables is the average cost data, by end use for customer abatement, and by feedstock category for RNG abatement, used to create the MACCs.

MACCs were developed for each of the three carbon pricing scenarios including minimum, maximum and mid-range (see section 1.4.2 for an explanation of carbon pricing scenarios used as inputs to the MACC).

[5] The model results for achievable abatement potential within this timeframe are driven by measure-level achievable adoption curves developed in the 2016 CPS.

[6] Lists of measures for each sector and the corresponding end use categories are included in Table 7 for industrial; Table 11 for commercial; and Table 15 for residential.

[7] For example, if the first bar represents a marginal abatement of 5 tCO_2e, the second bar represents 40 tCO_2e and the third bar represents 15 tCO_2e the label on the right edge of the third bar would read 60 tCO_2e.

Exhibit 1 Summary MACC Including Customer Conservation Measures and RNG Potential for Minimum LTCPF

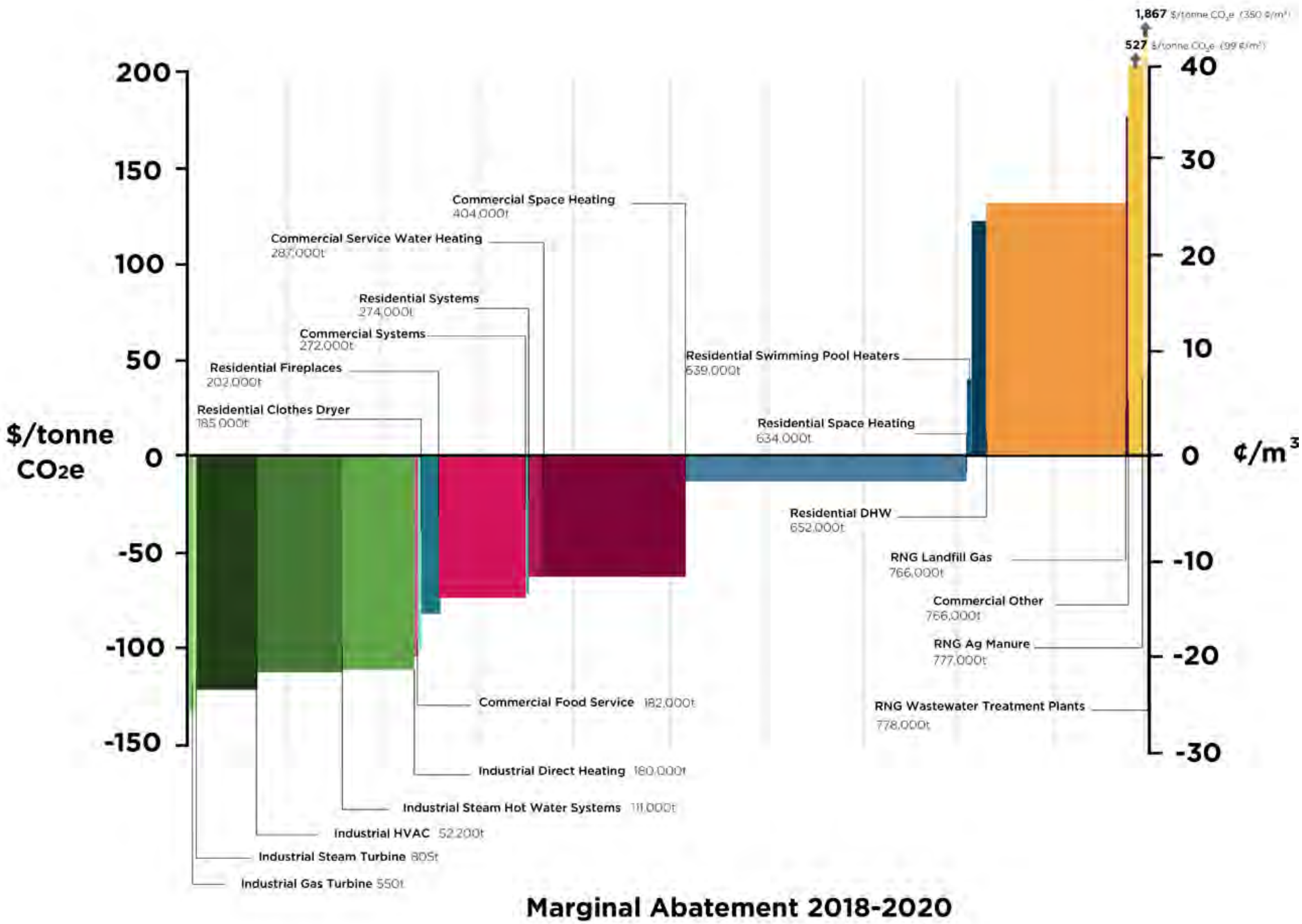

Table 1 Summary MACC Including Customer Conservation Measures and RNG Potential for Minimum LTCPF, Average Cost and Abatement Results

Customer Abatement End Use of RNG Category	Average $/tCO$_2$e	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO$_2$e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Industrial Gas Turbine	-130	-24	550	0.3	100%
Industrial Steam Turbine	-130	-24	250	0.1	100%
Industrial HVAC	-122	-23	51,400	27	100%
Industrial Steam Hot Water System	-112	-21	58,600	31	100%
Industrial Direct Heating	-111	-21	69,700	37	100%
Commercial Food Service	-105	-20	1,040	0.6	100%
Residential Clothes Dryers	-100	-19	3,830	2	97%
Residential Fireplaces	-83	-16	16,200	8.7	100%
Commercial Systems	-75	-14	70,100	37	86%
Residential Systems	-72	-13	1,850	1	100%
Commercial Service Water Heating	-62	-12	13,400	7	96%
Commercial Space Heating	-62	-12	117,000	63	94%
Residential Space Heating	13	2	230,000	122	64%
Residential Swimming Pool Heaters	40	8	5,480	3	74%
Residential Domestic Hot Water	127	24	12,900	7	57%
RNG Landfill Gas	133	25	114,000	61	0%
Commercial Other	176	33	3	0.002	0%
RNG Ag Manure	527	99	11,200	6	0%
RNG Wastewater Treatment Plants	1,867	350	800	0.4	0%
values may not sum to total due to rounding			**778,000**	**415**	

Exhibit 2 Summary MACC Including Customer Conservation Measures and RNG Potential for Maximum LTCPF

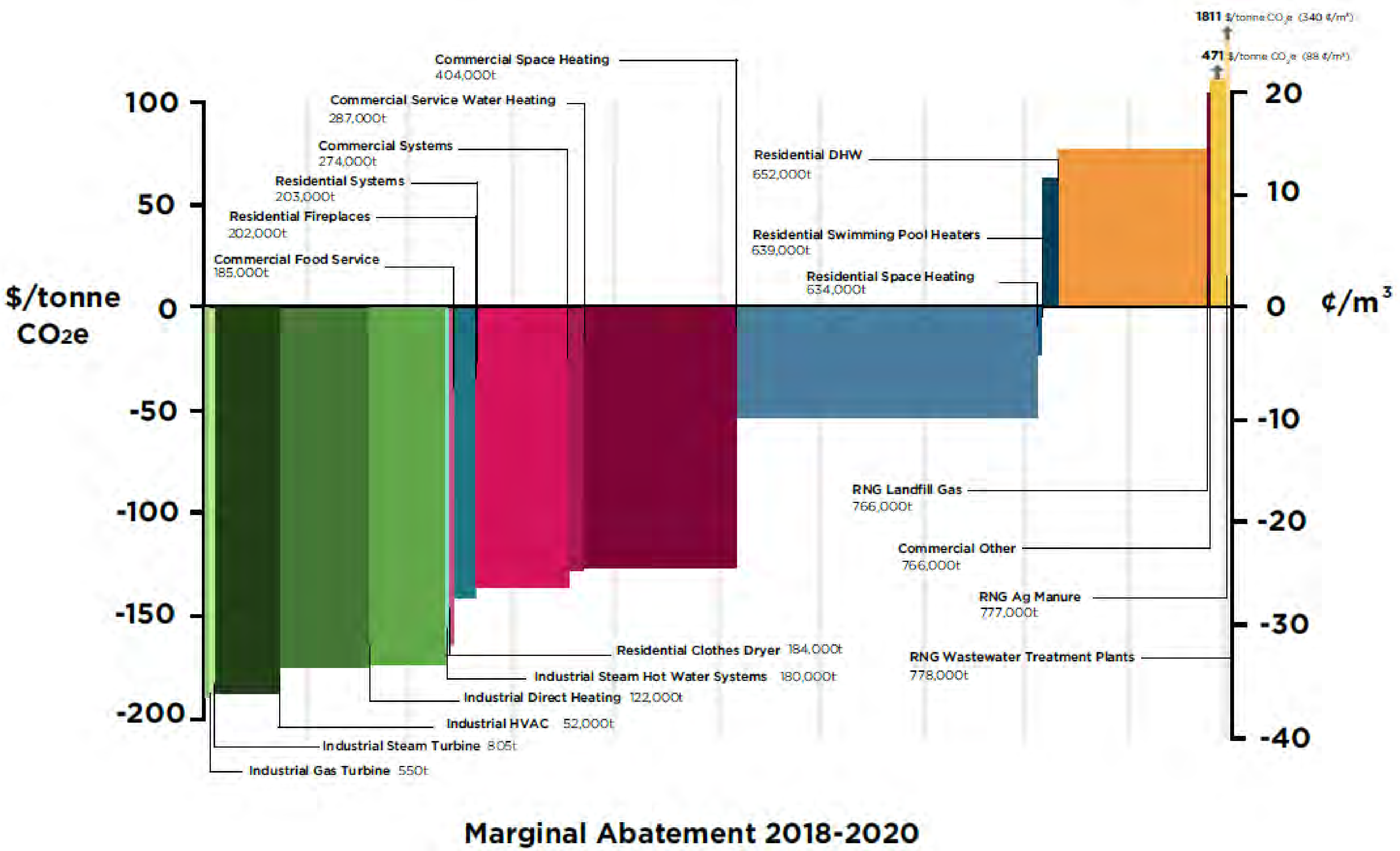

Table 2 Summary MACC Including Customer Conservation Measures and RNG Potential for Maximum LTCPF, Average Cost and Abatement Results

Customer Abatement End Use of RNG Category	Average $/tCO$_2$e	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO$_2$e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Industrial Gas Turbine	-186	-35	550	0.3	100%
Industrial Steam Turbine	-186	-35	250	0.1	100%
Industrial HVAC	-184	-34	51,400	27	100%
Industrial Direct Heating	-176	-33	69,700	37	100%
Industrial Steam Hot Water System	-175	-33	58,600	31	100%
Residential Clothes Dryers	-166	-31	3,830	2	98%
Commercial Food Service	-165	-31	1,040	0.6	100%
Residential Fireplaces	-143	-27	16,200	8.7	100%
Residential Systems	-143	-27	1,850	1	100%
Commercial Systems	-137	-26	70,100	37	100%
Commercial Service Water Heating	-127	-24	13,400	7	96%
Commercial Space Heating	-127	-24	117,000	63	97%
Residential Space Heating	-54	-10	230,000	122	76%
Residential Swimming Pool Heaters	-22	-4	5,480	3	74%
Residential Domestic Hot Water	63	12	12,900	7	57%
RNG Landfill Gas	77	14	114,000	61	0%
Commercial Other	106	20	3	0.002	0%
RNG Ag Manure	471	88	11,200	6	0%
RNG Wastewater Treatment Plants	1,811	340	800	0.4	0%
values may not sum to total due to rounding			**778,000**	**415**	

Exhibit 3 Summary MACC Including Customer Conservation Measures and RNG Potential for Mid-Range LTCPF

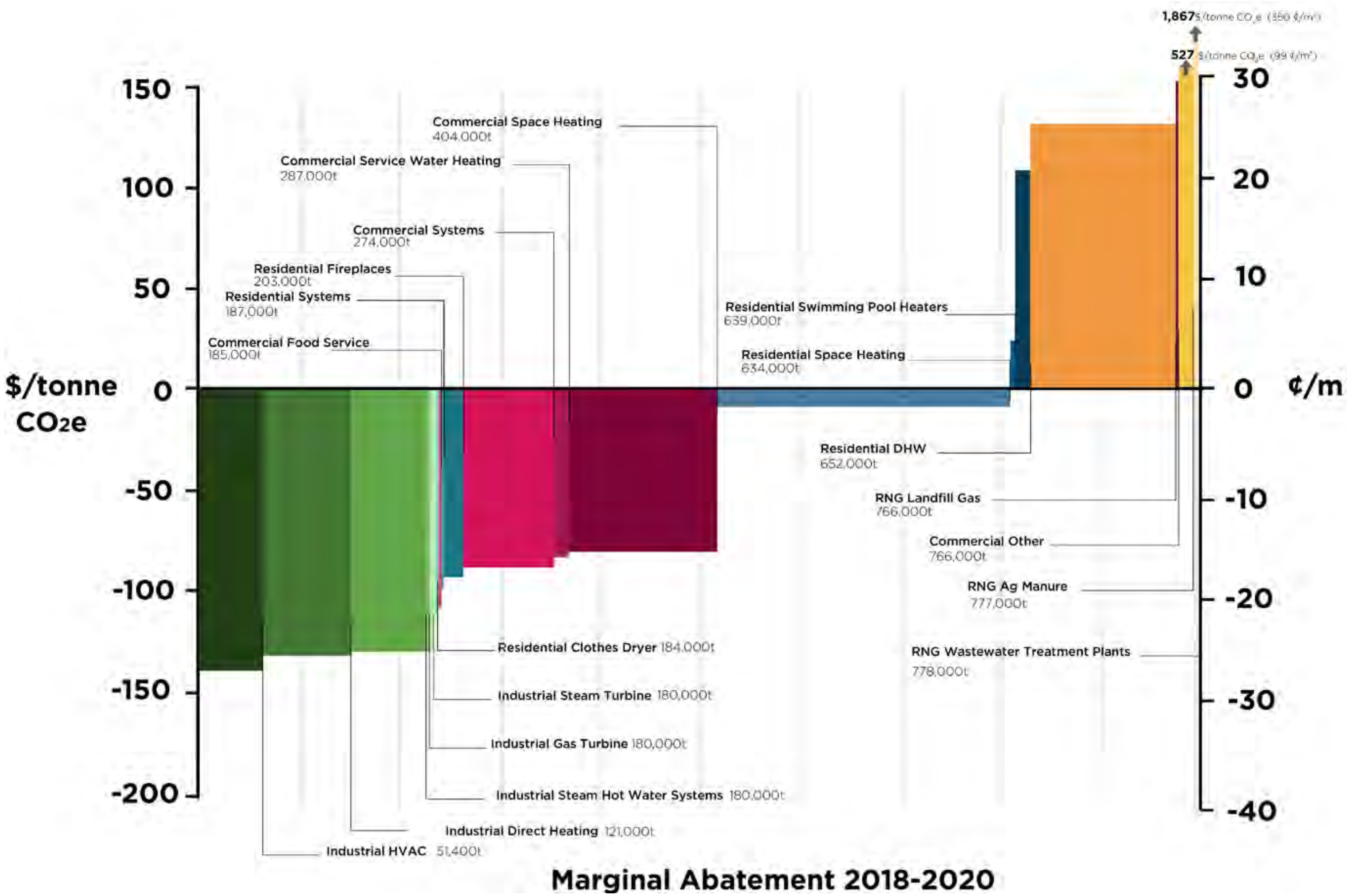

Table 3 Summary MACC Including Customer Conservation Measures and RNG Potential for Mid-Range LTCPF, Average Cost and Abatement Results

Customer Abatement End Use of RNG Category	Average $/tCO₂e	Average ¢/m³	Estimated 2018-2020 Abatement (tCO₂e)	Estimated 2018-2020 Abatement (million m³)	Estimated Cost Effective Abatement (%)
Industrial HVAC	-139	-26	51,400	27	100%
Industrial Direct Heating	-132	-25	69,700	37	100%
Industrial Steam Hot Water System	-131	-25	58,600	31	100%
Industrial Gas Turbine	-130	-24	550	0.3	100%
Industrial Steam Turbine	-130	-24	250	0.1	100%
Residential Clothes Dryers	-123	-23	3,830	2	98%
Commercial Food Service	-119	-22	1,040	0.6	100%
Residential Systems	-97	-18	1,850	1	100%
Residential Fireplaces	-94	-18	16,200	8.7	100%
Commercial Systems	-88	-16	70,100	37	86%
Commercial Service Water Heating	-83	-16	13,400	7	96%
Commercial Space Heating	-83	-15	117,000	63	96%
Residential Space Heating	-7	-1	230,000	122	65%
Residential Swimming Pool Heaters	24	5	5,480	3	74%
Residential Domestic Hot Water	108	20	12,900	7	57%
RNG Landfill Gas	133	25	114,000	61	0%
Commercial Other	151	28	3	0.002	0%
RNG Ag Manure	527	99	11,200	6	0%
RNG Wastewater Treatment Plants	1,867	350	800	0.4	0%
values may not sum to total due to rounding			**778,000**	**415**	

1. Introduction

1.1 Background

Ontario's cap and trade program is a regulatory instrument aimed at meeting the provincial government's greenhouse gas (GHG) emissions reduction targets. Beginning in January 2017, the cap and trade program and resulting price on carbon will impact the price end users pay for transportation fuels, natural gas and other fossil fuels.

Ontario's cap and trade program is based on the cap and trade program design of the Western Climate Initiative (WCI). The government of Ontario has signaled its intention to link with the WCI Partner jurisdictions' (i.e., California and Quebec) joint cap and trade market in 2018.

The cap and trade program defines a compliance obligation for Ontario's natural gas distributors, including Union Gas Limited, Enbridge Gas Distribution Inc. and Natural Resource Gas Ltd., collectively referred to as the "utilities". The utilities' compliance obligation includes:

- Facility-related obligations for facilities owned or operated by the utilities; and,
- Customer-related obligations for natural gas-fired electricity generators, and residential, commercial and industrial customers who are not independently covered under the cap and trade program (i.e., that are not Large Final Emitters (LFEs) or voluntary participants).

Under the cap and trade program, the utilities are required to purchase and remit emissions units (allowances or offset credits) for both sources of emissions over the 2017-2020 timeframe (the first compliance period). Utilities can also choose to reduce the amount of customer- and facility-related GHGs emitted in any given period (i.e., GHG abatement). Because GHG abatement activities reduce overall emissions, undertaking abatement means that the utility has to purchase fewer emissions units.

The costs associated with all cap and trade activities, including purchasing emissions units and GHG abatement, will be recovered from customers. Charged with regulating Ontario's natural gas and electricity sectors, including natural gas utility rates, the Ontario Energy Board (OEB) therefore has a new role in assessing the cost consequences of the utilities' cap and trade activities for the purpose of approving cost recovery in rates.

The OEB issued a Regulatory Framework for the Assessment of Costs of Natural Gas Utilities' Cap and Trade Activities (the "Regulatory Framework") on September 26, 2016. The Regulatory Framework describes the OEB's expectation for each utility to develop cap and trade Compliance Plans that include robust information regarding utilities' compliance strategies. The OEB will assess these Compliance Plans for cost effectiveness, reasonableness and optimization in its decision to approve recovery of cap and trade costs from customers. In the Regulatory Framework, the OEB indicated it will provide a province-wide, generic marginal abatement cost curve (MACC) for the utilities to use in developing their Compliance Plans, which will also be used by the OEB as a key input into its assessment of the cost consequences of those Plans.

1.2 Study Scope and Objectives

The objective of this study is to provide the OEB with its first province-wide MACC to inform the utilities in the development of their Compliance Plans and to be used by the OEB in its assessment of the cost consequences of utilities' Compliance Plans.

The MACC identifies the full range of customer conservation-related and renewable natural gas (RNG) abatement options and their associated savings in cubic metres and tonnes of CO_2 equivalent (CO_2e) and costs. The MACC is a diagram presenting the cost of natural gas GHG abatement (i.e., energy efficiency) options in dollars per tonne of CO_2e of GHG abatement[8] (also represented as dollars per cubic metre of natural gas savings) relative to a baseline. The abatement cost is calculated as a sum of lifetime costs and benefits (avoided costs), including the avoided cost of purchasing allowances. Therefore the zero line (x axis) in this study is the "cost effective" threshold, which represents the point at which the cost of implementing an abatement option is equivalent to the cost of purchasing allowances (based on the long-term carbon price forecast over the abatement option's lifetime). Values below the zero line are deemed cost effective relative to purchasing allowances, and values above the zero line are abatement options deemed to be more expensive than purchasing allowances.

The MACC will illustrate the full range of abatement options that could be implemented during the first compliance period. The abatement options considered for the MACC include:

- Customer abatement activities
- Renewable Natural Gas
- Facility abatement activities

Customer abatement activities and RNG are included in the final MACC, while facility abatement activities were excluded due to lack of data, as explained in Section 4 of this report.

Once implemented, abatement activities may deliver GHG emissions reductions for many years. Abatement options are displayed from lowest to highest cost, presented from the perspective of the utilities.

The study focuses on costs to the utilities, rather than costs to their customers, because the MACC is intended to inform the development of utilities' Compliance Plans, and to assist the OEB in evaluating those Plans. It is important to understand that costs for each abatement option were determined based on what it would cost the utility and not from the perspective of what it would cost the customer. This means that the MACC identifies what options are more cost effective for the utilities than purchasing allowances, and not what has the greatest overall economic benefit. This approach was selected because the MACC is specifically intended to inform the development of the utilities' Compliance Plans and the OEB's assessment of the cost consequences of those Plans. The utilities' Compliance Plans will identify costs to be recovered from ratepayers through the lens of the utility, and as such this study has developed a MACC that uses the same cost lens.

[8] Calculated using abatement option lifetime costs over lifetime natural gas savings or lifetime GHG abatement.

The MACC will be updated every three years, prior to the start of a new compliance period, as outlined in the OEB's Regulatory Framework.

The approach for this first province-wide MACC study was developed through consultation with the OEB and a Technical Advisory Group (TAG) comprised of technical experts and representatives from a cross-section of natural gas sector stakeholders. The approach and any associated limitations and caveats used in the development of the MACC are presented by key study category, including customer abatement in Section 2, RNG in Section 3, and facility abatement options in Section 4.

1.3 Key Methodological Features

The MACCs in this study differ from traditional MACCs because they were developed for the specific purpose of informing and evaluating the gas utilities' Compliance Plans. As a result, there are several important considerations defined below aimed at providing context to the results provided herein:

- Conservation-related abatement activities, described in Section 2, Customer Abatement, may involve the need for a customer to purchase new equipment or pay fuel/energy costs – these costs are not included in the MACC analysis.
- The benefits of avoided carbon costs ((i.e., lower overall compliance obligation resulting in fewer emissions units needing to be purchased) are included in the cost metric. This is intended take into account the fact that an abatement activity results in avoided carbon costs (avoided costs from having to purchase fewer emissions units) over its lifetime. Abatement activities with long measure lives, such as providing an incentive to a customer to buy an efficient furnace that may last 25 years, will avoid more carbon costs than an abatement activity that is shorter-lived.
- The MACCs represent a "menu of options" that include existing demand-side management (DSM) program savings and activities as well as potential future cap and trade-incented abatement activities that can be and/or are already being used for DSM and for cap and trade abatement activities. The utilities are currently involved in implementing existing DSM Plans, which will be in place until 2020, and other energy efficiency initiatives such as the Green Investment Fund and Green Ontario Fund. Future abatement programs and activities funded by the Climate Change Action Plan (CCAP) may also affect the achievable abatement potential and types of abatement activities available to utilities. For measures where existing DSM and/or other abatement programs are already in place, the average costs presented in the MACCs do not represent what the next incremental unit of savings will cost. This limits the applicability of these cost estimates for the utilities when assessing expansion of existing or new DSM programs.
- Abatement costs are "average" rather than "marginal" – depending on where / how an abatement activity is implemented, or whether it is already included in a DSM program, the costs may differ. Natural gas DSM activity is fairly mature in Ontario and there is typically a non-linear relationship between spending and savings in DSM. Customer abatement technologies, measures and programs tend to become increasingly expensive as it becomes necessary to seek less cost effective opportunities in harder to reach markets.

- The MACC was modelled using costs and adoption curves developed in the 2016 Conservation Potential Study[9] (CPS) which reflect business-as-usual (BAU) incentive levels. The results do not represent the maximum possible abatement that could be achieved through customer abatement, nor the maximum possible costs.
- The MACC cost metric is based on a net present value of lifetime costs and benefits, and does not consider the distribution of those cost streams over time. Many abatement activities are characterized by frontloaded costs and backloaded benefits. This study does not address any potential implications of this profile, including, but not limited to, availability of capital, financing constraints and risk.

1.4 Study Inputs

1.4.1 2016 Conservation Potential Study

The foundation for the development of this MACC study was the CPS completed by ICF for the OEB in 2016 that answered the question of how much natural gas conservation is cost effective in the absence of an explicit carbon price. The CPS was developed to assist the gas utilities and the OEB in assessing the achievable savings potential for DSM programs. Since DSM programs and customer abatement measures share many characteristics[10], the CPS was used as a reference to determine customer abatement cost and potential. The approach enables the compilation and analysis of a large quantity of market and technology data to generate an assessment of the total achievable conservation potential over a specified study time period, considering technical, economic and adoption constraints.

For the 2016 CPS, ICF developed a proprietary model which was populated with detailed data representing technologies, operation and maintenance and control measures that save natural gas across energy end uses in each sector of the Ontario economy. More than 50 measures were considered for each of the residential, commercial and industrial sectors, and all of the data inputs and assumptions used to develop the model were reviewed by the OEB and natural gas stakeholders.

The 2016 CPS study used 2014 as the base year and therefore the starting point for the analysis. In this MACC study, the marginal abatement presented in the results (see Sections 2.3 and 5) is calculated based on a reference year of 2017 in order to capture abatement potential associated with customer abatement measures installed in 2018, 2019 and 2020.

1.4.2 Long-Term Carbon Price Forecast

In May 2017, the OEB published ICF's Long-Term Carbon Price Forecast (LTCPF) Report for the 2018-2028 period. The LTCPF was intended to be used as an input into the development of

[9] Natural Gas Conservation Potential Study, July 7, 2016, ICF International, July 2016 (EB-2015-0117), http://www.ontarioenergyboard.ca/OEB/Industry/Regulatory+Proceedings/Policy+Initiatives+and+Consultations/Natural+Gas+Conservation+Potential+Study#20160711

[10] Demand-side Management assists gas utility customers to reduce their natural gas consumption through the implementation of energy efficient equipment or conservation measures, similar to anticipated customer abatement activities.

the MACC. As noted in the Long-Term Carbon Price Forecast Report (LTCPF Report)[11], there remain significant uncertainties with respect to the cap and trade market and program[12]. To reflect these uncertainties, the LTCPF study provided results for three carbon pricing scenarios – a minimum, a maximum and a mid-range scenario – presented in Exhibit 4, below.

This MACC study adopts the three scenarios from the LTCPF report as an input assumption to define the estimated avoided cost of purchasing allowances associated with utility abatement options.

Exhibit 4 Ontario Carbon Price Forecast Scenario Results Expressed in Real 2017 CAD $/tCO$_2$e

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Mid-Range LTCPF	17	18	18	19	20	21	31	36	43	50	57
Minimum LTCPF	17	18	18	19	20	21	22	23	24	25	27
Maximum LTCPF	67	70	74	77	81	85	89	94	98	103	108

The lifetimes of some customer abatement measures considered in this MACC study extend beyond 2028. To quantify lifetime costs for these measures for the purposes of the MACC, it was assumed that the minimum and maximum price forecast formulae (annual growth of 5% plus inflation) continue to apply beyond 2028 and a straight line extrapolation was applied to the mid-range forecast beyond 2028.

1.4.3 Assumptions

All costs presented in this report are in real 2017 Canadian dollars. Any stream of future costs across an abatement option lifetime is discounted using a real discount rate of 4%. Inflation is omitted from the analysis through the use of costs that are expressed in constant 2017 dollars and a real discount rate. All costs are inclusive of both positive costs and negative costs (i.e., avoided costs or benefits), unless otherwise noted.

Abatement is expressed in units of GHG emissions (tonnes of carbon dioxide equivalent, or t CO_2e) and in units of natural gas volume (cubic metres, or m^3). The default emission factor for emissions that would result from the complete combustion or oxidation of natural gas distributed is taken from the Ontario Guideline for Quantification, Reporting and Verification of Greenhouse Gas Emissions[13] and is used to convert between natural gas volume and GHG units[14].

[11] Long-Term Carbon Price Forecast Report, developed by ICF and published by the OEB on May 31, 2017 (“LTCPF Report”), https://www.oeb.ca/industry/policy-initiatives-and-consultations/consultation-develop-regulatory-framework-natural-gas

[12] Uncertainties include, for example, WCI linking, offset development, federal requirements, and CCAP initiatives.

[13] Guideline for Quantification, Reporting and Verification of Greenhouse Gas Emissions, Version January 2017, Ministry of the Environment and Climate Change, https://files.ontario.ca/guideline_for_quantification_reporting_and_verification_of_greenhouse_gas_emissions_2017.pdf

[14] The default emission factor is 1.87 kg CO_2e/m^3 (calculated per the ON.400 methodology for natural gas distribution, including the default factors from Table 400-2 for CO_2 and from Table 20-4 for CH_4 and N_2O emissions).

1.5 Report Organization

This report presents the MACC study results for the first compliance period. It is organized into the next seven sections as follows:

- Section 2 presents the background, approach and results for the three customer abatement sectors, including industrial, commercial and residential.
- Section 3 presents the background, approach, limitations and caveats and results for the RNG assessment.
- Section 4 presents the background and approach for facility abatement options.
- Section 5 presents the summary MACCs for all three customer abatement sectors (industrial, commercial and residential) and RNG.
- Section 6 presents study recommendations.
- Appendix A provides the background information on the air source heat pump analysis conducted for this study.
- Appendix B provides RNG results disaggregated by feedstock cost category.

2. Customer Abatement

Customer abatement activities have the largest GHG abatement potential of the three major abatement options (customer abatement, RNG and facility abatement) within the timeframe of the first compliance period.

2.1 Background

The Regulatory Framework indicates that the utilities are required to calculate charges for the recovery of costs associated with cap and trade activities based on the weighted average cost of compliance options described in their Compliance Plans for a particular rate year. The MACC developed in this study is designed to assist utilities in this task by presenting a consistent comparison of abatement options along a spectrum of costs.

As discussed, the foundation for the development of this MACC study was the CPS completed by ICF for the OEB in 2016 which estimated how much natural gas conservation is cost effective in the absence of an explicit carbon price.

In order to answer the question of how much natural gas abatement can be achieved, and how much is cost effective under three different carbon price scenarios, ICF leveraged all of the data inputs and assumptions from utilities and stakeholders that were used to develop the proprietary CPS model, and incorporated the LTCPFs.

For the MACC study, the CPS approach was applied to assess all technically feasible conservation measures using realistic adoption rates. This approach is intended to assist the utilities in identifying abatement measures that can be delivered cost effectively in comparison to emissions units such as allowances, in addition to informing the OEB's review of utilities' cap and trade Compliance Plans and associated cost recovery.

This MACC study reflects the costs and benefits of abatement options to a natural gas utility in Ontario. The MACCs presented here illustrate the average cost per tonne of GHG abatement[15] for measures over their lifetimes, inclusive of the avoided cost of carbon as defined by the carbon price forecasts in the LTCPF Report.

The results have been displayed in this manner to identify which measures that could be implemented in the first compliance period represent a lower cost to the utility than purchasing emissions units. It is important to note that measures in the MACC include both existing DSM activities as well as potential GHG abatement activities beyond DSM. Additionally, no cost effectiveness screen was applied – the estimated abatement potential includes all measures that could be implemented in the first compliance period, both above and below the 'zero line'. As a result, the total achievable abatement potential is equivalent across all LTCPF scenarios (although this is not true for the cost-effective potential).

The measures are grouped by major end use (e.g., residential space heating). The decision to present results by end use category was based on two key factors:

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[15] Calculated using abatement option lifetime costs over lifetime GHG abatement and measured is CO_2e.

- Abatement activity flexibility / Consumer choice is unpredictable – there are many different equipment options for customers to pursue efficiency, but most customers will not pursue all of them (e.g., a customer may replace their furnace with a high efficiency furnace *or* a condensing furnace, but not both), so savings associated with individual measures may vary significantly according to the abatement activity's design or consumer choice. By grouping measures, the abatement potential is expected to be representative of the achievable total regardless of consumer choice or abatement activity design at the individual measure level.
- Conservation measure interactions should be considered – if customers install more than one measure for one end use (e.g., a high efficiency furnace *and* wall insulation), the natural gas savings and GHG emissions reduction attributed to each are less than if only one measure was installed[16]. By grouping measures by end use category, the MACC is designed to illustrate a realistic total GHG abatement potential for a given end use, given measure interactive effects.

The 2016 CPS methodology for accounting for these interactions was used (see Section 2.6.1 of the 2016 CPS report); however, it should be noted that this is an assumption and other credible approaches could be used and would possibly produce different $/tonne values for each measure (but would likely not have much of an impact on the overall GHG abatement potential of each end use).

2.2 Approach

The CPS model was populated with inputs and assumptions that were subject to rigorous review through extensive consultation with the OEB, the two major utilities and other natural gas sector stakeholders before being used for the 2016 CPS. This MACC development study was designed to leverage the 2016 CPS data and assumptions, given the level of rigour and review that was involved, and considering the relatively short timeline to develop the MACC study. The following data and assumptions were used to develop the MACC and remain unchanged from the CPS:

- Lists of conservation measures for industrial, commercial and residential sectors and the associated measure-level assumptions/parameters including:
    - natural gas savings
    - electricity savings (or increases)
    - effective useful life, and
    - measure applicability
- Adoption rates for BAU case incentive levels
- End use classification (e.g., industrial HVAC, commercial space heating, etc.) – note that measures which affect more than one end use were grouped in a "systems" category for the MACC study
- Utility program and incentive costs

[16] For example, consider a building with and without wall insulation – if an efficient furnace has the potential to reduce the amount of gas used to heat the building by 5%, the gas savings are 5% of a smaller number in the case of the building with insulation than without, since wall insulation reduces the total amount of gas needed for heating.

- Treatment of conservation measure interactions
- All economic and market assumptions (including 4% discount rate)

The same caveats and limitations apply to this study as are documented in the 2016 CPS report, including that the model does not consider factors such as infrastructure requirements or lead time to implement abatement programs.

Cost Metric

The cost metric used in this study was developed to quantify the cost effectiveness of natural gas customer conservation abatement options under different carbon pricing assumptions from a utility perspective. The cost metric includes:

Benefits (avoided costs):

- Natural gas avoided costs, comprising commodity costs, upstream capacity costs and downstream distribution system costs[17]
- Avoided cost of carbon, based on the three LTCPF scenarios (as described in Section 1.4.2)

Costs:

- Utility incentive costs
- Utility program delivery costs

The data and assumptions for all cost and avoided cost components listed above remain unchanged from the 2016 CPS[18], with the exception of the carbon price which is based on the LTCPF Report.

The three MACC study scenarios – based on the minimum, maximum and mid-range carbon price forecasts – were developed by varying the LTCPF used in the cost metric.

Capped and Uncapped Participants

Estimates of natural gas consumption volumes representing ‘capped’ participants under Ontario’s cap and trade program were developed through consultation with the utilities, and their associated natural gas volumes were removed from the modelling exercise[19]. Facilities directly covered under the program are excluded from the utilities’ compliance obligations, so the associated abatement potential was excluded from the MACCs.

Heat Pumps

Heat pumps were assessed through an analysis separate from the CPS model exercise (please refer to Appendix A). As indicated in the CPS, air and ground source heat pumps represent a significant abatement opportunity in Ontario. However, heat pumps are considered a fuel switching initiative and are not comparable to energy efficiency alternatives, and are also

[17] For a detailed description of avoided costs, see chapter 3 of the 2016 CPS Report.
[18] While cost data and assumptions from the CPS were used for this analysis, the definition of the cost metric in this study is *not* the same as the cost metric in the CPS. The main driver behind the differences in what costs and benefits are included is that the CPS was based on a societal cost perspective, whereas this study’s objective is to evaluate costs from a utility perspective.
[19] Refer to Section 6.2 for recommendation to develop market penetration rates that might be more reflective of non-LFEs in future studies.

currently very high cost compared to other energy efficiency options for space heating. Given the extremely large abatement potential associated with this technology, heat pumps were not included in the MACC to avoid skewing the results for space heating customer abatement options.

2.3 Customer Abatement MACC Results

The customer abatement MACC results are presented by sector (industrial, commercial and residential) in the sub-sections that follow. The MACC diagrams illustrate the estimated achievable potential savings[20], in tonnes CO_2e and cubic metres of natural gas, for natural gas abatement through customer conservation measures (including DSM *and* incremental abatement beyond DSM) for the three different carbon pricing scenarios.

On each MACC, the zero dollars line (x axis) represents the “cost effective” threshold which includes the price of allowances over the measure’s lifetime. Values below the zero line are deemed to be less costly than the price of an allowance, and values above the zero line are measures that are deemed to be more expensive to implement than purchasing allowances. Each bar on the MACCs represents a group of conservation measures that are applicable to each end use within a particular sector. The height of the bars represents the average of a range of costs per tonne of GHG abated (or per cubic metre of natural gas saved) for measures implemented over the 2018-2020 study period[21].

The width of the bars represents the abatement potential for each group of measures. The marginal abatement for 2018-2020 (the y axis) is the sum of the marginal abatement potential achievable in 2018, 2019 and 2020. As a simple illustrative example, consider a measure which has a lifetime of 5 years and an abatement potential of 1 tCO_2e/yr per measure implementation (e.g., per installation or per customer). If 1 instance of this measure is implemented in 2018, the marginal abatement achieved in 2018 is 1 tCO_2e. If an additional 2 instances of the measure are implemented in 2019, and an additional 3 are implemented in 2020, the sum of the 2018-2020 marginal abatement potential is 6 tCO_2e (i.e., 6 instances of the measure implemented in total). The impact on total annual 2020 emissions is also 6 tCO_2e, since the annual abatement associated with the measures implemented in 2018 and 2019 persists for the 5 year measure lifetime.

The numeric labels associated with each bar on the MACCs indicate the sum of the marginal abatement, in tCO_2e and m^3, for all bars to the left of the label line[22]. Because not all measures in each group are necessarily cost effective, estimates of the proportion of the abatement that is associated with cost effective measures for each individual bar are also provided in the label (%

[20] The model results for achievable abatement potential within this timeframe are driven by measure-level achievable adoption curves developed in the 2016 CPS.

[21] This value corresponds to a Net Present Value (NPV) of measure lifetime costs (which includes avoided carbon costs over the lifetime of the measure) divided by lifetime tCO_2e or m^3 abatement. Since the carbon price changes over time, the lifetime avoided carbon costs for any given measure depend on the year in which it is implemented. The height of the bars on the MACC represent an average across a group of measures, and also an average across years of implementation from 2018-2020.

[22] For example, if the first bar represents a marginal abatement of 5 tCO_2e and the second bar represents 10 tCO_2e, the label on the right edge of the second bar would read 15 tCO_2e.

value in brackets). Each MACC diagram is followed by a table that presents the average cost data and estimated abatement potential used to create the MACC.

A table identifying all of the measures included in each end use category for that sector, as well as measure-level cost data[23] (both $/$tCO_2e$ and $/$m^3$) for each LTCPF scenario, is provided at the end of each of the industrial, commercial and residential sub-sections. It is important to note that the measure-specific data that appears in the summary tables is based on savings that take into consideration interactive effects between measures, as noted above. Although this approach results in a more accurate total abatement potential estimate by end use, these measure-level costs should not be read independently of the full modelled scenario results. The measure-level savings are heavily dependent on assumptions about the interactive effects between measures which are simultaneously deployed, and could vary significantly. The measure-level costs are presented as a range, since measure costs vary across subsectors, building types and regions.

2.3.1 Industrial Results

This section presents the results of the industrial customer abatement analysis for each of the three LTCPF scenarios in the format of a MACC diagram and a supporting data table. At the end of this section, there is a summary table that identifies all of the measures included in each industrial end use category as well as measure-level cost data for each LTCPF scenario.

Minimum LTCPF Scenario

Exhibit 5 presents the Minimum LTCPF MACC for the industrial sector. In this carbon price scenario, the results show that the average cost for a utility to implement the measures in all of the industrial end use categories in the 2018-2020 timeframe, including HVAC, steam hot water system and direct heating[24], is lower than the cost of purchasing allowances. The total marginal abatement potential over the 2018-2020 period is 180,000 tCO_2e (or 96 million m^3). These values also represent the estimated abatement associated with measures that are cost effective relative to the carbon price as defined in the LTCPF Report's Minimum LTCPF Scenario (no assessed measures were deemed non-cost effective).

[23] Tables of measure-level costs are provided to help the reader better understand the MACCs presented.
[24] Two additional end uses, the gas turbine and steam turbine end uses, are not visible on the graph due to their small abatement potential.

Exhibit 5 Industrial MACC for Minimum LTCPF

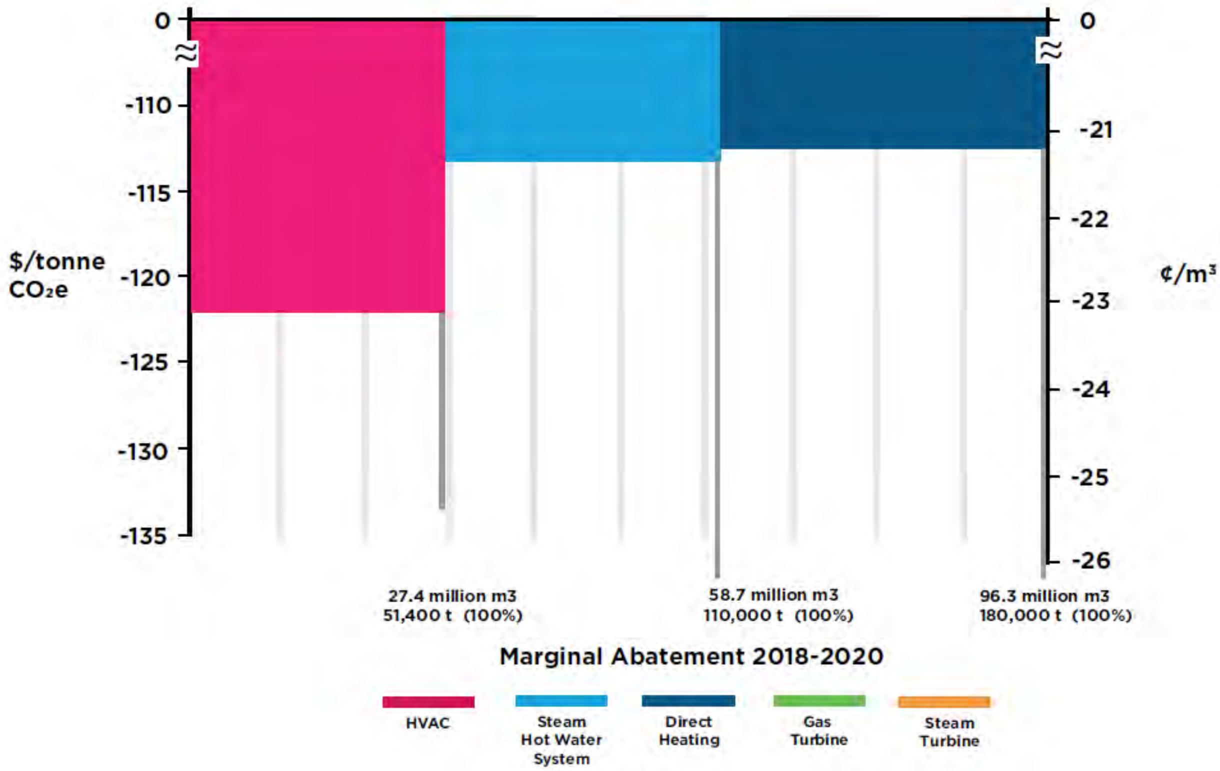


Table 4 Industrial MACC for Minimum LTCPF, Average Cost and Abatement Results

Industrial End Use	Average $/tCO$_2$e	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO$_2$e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Gas Turbine	-130	-24	550	0.3	100%
Steam Turbine	-130	-24	250	0.1	100%
HVAC	-122	-23	51,400	27	100%
Steam Hot Water System	-112	-21	58,600	31	100%
Direct Heating	-111	-21	69,700	37	100%
values may not sum to total due to rounding			**180,000**	**96**	

Maximum LTCPF Scenario

Exhibit 6 presents the Maximum LTCPF MACC for the industrial sector. Like for the minimum LTCPF scenario, the results show that the average cost for a utility to implement the measures in all of the industrial end use categories in the 2018-2020 timeframe, including HVAC, steam hot water system and direct heating, is lower than the cost of purchasing allowances. The total marginal abatement potential over the 2018-2020 period is 180,000 tCO$_2$e (or 96 million m^3). These values also represent the estimated abatement associated with measures that are cost effective relative to the carbon price as defined in the LTCPF Report's Maximum LTCPF Scenario.

Exhibit 6 Industrial MACC for Maximum LTCPF

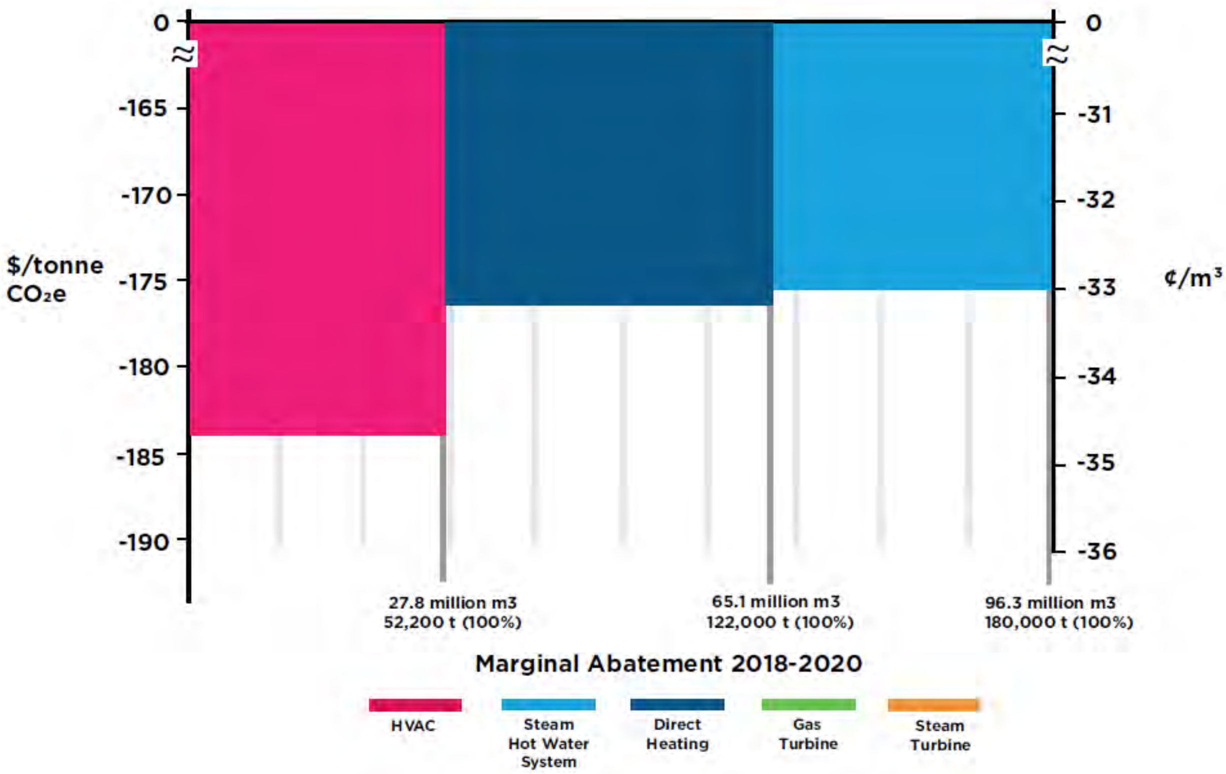


Table 5 Industrial MACC for Maximum LTCPF, Average Cost and Abatement Results

Industrial End Use	Average $/tCO$_2$e	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO$_2$e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Gas Turbine	-186	-35	550	0.3	100%
Steam Turbine	-186	-35	250	0.1	100%
HVAC	-184	-34	51,400	27	100%
Direct Heating	-176	-33	69,700	37	100%
Steam Hot Water System	-175	-33	58,600	31	100%
values may not sum to total due to rounding			**180,000**	**96**	

Mid-Range LTCPF Scenario

Exhibit 7 presents the Mid-Range LTCPF MACC for the industrial sector. Like for the minimum and maximum LTCPF scenarios, the results show that the average cost for a utility to implement the measures in all of the industrial end use categories in the 2018-2020 timeframe, including HVAC, steam hot water system and direct heating, is lower than the cost of purchasing allowances. The total marginal abatement potential over the 2018-2020 period is 180,000 tCO$_2$e (or 96 million m^3). These values also represent the estimated abatement associated with measures that are cost effective relative to the carbon price as defined in the LTCPF Report's Mid-Range LTCPF Scenario.

Exhibit 7 Industrial MACC for Mid-Range LTCPF

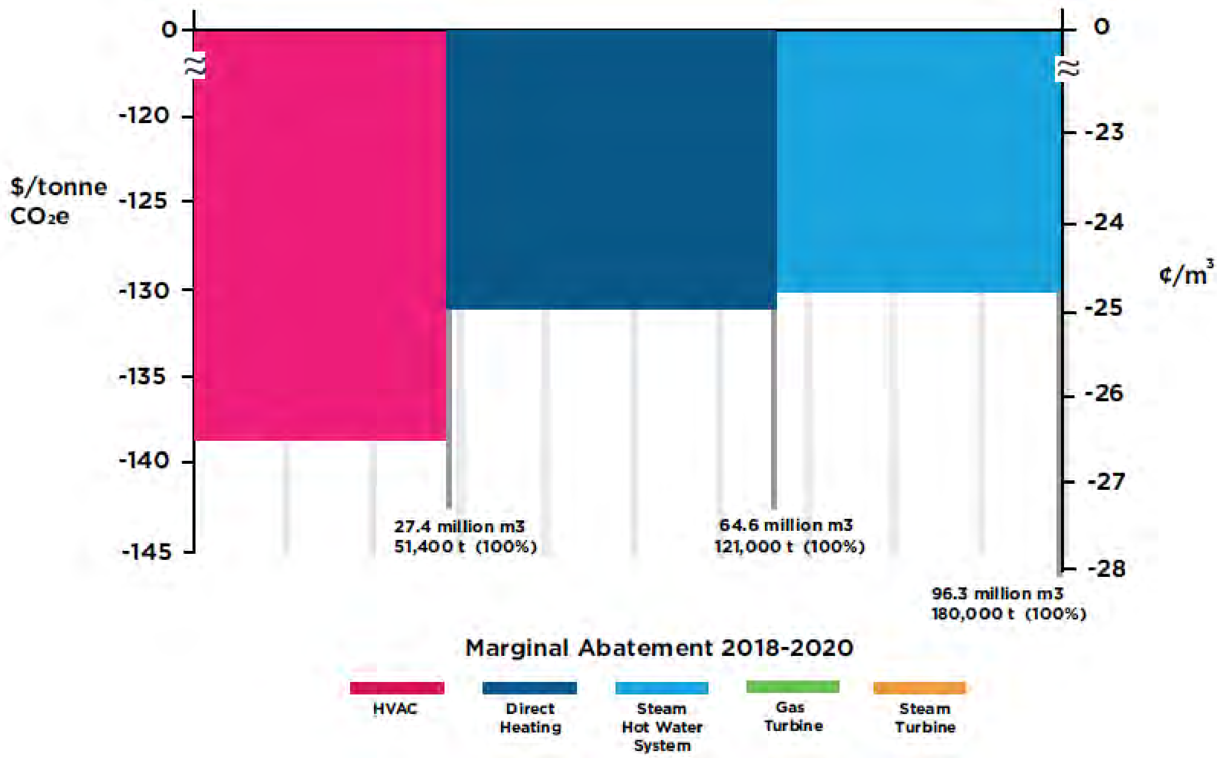


Table 6 Industrial MACC for Mid-Range LTCPF, Average Cost and Abatement Results

Industrial End Use	Average $/tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
HVAC	-139	-26	51,400	27	100%
Direct Heating	-132	-25	69,700	37	100%
Steam Hot Water System	-131	-25	58,600	31	100%
Gas Turbine	-130	-24	550	0.3	100%
Steam Turbine	-130	-24	250	0.1	100%
values may not sum to total due to rounding			**180,000**	**96**	

Table 7 Industrial Measure-Level Marginal Abatement Cost Data (Ranges) for 2018-2020 Timeframe[25]

Industrial End Use	Measure Name	Mid-Range LTCPF				Minimum LTCPF				Maximum LTCPF			
		$/m³		$/tCO₂e		$/m³		$/tCO₂e		$/m³		$/tCO₂e	
Direct Heating	High Efficiency Burners (Process)	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Direct Heating	Reduced Furnace Openings (Air & Chain Curtains)	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-107	-0.34	-0.31	-182	-168
Direct Heating	Exhaust Gas Heat Recovery	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Direct Heating	Insulation (Process)	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Direct Heating	Advanced Heating and Process Controls	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Direct Heating	Optimize Combustion	-0.24	-0.22	-131	-118	-0.24	-0.22	-127	-118	-0.35	-0.32	-186	-172
Direct Heating	High-efficiency Ovens & Dryers	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Direct Heating	High-efficiency Furnaces	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Direct Heating	Regenerative Thermal Oxidizers	-0.26	-0.24	-138	-127	-0.21	-0.20	-113	-108	-0.34	-0.32	-182	-169
Direct Heating	Process Heat Recovery	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Direct Heating	Process Improvements (changing cleaning chemicals, set points, exhaust, moisture control, etc.)	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-107	-0.34	-0.31	-182	-168
Direct Heating	Food and Beverage Manufacturing Process Improvements	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-107	-0.34	-0.31	-182	-167
Direct Heating	Refining Process Improvements	-0.26	-0.24	-138	-127	-0.21	-0.20	-113	-108	-0.34	-0.32	-182	-169
Direct Heating	Mining Process Improvements	-0.26	-0.23	-137	-124	-0.22	-0.21	-117	-110	-0.34	-0.31	-181	-167
Direct Heating	Primary Metal Manufacturing Process Improvements	-0.26	-0.24	-138	-127	-0.21	-0.20	-113	-108	-0.34	-0.32	-182	-169
Direct Heating	Non-Metallic Mineral Product Manufacturing Process Improvements	-0.26	-0.24	-138	-127	-0.21	-0.20	-113	-108	-0.34	-0.32	-182	-169
Direct Heating	Asphalt and Cement Manufacturing Process Improvements	-0.26	-0.24	-137	-126	-0.21	-0.20	-113	-107	-0.34	-0.31	-182	-168

[25] This table is provided to help the reader better understand the data underlying the presented MACCs. It is important to note that this measure-specific data is **based on savings that take into consideration interactive effects between measures**. These values should not be read independently of the full modelled scenario results; the savings depend on the interactive effects of the combination of other measures which are simultaneously deployed (cascading). The measure-level costs are presented as a range, since measure costs vary across subsectors, building types and regions.

Industrial End Use	Measure Name	Mid-Range LTCPF				Minimum LTCPF				Maximum LTCPF			
		$/m^3$		$/tCO_2e$		$/m^3$		$/tCO_2e$		$/m^3$		$/tCO_2e$	
Direct Heating	Fabricated Metal Manufacturing Process Improvements	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-107	-0.34	-0.31	-182	-168
Direct Heating	Transportation and Machinery Manufacturing Process Improvements	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-107	-0.34	-0.31	-182	-167
Gas Turbine	Gas Turbine Optimization	-0.25	-0.24	-132	-127	-0.25	-0.24	-132	-127	-0.36	-0.34	-191	-181
HVAC	Air Compressor Heat Recovery	-0.27	-0.25	-145	-133	-0.24	-0.22	-125	-119	-0.36	-0.33	-190	-177
HVAC	Ventilation Optimization	-0.27	-0.25	-146	-134	-0.24	-0.22	-126	-120	-0.36	-0.33	-190	-177
HVAC	Ventilation Heat Recovery	-0.27	-0.25	-145	-133	-0.23	-0.22	-125	-119	-0.36	-0.33	-190	-176
HVAC	Automated Temperature Control	-0.27	-0.25	-145	-133	-0.23	-0.22	-125	-119	-0.36	-0.33	-190	-176
HVAC	Destratification Fans	-0.27	-0.25	-145	-133	-0.23	-0.22	-125	-119	-0.36	-0.33	-190	-176
HVAC	Warehouse Loading Dock Seals	-0.27	-0.25	-145	-133	-0.23	-0.22	-125	-119	-0.36	-0.33	-190	-176
HVAC	Minimize Door Openings	-0.27	-0.25	-145	-134	-0.24	-0.22	-126	-120	-0.36	-0.33	-190	-177
HVAC	Solar Walls	-0.27	-0.25	-142	-132	-0.21	-0.20	-114	-108	-0.36	-0.33	-194	-179
HVAC	Radiant Heaters	-0.27	-0.25	-145	-133	-0.23	-0.22	-125	-119	-0.36	-0.33	-190	-176
HVAC	Greenhouse Curtains	-0.27	-0.24	-143	-130	-0.24	-0.23	-130	-123	-0.36	-0.33	-191	-178
HVAC	Greenhouse Envelope Improvements	-0.27	-0.25	-141	-133	-0.26	-0.25	-138	-133	-0.37	-0.35	-197	-186
HVAC	Improved Building Envelope	-0.27	-0.25	-145	-133	-0.23	-0.22	-125	-119	-0.36	-0.33	-190	-176
HVAC	High Efficiency Heating Units	-0.27	-0.25	-145	-133	-0.23	-0.22	-125	-119	-0.36	-0.33	-190	-176
Steam Hot Water System	Minimize Deaerator Vent Losses	-0.26	-0.24	-137	-125	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Steam Hot Water System	Insulation (Steam Systems)	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Steam Hot Water System	Boiler Tune Up	-0.24	-0.22	-130	-119	-0.24	-0.22	-127	-119	-0.35	-0.32	-186	-173
Steam Hot Water System	Condensing Economizers	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-107	-0.34	-0.31	-182	-167
Steam Hot Water System	Burn Digester Gas in Boilers	-0.26	-0.24	-138	-127	-0.21	-0.20	-113	-108	-0.34	-0.32	-182	-169
Steam Hot Water System	Steam Leak Repairs	-0.25	-0.22	-133	-120	-0.23	-0.21	-120	-113	-0.34	-0.31	-181	-168
Steam Hot Water System	Feedwater Economizers	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Steam Hot Water System	Boiler Combustion Air Preheat	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Steam Hot Water System	Blowdown Heat Recovery	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Steam Hot Water System	Automated Blowdown Control	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Steam Hot Water System	Condensate Return	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Steam Hot Water System	Steam Trap Survey and Repair	-0.25	-0.23	-131	-121	-0.23	-0.22	-123	-118	-0.34	-0.32	-183	-173
Steam Hot Water System	Boiler Right Sizing and Load Management	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Steam Hot Water System	Reduce Boiler Steam Pressure	-0.26	-0.24	-138	-127	-0.21	-0.20	-113	-108	-0.34	-0.32	-182	-169
Steam Hot Water System	Advanced Boiler Controls	-0.26	-0.23	-137	-124	-0.22	-0.21	-117	-110	-0.34	-0.31	-181	-167
Steam Hot Water System	Condensing Boiler	-0.26	-0.24	-137	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Steam Hot Water System	Direct Contact Water Heaters	-0.26	-0.24	-137	-126	-0.21	-0.20	-113	-107	-0.34	-0.31	-182	-167

Industrial End Use	Measure Name	Mid-Range LTCPF				Minimum LTCPF				Maximum LTCPF			
		$/m^3$		$/tCO_2e$		$/m^3$		$/tCO_2e$		$/m^3$		$/tCO_2e$	
Steam Hot Water System	High Efficiency Burners - Boilers	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-107	-0.34	-0.31	-182	-167
Steam Hot Water System	Chemical Manufacturing Process Improvements	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-107	-0.34	-0.31	-182	-167
Steam Hot Water System	Greenhouses Other EE Upgrades	-0.26	-0.24	-138	-126	-0.21	-0.20	-113	-106	-0.34	-0.31	-182	-167
Steam Hot Water System	Pulp and Paper Process Improvements	-0.26	-0.24	-138	-127	-0.21	-0.20	-113	-108	-0.34	-0.32	-182	-169
Steam Turbine	Steam Turbine Optimization	-0.25	-0.24	-132	-127	-0.25	-0.24	-132	-127	-0.36	-0.34	-190	-180

2.3.2 Commercial Results

This section presents the results of the commercial customer abatement analysis for each of the three LTCPF scenarios in the format of a MACC diagram and a supporting data table. At the end of this section, there is a summary table that identifies all of the measures included in each commercial end use category as well as measure-level cost data for each LTCPF scenario.

Minimum LTCPF Scenario

Exhibit 8 presents the Minimum LTCPF MACC for the commercial sector. In this carbon price scenario, the results show that the average cost for a utility to implement the measures in four of the five commercial end use categories in the 2018-2020 timeframe, including food service, systems, service water heating and space heating, is lower than the cost of purchasing allowances. The total marginal abatement potential over the 2018-2020 period is 202,000 tCO_2e (or 108 million m^3), and the estimated abatement associated with measures that are cost effective relative to the carbon price as defined in the LTCPF Report's Minimum LTCPF Scenario is 184,000 tCO_2e (or 98 million m^3).

Exhibit 8 Commercial MACC for Minimum LTCPF

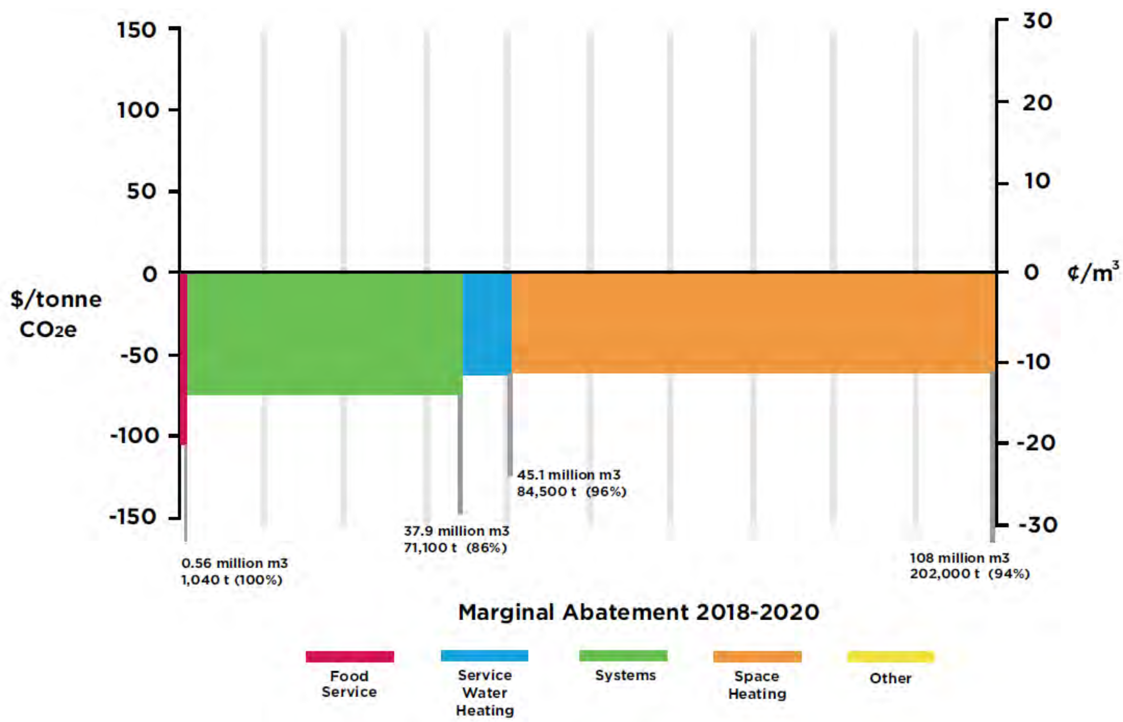


Table 8 Commercial MACC for Minimum LTCPF, Average Cost and Abatement Results

Commercial End Use	Average $/tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Food Service	-105	-20	1,040	0.6	100%
Systems	-75	-14	70,100	37	86%
Service Water Heating	-62	-12	13,400	7	96%
Space Heating	-62	-12	117,000	63	94%
Other	176	33	3	0.002	0%
values may not sum to total due to rounding			**202,000**	**108**	

Maximum LTCPF Scenario

Exhibit 9 presents the Maximum LTCPF MACC for the commercial sector. In this carbon price scenario, the results show that the average cost for a utility to implement the measures in four of the five commercial end use categories in the 2018-2020 timeframe, including food service, systems, service water heating and space heating, is lower than the cost of purchasing allowances. The total marginal abatement potential over the 2018-2020 period is 202,000 tCO_2e (or 108 million m^3), and the estimated abatement associated with measures that are cost effective relative to the carbon price as defined in the LTCPF Report's Maximum LTCPF Scenario is 198,000 tCO_2e (or 106 million m^3).

Exhibit 9 Commercial MACC for Maximum LTCPF

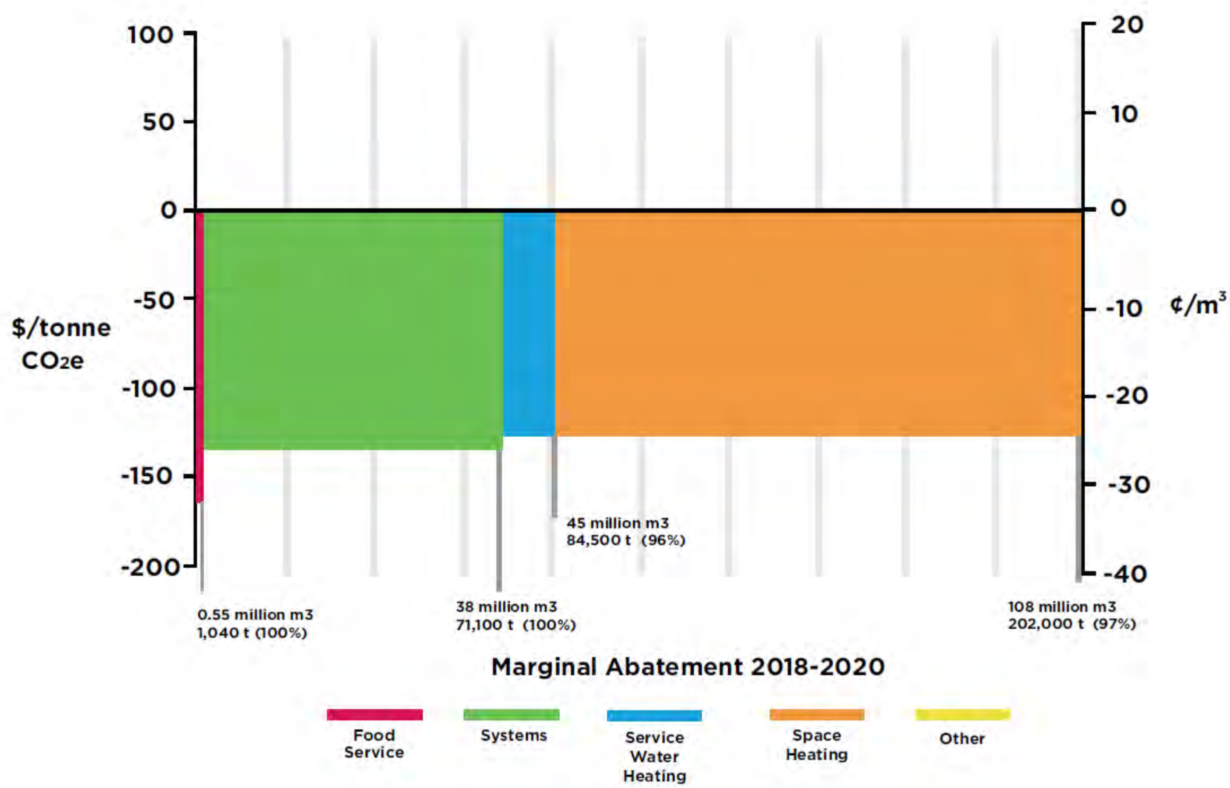


Table 9 Commercial MACC for Maximum LTCPF, Average Cost and Abatement Results

Commercial End Use	Average $/tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Food Service	-165	-31	1,040	0.6	100%
Systems	-137	-26	70,100	37	100%
Service Water Heating	-127	-24	13,400	7	96%
Space Heating	-127	-24	117,000	63	97%
Other	106	20	3	0.002	0%
values may not sum to total due to rounding			**202,000**	**108**	

Mid-Range LTCPF Scenario

Exhibit 10 presents the Mid-Range LTCPF MACC for the commercial sector. In this carbon price scenario, the results show that the average cost for a utility to implement the measures in four of the five commercial end use categories in the 2018-2020 timeframe, including food service, systems, service water heating and space heating, is lower than the cost of purchasing allowances. The total marginal abatement potential over the 2018-2020 period is 202,000 tCO_2e (or 108 million m^3), and the estimated abatement associated with measures that are cost effective relative to the carbon price as defined in the LTCPF Report's Mid-Range Scenario is 186,000 tCO_2e (or 99 million m^3).

Exhibit 10 Commercial MACC for Mid-Range LTCPF

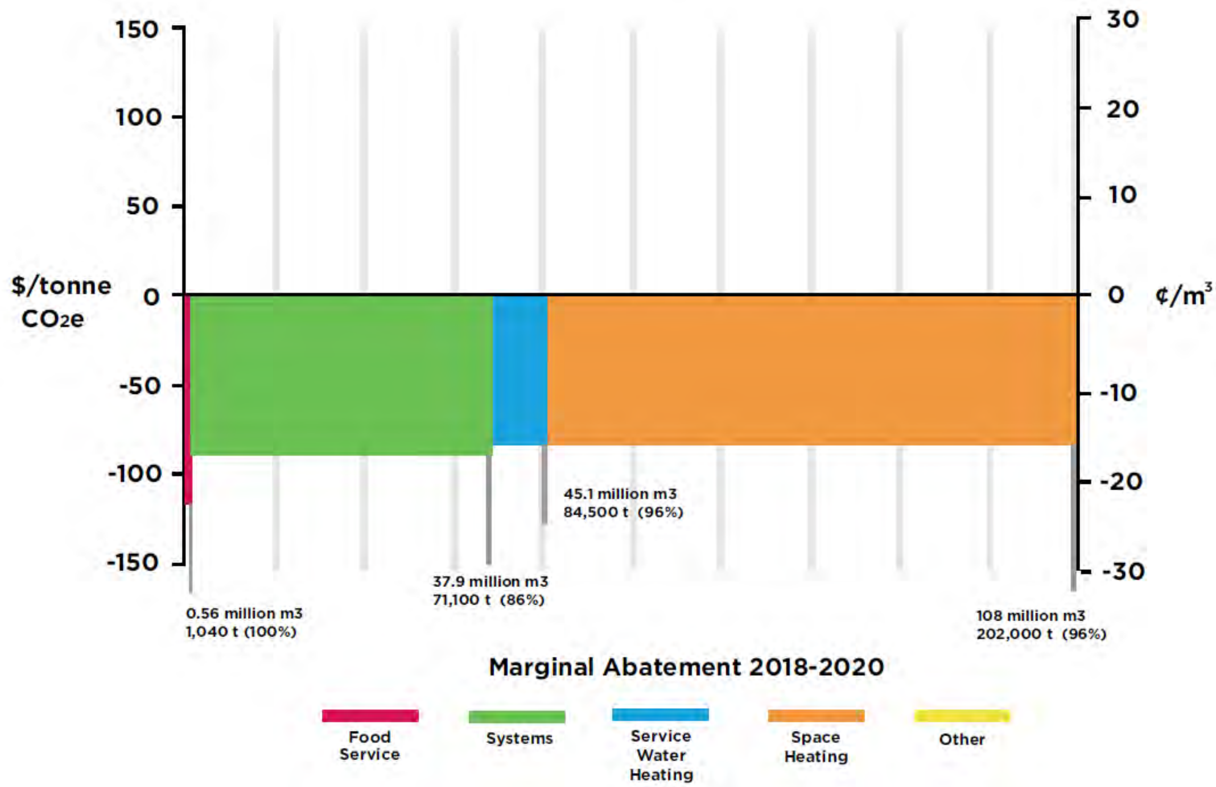


Table 10 Commercial MACC for Mid-Range LTCPF, Average Cost and Abatement Results

Commercial End Use	Average $/tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Food Service	-119	-22	1,040	0.6	100%
Systems	-88	-16	70,100	37	86%
Service Water Heating	-83	-16	13,400	7	96%
Space Heating	-83	-15	117,000	63	96%
Other	151	28	3	0.002	0%
values may not sum to total due to rounding			**202,000**	**108**	

Table 11 Commercial Measure-Level Marginal Abatement Cost Data (Ranges) for 2018-2020 Timeframe[26]

Commercial End Use	Measure Name	Mid-Range LTCPF				Minimum LTCPF				Maximum LTCPF			
		$/m^3$		$/tCO_2e$		$/m^3$		$/tCO_2e$		$/m^3$		$/tCO_2e$	
Space Heating	High-Performance Glazing	-0.26	0.81	-138	431	-0.21	0.85	-110	455	-0.36	0.72	-190	384
Space Heating	Roof Insulation	-0.25	0.88	-132	471	-0.20	0.93	-104	495	-0.35	0.80	-184	425
Space Heating	Wall Insulation	-0.23	0.89	-122	473	-0.18	0.93	-94	497	-0.33	0.80	-174	427
Space Heating	Super-High Efficiency Furnaces	-0.24	-0.22	-130	-120	-0.20	-0.19	-107	-102	-0.33	-0.30	-174	-162
Space Heating	Condensing Boilers (for Space Heating)	-0.26	-0.23	-137	-123	-0.21	-0.19	-113	-104	-0.34	-0.31	-181	-165
Space Heating	Condensing Make-Up Air Units	-0.27	-0.24	-142	-127	-0.22	-0.20	-117	-108	-0.35	-0.32	-186	-169
Space Heating	Condensing Unit Heaters	-0.24	-0.22	-126	-115	-0.19	-0.18	-103	-98	-0.32	-0.29	-170	-157
Space Heating	Destratification Fans	-0.14	-0.12	-72	-62	-0.10	-0.09	-52	-48	-0.22	-0.20	-117	-105
Space Heating	Gas Fired Rooftop Units (Two-Stage)	-0.23	-0.20	-124	-106	-0.19	-0.17	-104	-92	-0.31	-0.28	-168	-150
Space Heating	High Efficiency Boilers (for Space Heating)	-0.26	-0.21	-139	-114	-0.21	-0.18	-114	-94	-0.34	-0.29	-183	-155
Space Heating	Heat Reflector Panels	-0.24	-0.21	-127	-111	-0.20	-0.18	-104	-94	-0.32	-0.29	-171	-153
Space Heating	Boilers - High Efficiency Burners	-0.17	-0.13	-93	-69	-0.13	-0.09	-69	-50	-0.26	-0.21	-137	-111
Space Heating	Infrared Heaters	-0.24	-0.22	-127	-116	-0.20	-0.19	-105	-100	-0.32	-0.30	-171	-158
Space Heating	Boilers - Feedwater Economizers	0.66	0.71	354	377	0.71	0.74	378	396	0.58	0.63	309	335
Space Heating	Boilers - Combustion Air Preheat	0.69	0.73	368	392	0.73	0.76	388	407	0.61	0.65	324	348
Space Heating	Boilers - Blowdown Heat Recovery	0.45	0.49	240	264	0.50	0.53	265	283	0.37	0.42	196	222
Space Heating	Refrigeration Waste Heat Recovery	-0.27	-0.25	-142	-131	-0.23	-0.22	-122	-117	-0.35	-0.33	-186	-174
Space Heating	Heat Recovery Ventilation	-0.22	0.05	-117	27	-0.18	0.08	-98	40	-0.30	-0.03	-162	-17
Space Heating	Energy Recovery Ventilation	-0.25	-0.11	-133	-59	-0.21	-0.09	-114	-46	-0.33	-0.19	-178	-103
Space Heating	Energy Recovery Ventilation (Enhanced)	-0.28	-0.22	-149	-119	-0.24	-0.20	-129	-105	-0.36	-0.30	-194	-162
Space Heating	Ventilation Fan VFDs	-0.27	-0.25	-145	-133	-0.23	-0.22	-125	-119	-0.35	-0.33	-189	-177
Space Heating	Demand Control Kitchen	-0.24	-0.22	-131	-120	-0.21	-0.20	-111	-106	-0.33	-0.31	-175	-163

[26] This table is provided to help the reader better understand the data underlying the presented MACCs. It is important to note that this measure-specific data is **based on savings that take into consideration interactive effects between measures**. These values should not be read independently of the full modelled scenario results; the savings depend on the interactive effects of the combination of other measures which are simultaneously deployed (cascading). The measure-level costs are presented as a range, since measure costs vary across subsectors, building types and regions.

Commercial End Use	Measure Name	Mid-Range LTCPF				Minimum LTCPF				Maximum LTCPF			
		$/m^3$		$/tCO_2e$		$/m^3$		$/tCO_2e$		$/m^3$		$/tCO_2e$	
	Ventilation												
Space Heating	Adaptive Thermostats	-0.25	-0.12	-136	-65	-0.22	-0.09	-116	-51	-0.34	-0.20	-180	-108
Space Heating	Demand Control Ventilation	-0.26	-0.21	-138	-113	-0.23	-0.20	-124	-106	-0.35	-0.30	-185	-161
Space Heating	Demand Control Ventilation (Enhanced)	-0.26	-0.24	-139	-127	-0.22	-0.21	-119	-113	-0.34	-0.32	-184	-171
Space Heating	Air Curtains	-0.27	-0.23	-143	-123	-0.23	-0.20	-123	-109	-0.35	-0.31	-187	-166
Space Heating	Use Shades/Blinds	-0.28	-0.26	-150	-138	-0.28	-0.26	-150	-138	-0.39	-0.36	-208	-190
Systems	New Construction - 25% Better	-0.24	-0.08	-130	-42	-0.19	-0.03	-102	-18	-0.34	-0.17	-182	-88
Systems	New Construction - 40% Better	-0.25	-0.11	-136	-58	-0.20	-0.06	-108	-34	-0.35	-0.20	-188	-104
Systems	Advanced BAS/Controllers	-0.22	0.33	-119	175	-0.18	0.35	-99	189	-0.31	0.25	-163	132
Systems	Operations and Maintenance Improvements	-0.28	-0.26	-150	-138	-0.28	-0.26	-150	-138	-0.39	-0.36	-208	-190
Systems	Building Recommissioning (Standard)	-0.27	-0.26	-142	-136	-0.26	-0.26	-138	-136	-0.37	-0.36	-198	-190
Systems	Building Recommissioning (Enhanced)	-0.27	-0.26	-142	-136	-0.26	-0.26	-138	-136	-0.37	-0.36	-198	-190
Systems	Faucet Aerators	-0.24	-0.22	-131	-116	-0.22	-0.20	-118	-109	-0.33	-0.31	-178	-164
Systems	Low-Flow Showerheads	-0.23	-0.18	-123	-99	-0.21	-0.17	-110	-92	-0.32	-0.27	-171	-147
Service Water Heating	Condensing Boilers (for Service Water Heating)	-0.22	-0.14	-115	-73	-0.17	-0.10	-91	-54	-0.30	-0.22	-160	-115
Service Water Heating	Condensing Storage Water Heaters	-0.22	0.04	-115	24	-0.18	0.07	-95	38	-0.30	-0.04	-160	-20
Service Water Heating	Condensing Tankless Water Heaters	-0.22	-0.03	-120	-18	-0.18	0.00	-95	1	-0.31	-0.11	-164	-60
Service Water Heating	Drain Water Heat Recovery (DWHR)	-0.25	-0.23	-134	-120	-0.20	-0.18	-106	-98	-0.34	-0.31	-181	-163
Service Water Heating	High Efficiency Boilers (for Service Water Heating)	-0.17	0.13	-89	72	-0.12	0.17	-64	91	-0.25	0.06	-133	30
Service Water Heating	Indirect Water Heaters	0.15	0.23	81	121	0.19	0.25	101	135	0.07	0.15	37	78
Service Water Heating	Solar Water Preheat (DHW)	0.28	0.44	152	234	0.34	0.49	179	261	0.20	0.35	105	187
Service Water Heating	Commercial Ozone Laundry Treatment	-0.26	-0.23	-136	-124	-0.22	-0.21	-116	-110	-0.34	-0.31	-181	-168
Service Water Heating	ENERGY STAR Dishwashers	-0.24	-0.21	-126	-114	-0.20	-0.19	-106	-100	-0.32	-0.30	-170	-158
Service Water Heating	ENERGY STAR Clothes Washers	-0.26	-0.22	-140	-116	-0.23	-0.20	-125	-107	-0.35	-0.30	-187	-163
Service Water Heating	CEE Tier 2 Clothes Washers	-0.16	-0.12	-85	-65	-0.13	-0.11	-70	-56	-0.25	-0.21	-132	-112
Service Water Heating	Pre-Rinse Spray Nozzles	-0.22	-0.13	-119	-71	-0.22	-0.13	-116	-68	-0.33	-0.23	-175	-125
Food Service	ENERGY STAR Griddles	-0.25	-0.23	-135	-124	-0.21	-0.20	-114	-109	-0.34	-0.31	-179	-167
Food Service	ENERGY STAR Convection Ovens	-0.22	-0.20	-119	-108	-0.19	-0.18	-102	-98	-0.31	-0.29	-165	-153

Commercial End Use	Measure Name	Mid-Range LTCPF				Minimum LTCPF				Maximum LTCPF			
		$/m^3$		$/tCO_2e$		$/m^3$		$/tCO_2e$		$/m^3$		$/tCO_2e$	
Food Service	ENERGY STAR Fryers	-0.21	-0.19	-112	-101	-0.18	-0.17	-96	-91	-0.30	-0.27	-158	-147
Food Service	ENERGY STAR Steam Cookers	-0.25	-0.23	-133	-122	-0.22	-0.21	-117	-112	-0.34	-0.31	-179	-168
Food Service	Pizza/Bakery Oven Insulation	-0.20	-0.18	-108	-97	-0.17	-0.16	-92	-87	-0.29	-0.27	-154	-142
Food Service	High Efficiency Underfired Broilers	-0.24	-0.22	-126	-115	-0.21	-0.20	-110	-105	-0.32	-0.30	-172	-161
Other	Solar Water Preheat (Pools)	0.24	0.49	127	259	0.29	0.53	154	282	0.15	0.41	80	216

2.3.3 Residential Results

This section presents the results of the residential customer abatement analysis for each of the three LTCPF scenarios in the format of a MACC diagram and a supporting data table. At the end of this section, there is a summary table that identifies all of the measures included in each residential end use category as well as measure-level cost data for each LTCPF scenario.

Minimum LTCPF Scenario

Exhibit 11 presents the Minimum LTCPF MACC for the residential sector. In this carbon price scenario, the results show that the average cost for a utility to implement the measures in three of the six residential end use categories in the 2018-2020 timeframe, including clothes dryers, fireplaces and systems, is lower than the cost of purchasing allowances. The total marginal abatement potential over the 2018-2020 period is 270,000 tCO_2e (or 144 million m^3), and the estimated abatement associated with measures that are cost effective relative to the carbon price as defined in the LTCPF Report's Minimum Scenario is 180,000 tCO_2e (or 96 million m^3).

Exhibit 11 Residential MACC for Minimum LTCPF

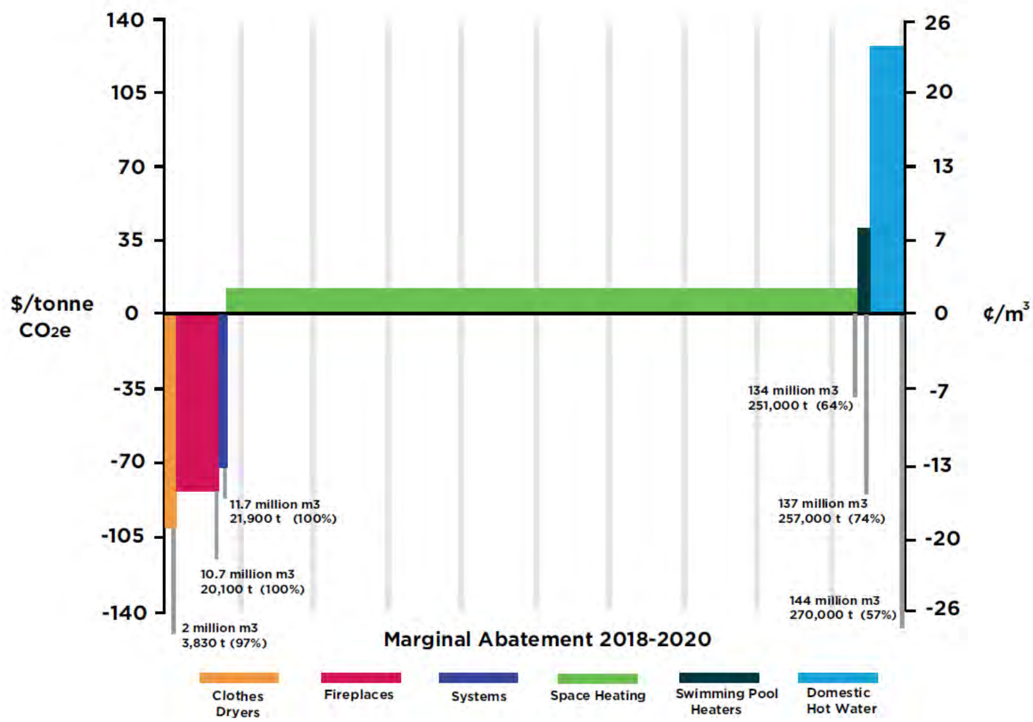


Table 12 Residential MACC for Minimum LTCPF, Average Cost and Abatement Results

Residential End Use	Average $/tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Clothes Dryers	-100	-19	3,830	2	97%
Fireplaces	-83	-16	16,200	8.7	100%
Systems	-72	-13	1,850	1	100%
Space Heating	13	2	230,000	122	64%
Swimming Pool Heaters	40	8	5,480	3	74%
Domestic Hot Water	127	24	12,900	7	57%
values may not sum to total due to rounding			**270,000**	**144**	

Maximum LTCPF Scenario

Exhibit 12 presents the Maximum LTCPF MACC for the residential sector. In this carbon price scenario, the results show that the average cost for a utility to implement the measures in five of the six residential end use categories in the 2018-2020 timeframe, including clothes dryers, fireplaces, systems, space heating and swimming pool heaters, is lower than the cost of purchasing allowances. The total marginal abatement potential over the 2018-2020 period is 270,000 tCO_2e (or 144 million m^3), and the estimated abatement associated with measures that are cost effective relative to the carbon price as defined in the LTCPF Report's Maximum LTCPF Scenario is 207,000 tCO_2e (or 110 million m^3).

Exhibit 12 Residential MACC for Maximum LTCPF

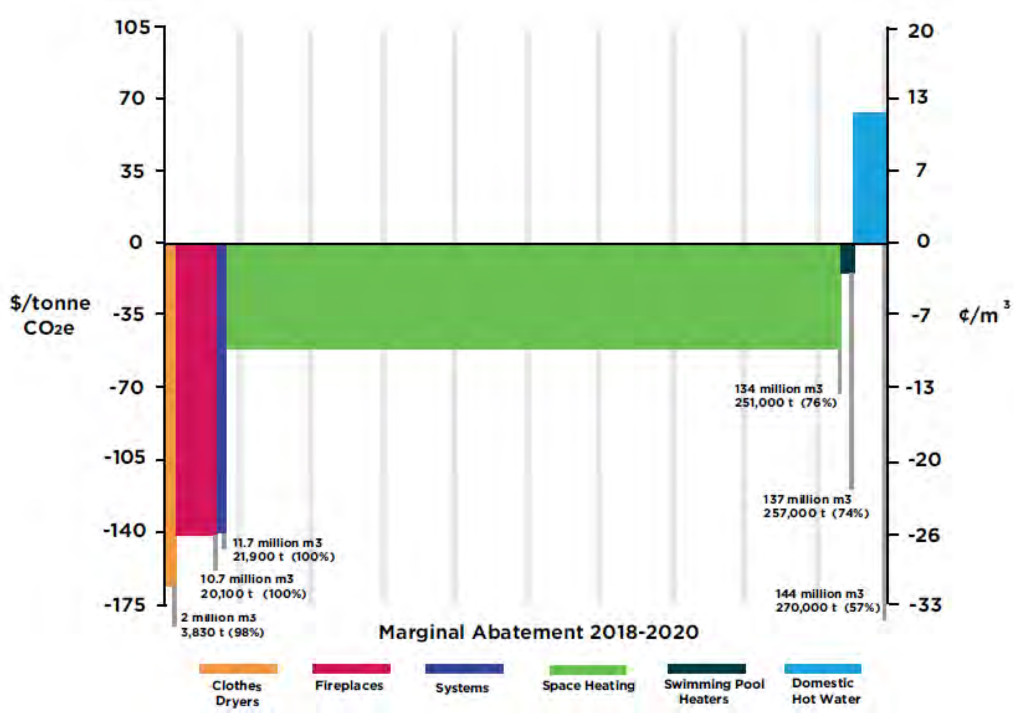


Table 13 Residential MACC for Maximum LTCPF, Average Cost and Abatement Results

Residential End Use	Average $/$tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Clothes Dryers	-166	-31	3,830	2	98%
Fireplaces	-143	-27	16,200	8.7	100%
Systems	-143	-27	1,850	1	100%
Space Heating	-54	-10	230,000	122	76%
Swimming Pool Heaters	-22	-4	5,480	3	74%
Domestic Hot Water	63	12	12,900	7	57%
values may not sum to total due to rounding			**270,000**	**144**	

Mid-Range LTCPF Scenario

Exhibit 13 presents the Mid-Range LTCPF MACC for the residential sector. In this carbon price scenario, the results show that the average cost for a utility to implement the measures in four of the six residential end use categories in the 2018-2020 timeframe, including clothes dryers, systems, fireplaces and space heating, is lower than the cost of purchasing allowances. The total marginal abatement potential over the 2018-2020 period is 270,000 tCO_2e (or 144 million m^3), and the estimated abatement associated with measures that are cost effective relative to the carbon price as defined in the LTCPF Report's Mid-Range LTCPF Scenario is 182,000 tCO_2e (or 97 million m^3).

Exhibit 13 Residential MACC for Mid-Range LTCPF

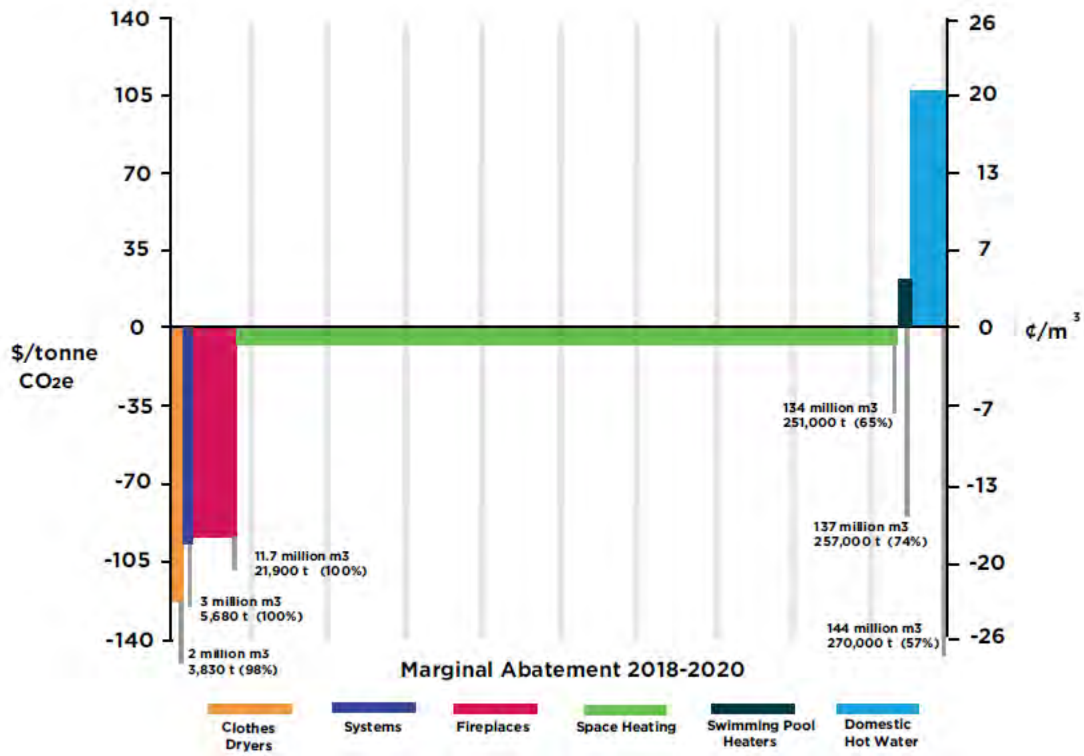


Table 14 Residential MACC for Mid-Range LTCPF, Average Cost and Abatement Results

Residential End Use	Average $/tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Clothes Dryers	-123	-23	3,830	2	98%
Systems	-97	-18	1,850	1	100%
Fireplaces	-94	-18	16,200	8.7	100%
Space Heating	-7	-1	230,000	122	65%
Swimming Pool Heaters	24	5	5,480	3	74%
Domestic Hot Water	108	20	12,900	7	57%
values may not sum to total due to rounding			**270,000**	**144**	

Table 15 Residential Measure-Level Marginal Abatement Cost Data (Ranges) for 2018-2020 Timeframe[27]

Residential End Use	Measure Name	Mid-Range LTCPF				Minimum LTCPF				Maximum LTCPF			
		$/m^3		$/tCO$_2$e		$/m^3		$/tCO$_2$e		$/m^3		$/tCO$_2$e	
Space Heating	Attic/Ceiling Insulation	-0.12	-0.08	-62.9	-42.3	-0.07	-0.03	-34.8	-18.2	-0.22	-0.17	-115	-89
Space Heating	Basement Wall Insulation (R-12)	-0.17	-0.04	-89.3	-20.5	-0.11	0.01	-61.1	3.6	-0.26	-0.13	-141	-66.8
Space Heating	Crawlspace Insulation	0.62	2.25	330	1,201	0.67	2.30	358	1,227	0.52	2.17	278	1,155
Space Heating	Draft Proofing Kit	-0.19	-0.17	-101	-89.5	-0.19	-0.17	-101	-89.5	-0.30	-0.27	-159	-141
Space Heating	Wall Insulation	-0.19	0.51	-103	272	-0.14	0.55	-75	296	-0.29	0.42	-155	225
Space Heating	Zoned-Up Windows: (ENERGY STAR) Rating for a Colder Climate	-0.24	0.30	-128	162	-0.19	0.35	-100	186	-0.34	0.22	-180	115
Space Heating	Heat Reflector Panels	-0.25	-0.22	-133	-117	-0.20	-0.18	-106	-95	-0.34	-0.30	-180	-160
Space Heating	Air Leakage Sealing and Insulation (Old Homes)	-0.22	-0.10	-116	-54.7	-0.16	-0.06	-88.0	-30.6	-0.31	-0.19	-168	-101
Space Heating	Super High-Performance Windows	-0.55	-0.07	-291	-39.2	-0.49	-0.03	-263	-15.1	-0.64	-0.16	-343	-85.5
Space Heating	Professional Air Sealing/Weather Stripping/Caulking	-0.19	0.14	-101	75.8	-0.14	0.19	-73.4	99.8	-0.29	0.06	-153	29.4
Space Heating	Condensing Gas Boilers	0.27	1.89	146	1,008	0.32	1.94	170	1,033	0.19	1.81	102	964
Space Heating	Early Furnace Replacement - 60% AFUE - 90% AFUE Furnace	-0.09	-0.08	-47.8	-43.5	-0.09	-0.08	-47.8	-43.5	-0.20	-0.18	-106	-96.7
Space Heating	Early Furnace Replacement - 70% AFUE - 90% AFUE Furnace	0.04	0.04	19.7	24.0	0.04	0.04	19.7	24.0	-0.07	-0.05	-38.1	-29.2
Space Heating	High Efficiency Condensing Furnace	0.32	0.49	172	262	0.36	0.53	194	285	0.24	0.41	128	218
Space Heating	95% or Higher Efficiency Furnace	-0.21	-0.08	-110	-40.7	-0.16	-0.04	-87.0	-23.4	-0.29	-0.16	-154	-82.8
Space Heating	Programmable Thermostat	-0.20	-0.16	-109	-86.7	-0.17	-0.14	-89.0	-72.6	-0.29	-0.24	-153	-130
Space Heating	Adaptive Thermostats	-0.30	-0.28	-159	-147	-0.26	-0.25	-139	-133	-0.38	-0.36	-203	-190
Space Heating	Adaptive Thermostats - Direct Install (from base measure Programmable Thermostat)	-0.28	-0.17	-149	-92.5	-0.24	-0.15	-129	-78.4	-0.36	-0.25	-194	-136
Space Heating	Close windows and blinds	-0.29	-0.26	-156	-139	-0.29	-0.26	-156	-139	-0.40	-0.36	-214	-191
Space Heating	Maintain Weatherstripping	0.06	0.86	32.6	457	0.06	0.86	34.2	461	-0.04	0.75	-22.3	402
Systems	High-Efficiency (ENERGY STAR®)	-0.27	-0.20	-145	-109	-0.24	-0.18	-126	-96.1	-0.36	-0.29	-189	-153

[27] This table is provided to help the reader better understand the data underlying the presented MACCs. It is important to note that this measure-specific data is **based on savings that take into consideration interactive effects between measures**. These values should not be read independently of the full modelled scenario results; the savings depend on the interactive effects of the combination of other measures which are simultaneously deployed (cascading). The measure-level costs are presented as a range, since measure costs vary across subsectors, building types and regions.

Residential End Use	Measure Name	Mid-Range LTCPF				Minimum LTCPF				Maximum LTCPF			
		$/m^3		$/tCO$_2$e		$/m^3		$/tCO$_2$e		$/m^3		$/tCO$_2$e	
	Clothes Washers												
Domestic Hot Water	Faucet Aerator (Bathroom, 1.5 GPM)	-0.23	-0.21	-125	-114	-0.21	-0.20	-111	-107	-0.32	-0.30	-172	-162
Domestic Hot Water	Faucet Aerator (Kitchen, 1.5 GPM)	-0.24	-0.22	-128	-118	-0.22	-0.21	-115	-110	-0.33	-0.31	-176	-165
Domestic Hot Water	High-Efficiency (ENERGY STAR®) Dishwashers	0.65	3.36	346	1,793	0.68	3.39	360	1,808	0.56	3.27	299	1,747
Domestic Hot Water	Low-Flow Shower Head (1.5 GPM)	-0.20	-0.17	-104	-92.7	-0.17	-0.16	-91.1	-85.6	-0.28	-0.26	-152	-141
Domestic Hot Water	Pipe Wrap	-0.25	-0.23	-135	-124	-0.22	-0.21	-115	-110	-0.34	-0.31	-179	-167
Domestic Hot Water	DHW Tank Insulation	0.03	0.60	18.7	317	0.07	0.62	36.2	329	-0.05	0.51	-26.6	273
Domestic Hot Water	Faucet Aerator (Bathroom, 1.0 GPM)	-0.24	-0.22	-128	-118	-0.22	-0.21	-115	-111	-0.33	-0.31	-176	-166
Domestic Hot Water	Faucet Aerator (Kitchen, 1.0 GPM)	-0.24	-0.22	-130	-120	-0.22	-0.21	-117	-113	-0.33	-0.31	-178	-168
Domestic Hot Water	Low-Flow Shower Head (1.25 GPM)	-0.33	-0.31	-178	-165	-0.31	-0.30	-165	-158	-0.42	-0.40	-226	-213
Domestic Hot Water	Early Hot Water Heater Replacement (0.575 to 0.62 EF)	0.44	0.45	232	239	0.44	0.45	232	239	0.33	0.34	177	180
Domestic Hot Water	High Efficiency Gas Storage Water Heater	0.51	0.57	270	305	0.55	0.60	291	321	0.42	0.49	226	263
Domestic Hot Water	Tankless Water Heater (High Efficiency Non-Condensing)	0.63	0.70	337	375	0.68	0.74	361	397	0.55	0.62	292	333
Domestic Hot Water	Condensing Gas Water Heaters	-3.95	2.52	-2,105	1,344	-3.91	2.55	-2,088	1,360	-4.03	2.44	-2,150	1,300
Domestic Hot Water	Tankless Water Heater (Condensing)	-0.98	0.28	-521	147	-0.93	0.31	-497	166	-1.06	0.20	-566	105
Domestic Hot Water	Active Solar Water Heating Systems	0.87	3.05	461	1,629	0.92	3.10	489	1,656	0.78	2.97	415	1,582
Domestic Hot Water	DHW Recirculation Systems (e.g. Metlund D'MAND®)	0.04	0.76	19.7	403	0.08	0.80	42.7	425	-0.05	0.68	-24.2	361
Domestic Hot Water	Wastewater Heat Recovery Systems	0.25	1.34	134	717	0.30	1.40	163	745	0.15	1.25	83	665
Domestic Hot Water	Minimize Hot and Warm Clothes Wash	-0.26	-0.24	-137	-126	-0.26	-0.24	-137	-126	-0.37	-0.33	-195	-178
Domestic Hot Water	Reduce Temperature of DHW	-0.26	-0.24	-137	-126	-0.26	-0.24	-137	-126	-0.37	-0.33	-195	-178
Clothes Dryers	High-Efficiency Gas Clothes Dryers	0.08	0.81	40.7	433	0.12	0.85	63.7	451	-0.01	0.73	-3.2	391
Clothes Dryers	Use sensor for clothes dryer	-0.05	0.34	-24.1	180	0.00	0.37	-1.2	197	-0.13	0.26	-68.1	138
Clothes Dryers	Clothes lines and drying racks	-0.25	-0.21	-133	-115	-0.20	-0.18	-108	-94.7	-0.33	-0.29	-178	-156
Swimming Pool Heaters	Insulating Pool Covers	-0.24	-0.12	-125	-62	-0.21	-0.10	-112	-54.5	-0.32	-0.21	-173	-110
Swimming Pool Heaters	High-Efficiency Gas-Fired Pool Heaters	1.48	2.09	787	1,116	1.48	2.10	790	1,120	1.38	2.00	735	1,064
Swimming Pool Heaters	Solar Pool Heaters	-0.23	-0.19	-123	-101	-0.18	-0.15	-98	-82.1	-0.31	-0.27	-167	-143
Fireplaces	Fireplace Intermittent Ignition Control Retrofit	-0.17	-0.10	-90.9	-55.5	-0.15	-0.10	-81.2	-51.5	-0.26	-0.20	-141	-106

Residential End Use	Measure Name	Mid-Range LTCPF				Minimum LTCPF				Maximum LTCPF			
		$/m^3		$/tCO$_2$e		$/m^3		$/tCO$_2$e		$/m^3		$/tCO$_2$e	
Fireplaces	High Efficiency Fireplace with Pilotless Ignition (freestanding fireplace)	-0.25	-0.21	-131	-110	-0.20	-0.17	-107	-91.3	-0.33	-0.29	-176	-152
Fireplaces	High Efficiency Fireplace with Pilotless Ignition (insert)	-0.25	-0.21	-131	-110	-0.20	-0.17	-107	-91.0	-0.33	-0.28	-175	-152
Fireplaces	High Efficiency Fireplace with Pilotless Ignition (Zero Clearance <40 kBtu/h)	-0.24	-0.21	-131	-110	-0.20	-0.17	-106	-90.5	-0.33	-0.28	-175	-151
Fireplaces	High Efficiency Fireplace with Pilotless Ignition (Zero Clearance ≥40 kBtu/h)	-0.25	-0.21	-135	-114	-0.21	-0.18	-110	-94.8	-0.34	-0.29	-179	-156

3. Renewable Natural Gas

Renewable Natural Gas represents an abatement[28] option available to gas utilities. RNG provides the opportunity for GHG abatement by reducing the emission intensity (tCO_2e/m^3) of the natural gas delivered to end users.

3.1 Background

In order to support the assessment of the utilities' cap and trade costs over the study period, it is important to consider not only the abatement that can be achieved through natural gas abatement activities implemented by natural gas customers (Section 2), but also opportunities for abatement aimed at reducing the GHG emissions intensity of the natural gas fuel itself by introducing RNG into the natural gas grid to replace some of the conventional natural gas within the distribution systems. It is important to emphasize that this study was a desk-based literature review, not an in-depth survey or on-the-ground potential assessment.

RNG is biogas that has been processed to match the specifications (energy content and quality) of conventional fossil-derived natural gas, and which can be injected into the natural gas pipeline. It is functionally equivalent to conventional natural gas, and can be used by utilities' customers to replace natural gas without generating fossil fuel-related GHG emissions[29]. By sourcing and procuring RNG, utilities can reduce their cap and trade compliance obligation associated with the gas they deliver to customers[30].

RNG can be produced from various feedstocks using a series of steps – namely collection of a feedstock, delivery to a processing facility for biomass-to-gas conversion, gas conditioning, compression, and injection into the pipeline. ICF developed resource potential curves to estimate the potential for deployment of RNG for pipeline injection. The MACCs present the cost of GHG abatement (in units of dollars per tonne of GHGs avoided, or dollars per cubic metre of RNG delivered to the grid) as a function of supply (in cubic metres). These curves are based on a combination of a) the availability of feedstocks for conversion to RNG, and b) the costs of converting feedstocks into RNG using anaerobic digestion and thermal gasification technologies.

[28] The term abatement, when associated with RNG, refers to substitution of RNG for fossil-derived natural gas, including the associated emissions reduction.
[29] Since RNG is functionally equivalent to fossil-derived natural gas, there is no limit to the percentage it can make up in the pipeline – there can be, however, technical or cost limitations on the processing side to upgrade biogas to meet pipeline specifications.
[30] RNG can be modelled as a volumetric abatement option or a GHG intensity abatement option. This study treats RNG as a volumetric abatement option, separate and independent from conservation abatement activities. If considered as an intensity reduction, RNG would reduce the cap and trade compliance obligation associated with each m^3 of natural gas delivered to customers, which also affects the cost effectiveness and emissions abatement success associated with conservation measures.

3.2 Approach

Resource and RNG Potential

To estimate the resource potential for RNG across Canada and in Ontario within the study scope and timeline, ICF completed a desk-based literature review of publicly available documents. Input was also sought from known experts in the field of RNG/renewable fuels as to the applicability of the available literature. Several studies were reviewed including:

- Canadian Biogas Study: Benefits to the Economy, Environment and Energy, Biogas Association, December 2013.
- Potential Production of Renewable Natural Gas from Ontario Wastes, Alberta Innovates Technology Futures, May 2011.
- Economic Study on Renewable Natural Gas Production and Injection Costs in the Natural Gas Distribution Grid in Ontario: Biogas plant costing report, Electrigaz Technologies, September 2011.

Through discussion with stakeholders and internal and external subject matter experts it was determined that the Canadian Biogas Study is the most comprehensive study that is publicly available regarding feedstock resource potential, with a national focus (and broken down by province). ICF explicitly asked for direction from multiple stakeholders regarding other references, and the Canadian Biogas Study was consistently referred to as the most reliable basis for this analysis. However, while this study provides an indication of the magnitude, it is worth noting that this study is over four years old and may not present a balanced and up to date view of the potential.

The table below provides an overview of the feedstocks considered in this analysis[31]:

Table 16 RNG Feedstocks

Feedstock for RNG	Description
Landfill gas (LFG)	Biogenic waste in landfills produces a mix of gases, including methane (40-60%).
Wastewater treatment (WWT) gas	Wastewater consists of waste liquids and solids from household, commercial and industrial water use. In the processing of wastewater, a sludge is produced, which can be anaerobically digested to produce methane.
Animal manure	Manure produced by livestock, including dairy cows, beef cattle, swine, sheep, goats, poultry, and horses.
Source separated organics (SSO)	Food waste separated from the garbage stream of either residential, commercial, or institutional sources for separate collection and processing.
Agricultural residue	The material left in the field, orchard, or other agricultural setting after a crop has been harvested. Inclusive of unusable portion of crop, stalks, stems, leaves, branches, and seed pods.

[31] Section 3.3 of this report identifies several feedstocks that have not been included in this analysis with a reason provided for the exclusion.

ICF used the RNG production estimates from the Canadian Biogas Study to develop the abatement potential estimates through 2028. While the study does not explicitly indicate the timeframe by which the resource can be developed, ICF assumed that the production potential is limited by investment rather than technological development. In that regard, ICF assumed that nearly 100% of the RNG production potential estimated in the Canadian Biogas Study is achievable by 2028 for each feedstock. The table below shows the annual RNG production potential for pipeline injection used in the analysis, in units of million cubic metres.

Table 17 RNG Resource Potential in 2028 for Canada and Ontario

Feedstock for RNG	Canada Resource Potential Estimate (million m^3/y)	Ontario Resource Potential Estimate (million m^3/y)
LFG	290	113
WWT gas	180	71
Animal manure	874	191
SSO (Residential and Commercial)	300	110
Agricultural residue	774	142
Total	**2,418**	**627**

RNG Production and Cost

ICF considered RNG production via two conversion technologies: anaerobic digestion or thermal gasification.

- Anaerobic digestion is the process whereby microorganisms break down organic material in an environment without oxygen. In the context of RNG production, the process generally takes place in a controlled environment, referred to as a digester or reactor[32]. When organic material is introduced to the digester, it is broken down over time by microorganisms, and the gaseous products of that process contain a large fraction of methane and carbon dioxide.
- Thermal gasification describes a broad range of processes whereby a carbon-containing feedstock is converted into a mixture of gases referred to as synthetic gas or syngas, including hydrogen, carbon monoxide, steam, carbon dioxide, methane, and trace amounts of other gases (e.g., ethane, hydrogen sulfide, and nitrogen). The process occurs at high temperatures (650-1350°C) and varying pressures (depending on the gasification system). There is limited commercial-scale deployment of thermal gasification technologies.

ICF made the simplifying assumption that RNG production from LFG, wastewater treatment plants, animal manure, and SSO would occur via anaerobic digestion. It was also assumed that agricultural residue would be converted to RNG via thermal gasification[33].

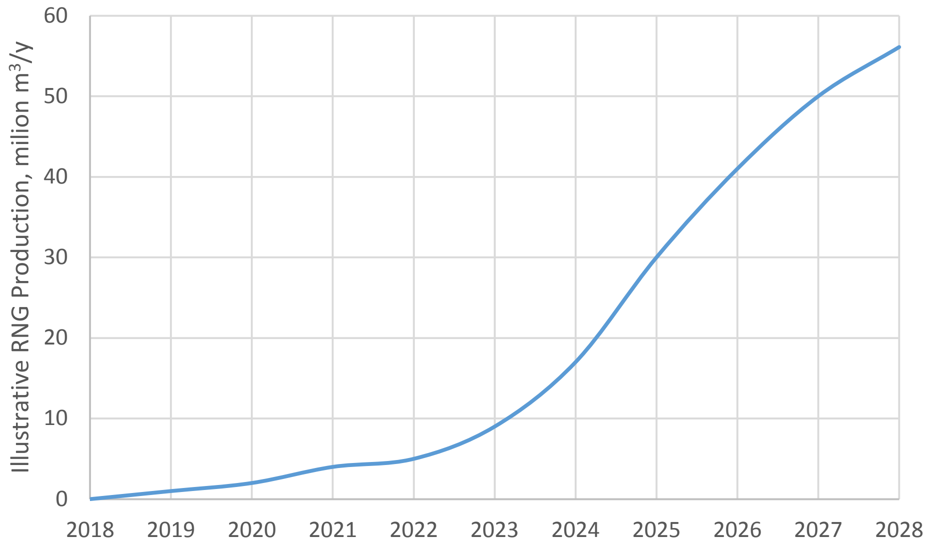
The main cost components considered in ICF's analysis include:

[32] The exception is landfill gas – anaerobic digestion takes place within landfills; the resultant gases would migrate to the surface and be released to atmosphere in the absence of gas collection equipment.
[33] This division of feedstocks between the two conversion technologies considered in this study was done to reduce the number of assumptions needed to estimate the potential for each feedstock.

- Collection - This refers to a variety of cost elements, including the capture of gas from landfills or wastewater treatment plants or the collection of a feedstock. Note that consideration of tipping fees was excluded from the analysis, see note in Section 3.3.
- Upgrading biogas for injection - Broadly speaking, raw biogas needs to upgraded and scrubbed of contaminants prior to injection into a transmission pipeline. The primary cost components for upgrading biogas that ICF included in the analysis are: conditioning the biogas, compression of the biogas, sulfur removal, and a nitrogen rejection system. ICF notes that there are a variety of biogas conditioning systems that are commercially available with different approaches to conditioning gas prior to injection. Our assumptions for conditioning align with what we consider conservative estimates (i.e., our assumed costs are on the high side of the possible range).
- Other equipment expenditures - This refers to other capital expenditures including digesters, thermal gasification equipment, etc.
- Pipeline interconnect - Pipeline interconnect represents the combination of the point of receipt from the customer pipeline and the pipeline extension to the utility pipeline. These costs vary by project size, complexity, and distance from common carrier pipeline.
- Construction and engineering - The deployment of biogas projects requires significant investments in construction and engineering, including site design, labour to install equipment, etc.
- Operations and maintenance - ICF includes the costs of operating and maintaining the biogas production facility - including collection, conditioning, compression, and injection. These costs are generally expressed as a percentage of the capital expenditures, and range from 5-15%.
- Financing - ICF excludes financing costs in order to align with the cost components used in the customer abatement analysis described in Section 2 of this report.
- Emissions reductions or offset credits associated with RNG - ICF excluded any potential proceeds from the sale of emissions reductions or offset credits associated with the RNG in the estimates of cost to deliver RNG to the natural gas grid in \$/tonne CO_2e, and the equivalent cost in \$/m^3. For further explanation, see the last bullet under the ‘Costs’ sub-heading in Section 3.3.

In all scenarios, ICF assumed an s-curve of deployment (see Exhibit 14 below for an illustrative example) of RNG production facilities. The underlying principle of this assumption is that the initial investments will be modest over the first 5-7 years (2018-2024), but that deployment in the out-years ramps up. ICF’s deployment curves should not be considered a forecast; rather, they are meant to capture plausible investment in RNG production considering the barriers to financing, permitting a project, and completing it (typically with an 18-36 month timeframe between project financing and coming online).

Exhibit 14 Illustrative S-Curve Representing Assumed Deployment of RNG Facilities for One Feedstock Type from 2018-2028



ICF's RNG production cost modelling is dependent on the size of the system, and is linked to the inlet flow of biogas for conditioning. The Canadian Biogas Study has limited information regarding the size of each digester facility assumed, however, ICF extracted feedstock specific data to the extent feasible. The sub-sections below outline the size of digester facilities assumed for landfill operations, wastewater treatment facilities, animal manure, and source separated organics (SSO). It also includes our approach to developing thermal gasification costs.

For each feedstock, ICF calculated the levelized cost of energy (LCOE)[34] in $\$/m^3$ by incorporating the capital expenditures from equipment, operations and maintenance (O&M), and a discount rate of 4% for our calculations.

Landfill gas

ICF developed abatement cost estimates using five different facility size estimates based on a survey of 63 landfill sites reported in the Canadian Biogas Study (which is sourced from a separate study[35]). The table below includes the assumed biogas flow for each facility in units of standard cubic feet per minute (SCFM) and the calculated annual output of RNG. The table also includes the assumed share of the market for each production facility size. ICF calculates RNG production assuming a methane content of landfill gas of 48% and a capacity factor (i.e., how frequently the system is operational) of 90%[36]. Table 18 below presents ICF's calculated LCOE for each landfill size.

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[34] LCOE is similar to the cost components of the MACC cost metric but is not equivalent to the cost metric itself because it only includes positive costs – it does not incorporate the commodity cost of fossil-derived natural gas and the forecasted price of allowances (avoided costs or benefits in the MACC cost metric).
[35] Identification of Potential Additional Greenhouse Gas Emissions Reductions From Canadian Municipal Solid Waste Landfills. Contract Number K2A82-11-0009. Prepared for Environment Canada By Conestoga-Rovers and Associates, August, 2012
[36] Methane content of landfill gas and capacity factor assumptions are ICF Expert opinions.

Table 18 LFG Facility Assumptions by Facility Size (from smallest to largest landfill)

Biogas flow (SCFM)	RNG Annual Production (million m^3/y)	Estimated Share of Market	LCOE ($/$m^3$)
360	2.3	10%	$0.82
500	3.2	50%	$0.71
1,200	7.7	20%	$0.46
2,500	13.8	10%	$0.38
3,250	21	10%	$0.33

ICF notes that for the largest landfill category we did not include the costs of collecting biogas in the estimates, because we assume that these large landfills are regulated and required to capture and flare biogas rather than allowing it to vent to the atmosphere. It is possible that other landfills have collection systems in place, particularly the larger landfills (e.g., with biogas flow greater than 1,000 SCFM). In that regard, it is conceivable that we have over-stated the LCOE of RNG production because the collection systems can represent a significant share of the cost.

Wastewater treatment gas

ICF developed abatement cost estimates based on four different sized wastewater treatment plants using internal modelling from other jurisdictions, and input from subject matter experts. Because there was no available information regarding the distribution of WWT plant sizes, ICF made the simplifying assumption that the market share would be split evenly between the four facility sizes considered in our analysis. The table below includes the assumed biogas flow for each facility in units of SCFM and the calculated annual output of RNG. ICF calculates RNG production assuming a methane content of gas captured from WWT plants of 56% and a capacity factor of 90%[37]. Table 19 below includes our calculated LCOE of each WWT plant size.

Table 19 WWT Facility Assumptions by Facility Size (from smallest to largest WWT facility)

Biogas flow (SCFM)	RNG Annual Production (million m^3/y)	Estimated Share of Market	LCOE ($/$m^3$)
60	0.43	25%	$3.73
110	0.81	25%	$2.34
525	3.94	25%	$0.67
1,170	8.75	25%	$0.48

Animal manure

ICF developed abatement cost estimates based on three different sized farms. The farm sizes and number of cattle are based on the Electrigaz study. They define three farms: a baseline agricultural facility with 1,315 dairy cows, a large agricultural facility with 2,616 dairy cows, and an agricultural cooperative with 3,950 dairy cows. ICF made the simplifying assumption that the market share would be split evenly between these three facility sizes. The table below includes the assumed biogas flow for each farm size in units of SCFM and the calculated annual output of RNG. ICF calculates RNG production assuming a methane content of gas captured from

[37] Methane content of WWT gas and capacity factor assumptions are ICF Expert opinions.

dairy manure of 60% and a capacity factor of 95%[38]. Table 20 below includes our calculated LCOE of each agricultural facility size.

Table 20 Livestock Farm Assumptions by Farm Size (from smallest to largest farm facility)

Facility	Dairy Cows	Biogas flow (SCFM)	RNG Annual Production (million m^3/y)	Estimated Market Share	LCOE ($/$m^3$)
Baseline	1,315	90	0.75	33%	$1.66
Large	2,616	180	1.50	33%	$1.06
Co-op	3,950	265	2.25	33%	$0.87

Source separated organics

The RNG production potential for SSO was distinguished by residential and commercial sources in the Canadian Biogas Study, but residential and commercial applications have been combined here. The anaerobic digestion of SSO requires the development of a separate digester facility – it is not merely the collection of biogas analogous to the functioning of a landfill or WWT plant. This can add significant cost. Furthermore, there are different sized WWT facilities in the literature. The Canadian Biogas Study assumes the construction of facilities that can handle 60,000 tonnes of SSO via anaerobic digestion. ICF used that single facility size to develop the RNG production estimate for SSO; although we note that there are facilities that process as much as 100,000 tonnes[39]. In that regard, it is conceivable that the LCOE for RNG from SSO may be over-stated if larger facilities are constructed in response to the appropriate price signal.

Informed by discussion with subject matter experts, ICF assumed that a facility processing 60,000 tonnes of waste would produce approximately 500 SCFM of biogas and calculated yield of about 4 million m^3/year of RNG, assuming a 60% methane content and a capacity factor of 90%[40]. ICF also assumed an additional capital expenditure of organics processing ($14 million) and the cost of the digester ($17.5 million). The total capital costs are on the order of $40-45 million for this type of RNG production. This yields a LCOE of $2.90/$m^3$.

Agricultural residue

As noted previously, ICF made the broad assumption that agricultural residue is converted to biogas via thermal gasification. ICF used a combination of internal estimates on conversion efficiency of a thermal gasification facility and feedstock pricing to develop a series of RNG production estimates for agricultural residue. These estimates have a high degree of uncertainty for two reasons: 1) thermal gasification of biomass has not been developed at commercial scale, so cost information is scarce, and 2) the market for agricultural residues is not mature (because the residue is primarily used as ground cover as part of agricultural operations for nutrient loadings), therefore feedstock pricing is speculative. To address these uncertainties, ICF developed six estimates of RNG production from a thermal gasification facility, assuming different yields of gasification and different feedstock pricing scenarios.

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[38] Methane content of agricultural manure and capacity factor assumptions are ICF Expert opinions.
[39] Stormfisher Biogas in London can process up to 100,000 tonnes/yr, http://www.stormfisher.com/about-us/
[40] Methane content of SSO feedstock and capacity factor assumptions are both ICF Expert opinions.

Table 21 Agricultural Residue Assumptions by Varying Yield and Feedstock Price

RNG Yield	RNG Annual Production (million m^3/y)	Feedstock Price ($/tonne)	Estimated Share of Market	LCOE ($/$m^3$)
Low	105	$23.50	17%	$0.90
		$130	17%	$1.57
Medium	115	$23.50	17%	$0.81
		$60	17%	$1.01
High	140	$23.50	17%	$0.66
		$60	17%	$0.83

3.3 Limitations and Caveats

Resource and RNG Potential Data

- While the consensus among RNG experts was that the Canadian Biogas Study was the best available study to provide national and provincial estimates of RNG potential for this analysis, it is over four years old and referenced RNG potential data from other reports that are no longer available for review. With many of the study's key references unavailable or inaccessible, it was difficult for ICF to conduct a critical evaluation of the methodologies employed to build up the national and provincial estimate. Further, because this information and baseline data are not readily available, it makes it impractical for ICF (or other reviewers) to assess the results in the context of revised or updated methodologies to develop resource assessments (e.g., using updated sustainability criteria).

- ICF did not include forest residue as a potential feedstock because it was excluded from the Canadian Biogas Study and due to the uncertainty of availability and accessibility (i.e. the potential costs of transporting the feedstock could be prohibitive)[41]. Even if forest residue was added to the possible feedstocks in this study, it would not change the available RNG potential in the 2018-2020 study period, as the timeline on thermal gasification extends several years past 2020.

- ICF did not include the production of hydrogen via steam reformation of biomethane. Renewable hydrogen could also conceivably be produced by electrolysis using renewable energy generation; however, this was not in the scope of consideration (the focus of this study was on biomethane, not any source of renewable gas). This was a scoping decision at the outset of the project. ICF notes that renewable hydrogen from either SMR or electrolysis are more expensive (on a dollar per tonne basis) than the RNG abatement opportunities presented in the analysis[42].

[41] Refer to Natural Resources Canada's Forest Bioproduct Innovation work for information about forest residue in future studies.
[42] ICF Expert opinion

- ICF did not consider industrial gases because these are not biogenic or considered renewable. This analysis did include thermal gasification (of agricultural residue) which is a syngas process.

- This analysis excluded the consideration of purpose grown energy crops because of the uncertainty associated with the potential for this feedstock and the lack of reliable documentation.

- Two new Ontario policy proposals including an organics ban at landfills and the prohibition of spreading untreated sewage sludge on agricultural fields have not been accounted for in this RNG assessment. These policies could potentially decrease production of RNG from LFG facilities (due to less feedstock availability), and accelerate the production of RNG from WWT and SSO facilities.

- This analysis presents the total resource potential for RNG, and does not consider competing uses for the resource – all feedstocks could be used for a purpose other than generating RNG (such as on-site biogas combustion for heat or electricity generation, or conversion to liquid biofuels).

Costs

- Since the RNG originates from across Canada, this analysis makes a simplifying assumption that the upstream capacity costs associated with RNG are equivalent to fossil-derived natural gas. In reality, these costs would be dependent on the distance and sources of RNG flowing into Ontario, which may not be equivalent to fossil-derived natural gas. Upstream capacity costs are approximately 10-20% of natural gas commodity costs (in the 2016 CPS avoided cost assumptions).

- Future changes in technology costs, i.e. improvement in efficiency and drop in price over time, have not been included in the analysis. This simplifying assumption may cause the forecasted $/m^3 and $/t CO_2e estimates for the later years of the study period to be higher than they would actually be.

- This RNG assessment developed cost estimates for 19 different-sized RNG production facility categories within the five feedstock categories (including the five LFG, four WWT, three agricultural manure, one SSO and six agricultural residue categories described in the feedstock tables in Section 3.2 above). While efforts were made to disaggregate feedstock potential into various realistic cost categories, these costs are still averages and should be considered illustrative.

- Waste tipping fees were assumed to be zero to simplify the assumptions in this analysis. For some feedstocks, accounting for the avoided cost of tipping fees may improve the economics of an RNG project, e.g., SSO projects.

- The estimates of cost to deliver RNG to the natural gas grid in $/tonne CO_2e, and the equivalent cost in $/m^3 do not account for the sale of any associated emissions reductions or offset credits in Ontario's nascent cap and trade offset system. Several of the RNG feedstocks[43] identified in this study may have the potential to generate offset credits through avoidance of methane venting to the atmosphere. The financial value of those offsets, however, has not been included in the cost estimates[44]. Given that the Ontario offset system is still under development and the protocols[45] expected to be relevant for this study are not yet finalized, there is still a great deal of uncertainty around what RNG projects might be able to generate offsets and those not eligible due to rules that are still unknown.

3.4 Results

Table 22 below summarizes the Canadian national and Ontario provincial RNG annual potential by 2028 by feedstock[46]. The table also presents the range[47] of costs (LCOE[48]), in dollars per cubic metre, to get the RNG into the Ontario natural gas pipeline system.

Table 22 Summary of the National and Ontario Provincial RNG Potential in 2028 by Feedstock

Feedstock	National Potential by 2028 (million m^3/yr)	National Potential by 2028 (tCO_2/yr)	Ontario Potential by 2028 (million m^3/yr)	Ontario Potential by 2028 (tCO_2/yr)	LCOE ($/$m^3$)	Notes
Landfill gas	290	540,000	113	210,000	$0.33-$0.82	Evaluated 5 different sized facilities based on survey referenced in Canadian Biogas Study; linked to study for Environment Canada
WWT gas	180	340,000	71	135,000	$0.48-$3.73	Evaluated 4 different sized facilities – ICF analysis
Animal manure	874	1,640,000	191	360,000	$0.87-$1.66	Considered 3 different farms (Electrigaz study): baseline, large, and co-op
SSO residential & commercial	300	560,000	110	210,000	$2.90	Assumed a single facility capable of processing 60,000 tonnes/yr per Canadian biogas study. Larger/smaller facilities conceivable

43 LFG, WWT, agricultural manure and SSO
44 Note that the current value of offsets in the WCI joint market could make some RNG facilities more economic.
45 An offset protocol is a jurisdiction and cap and trade program-specific set of rules that determine eligibility of an offset credit.
46 The national and Ontario potential by 2028, in million cubic metres, is referenced from the Canadian Biogas Study.
47 Range represents the group of facility size categories described in the *notes* column of the table.
48 LCOE includes positive costs only and is not equivalent to the MACC cost metric – it does not include avoided costs or benefits in the MACC cost metric (commodity cost of fossil-derived natural gas and the forecasted price of allowances).

Feedstock	National Potential by 2028 (million m^3/yr)	National Potential by 2028 (tCO_2/yr)	Ontario Potential by 2028 (million m^3/yr)	Ontario Potential by 2028 (tCO_2/yr)	LCOE ($/$m^3$)	Notes
Agricultural residue	774	1,450,000	142	265,000	$0.66-$1.57	Produced via thermal gasification, assuming varying efficiency of processing Included 6 feedstock price estimates: $23.50-$130 per dry tonne

Graphs presenting the RNG abatement potential by 2020 and 2028 described in Table 22, and disaggregated by feedstock cost category, are provided in Appendix B.

Cost Metric for RNG

The cost metric used to quantify the cost effectiveness of renewable natural gas abatement options under different carbon pricing assumptions in this study differs from the MACC cost metric described in Section 2.2 for customer abatement. The RNG cost metric includes:

Benefits (avoided costs):

- Natural gas avoided costs, comprising commodity costs only (upstream capacity costs and downstream distribution system costs have been removed)
- Avoided cost of carbon, based on the three LTCPF scenarios (as described in Section 1.4.2)

Costs:

- LCOE

For the MACCs that follow, RNG was grouped by feedstock category in the same manner that the customer abatement measures were grouped by end use. The RNG MACCs in Sections 3.4.1 and 3.4.2 can be read in the same way as the customer abatement MACCs (refer Section 2.4).

3.4.1 Minimum and Mid-Range LTCPF Scenario

Exhibit 15 below presents the minimum (and mid-range[49]) LTCPF MACC for national RNG abatement potential. In both of these carbon price scenarios, the results show the average cost to bring the RNG to market is more expensive than the price of an allowance plus the avoided fossil-derived natural gas commodity cost, for the 2018-2020 timeframe[50]. The marginal abatement potential by 2020 is 67 million m^3 (resulting in a 126,000 tCO_2e GHG reduction). Table 23 presents the average cost data and estimated abatement used to create the MACC.

[49] For the RNG MACC, the minimum and mid-range scenarios for 2018-2020 are identical because the price of carbon in those years is identical in these two scenarios.
[50] The zero-line in the RNG MACC in Exhibit 15 and Exhibit 16 is equivalent to the zero-line in the customer conservation MACCs in Section 2.

Exhibit 15 RNG MACC for Minimum and Mid-Range LTCPF

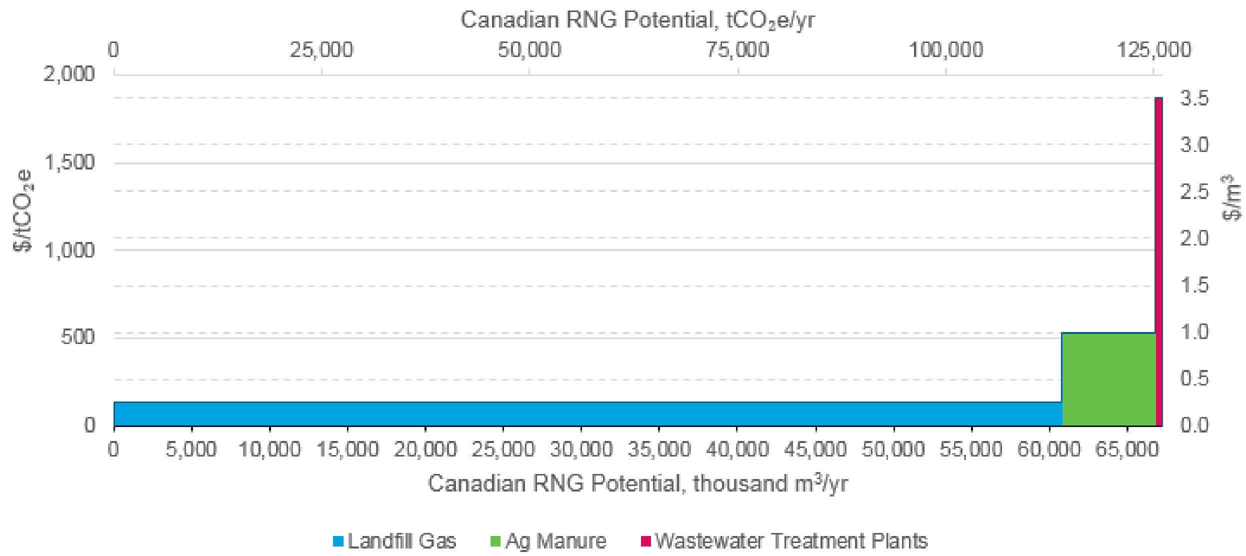

Table 23 RNG MACC for Minimum and Mid-Range LTCPF, Average Cost and Abatement Results

RNG Feedstock	Average $/$tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)
Landfill Gas	133	25	114,000	61
Agricultural Manure	527	99	11,200	6
Wastewater Treatment Gas	1,867	350	800	0.4
values may not sum to total due to rounding			**126,000**	**67**

3.4.2 Maximum LTCPF Scenario

Exhibit 16 below presents the maximum LTCPF MACC for national RNG abatement potential. In this carbon price scenario, the results show the average cost to bring the RNG to market is over and above the price of an allowance and the natural gas commodity cost for the 2018-2020 timeframe. The marginal abatement potential by 2020 is 67 million m^3 (resulting in 126,000 tCO_2e GHG reduction). Table 24 presents the average cost data and estimated abatement used to create the MACC.

Exhibit 16 RNG MACC for Maximum LTCPF

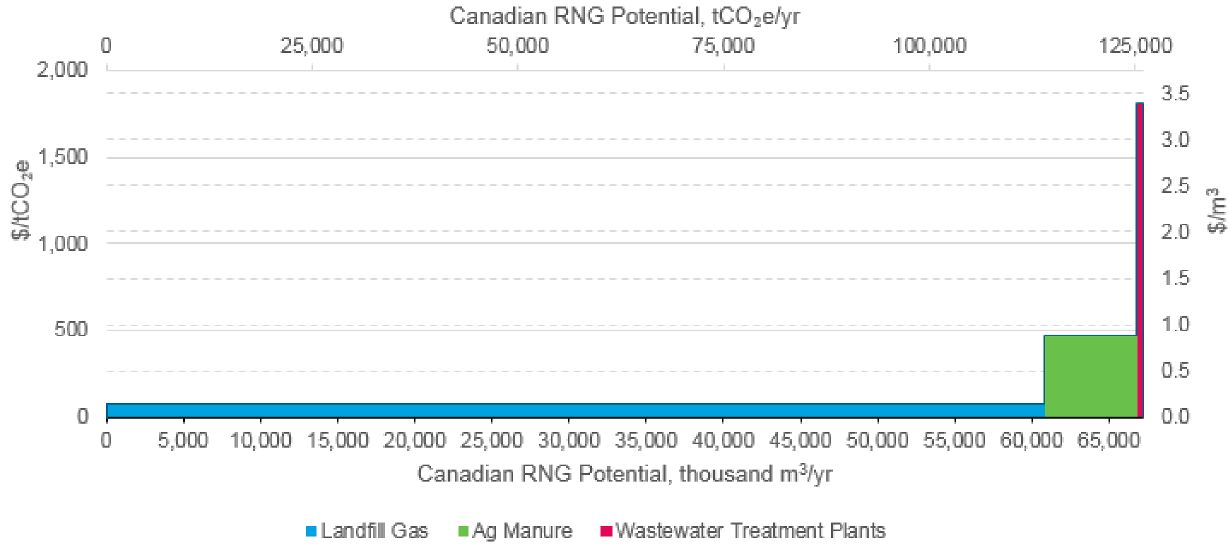

Table 24 RNG MACC for Maximum LTCPF, Average Cost and Abatement Results

RNG Feedstock	Average $/$tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)
Landfill Gas	77	14	114,000	61
Agricultural Manure	471	88	11,200	6
Wastewater Treatment Gas	1,811	340	800	0.4
values may not sum to total due to rounding			**126,000**	**67**

4. Facility Abatement

Facility abatement is the third key abatement opportunity considered for the MACC.

4.1 Background

As discussed in Section 1, the utilities are required to acquire and remit emissions units for both facility and customer-related emissions over the 2017-2020 timeframe. The vast majority of this obligation (>99%) results from the residential, commercial and small industrial (<10,000 tCO_2e/yr) customers (end users) as well as consumption by the natural gas-fired generating stations.

Facility emissions, which include emissions associated with transmission, storage and distribution segments, total between 250,000 and 350,000 tCO_2e/yr, which accounts for less than 1% of the utilities' estimated total cap and trade compliance obligation.

The gas utilities operate in distinct business areas / operations. In Ontario these include:

- Natural Gas Transmission,
- Natural Gas Storage, and
- Natural Gas Distribution.

There are four main categories of emissions from these operations;

- Fugitive emissions from piping and associated equipment components. These emissions include unintentional leaks from underground pipeline, seals, packings or gaskets resulting from corrosion, faulty connection, inadequate maintenance or wear.
- Vented emissions are intentional releases to the environment (by design or operational practice). Sources include equipment and pipeline blowdowns and purging, metering & regulating station control loops, accidental third party dig-ins, and gas operated devices that use natural gas as the supply medium.
- Combustion emissions include CO_2, CH_4 and N_2O emitted from the combustion of fossil fuels to fire compressor station engines, turbines and pipeline heaters.
- Miscellaneous (other) emissions include emissions from vehicles, domestic fuel consumption for building heating and indirect emissions associated with electrical usage.

In Ontario's GHG reporting Regulation[51], these fall under the specified activities of 'general stationary combustion', and 'operation of equipment related to the transmission, storage and transportation of natural gas'.

In addition to the above, the utilities have a compliance obligation associated with their commercial buildings. The abatement opportunities for utilities' commercial buildings within Facilities emissions are included within the relevant Customer Abatement measures discussed in Section 2.

[51] O. Reg. 143/16: Quantification, Reporting and Verification of Greenhouse Gas Emissions

4.2 Approach

A high-level assessment of facility emissions abatement options was planned for inclusion in the scope of this study.

However, it was concluded that a high-level illustration of abatement cost without utility context would be of limited applicability and relevance to the objective of this study due to the small contribution of facility emissions to utilities' overall compliance obligations and because each natural gas utility has a unique emissions profile and corresponding unique facility abatement opportunities.

Small contribution of Facility Emissions to Utilities' Compliance Obligations

As discussed, under the cap and trade program, the utilities are responsible for the GHG emissions from customers[52] as well as facility-related obligations for facilities owned or operated by the utilities. The vast majority (over 99 percent) of the utility's compliance obligation results from customer-related emissions. Facility emissions, which include emissions associated with transmission, storage, and distribution, account for less than 1% of the utilities' total cap and trade compliance obligation.

Unique Emissions Profiles

Facility emissions vary significantly between the individual natural gas utilities based on differing infrastructure and assets, and annually based on operational requirements. There is currently limited publicly available information on emissions by technology and utility-specific activity data that could inform an illustrative high level MACC for Facilities. As part of this study, entity-level information (historic and forward planning) relevant to assessing abatement options (research and estimates that have been conducted to date related to Facility abatement opportunities) was requested from the gas utilities.

The utilities indicated that they are in the process of completing facility abatement opportunity studies along with descriptions of GHG abatement measures to inform their 2018 Compliance Plans. The results will be available within their Compliance Plans but not within the timeline of this MACC study. As such it was concluded to re-assess this area upon release of the relevant facility level context.

As a result of these issues, facility abatement activities were excluded from this MACC.

[52] Customer-related obligations include obligations for natural gas-fired electricity generators, and residential, commercial and industrial customers who are not independently covered under the cap and trade program (i.e., that are not LFEs or voluntary participants).

5. Summary MACCs

Exhibit 17, Exhibit 18 and Exhibit 19 and supporting Table 25, Table 26 and Table 27 presented in this section are compilations of the customer abatement MACCs presented in Section 2 and the RNG MACCs presented in Section 3 for the 2018-2020 study period. Each summary MACC – one is presented for each LTCPF carbon pricing scenario – illustrates the estimated achievable potential savings[53] in tonnes CO_2e and cubic metres of natural gas, for natural gas abatement through customer conservation measures and for RNG abatement.

The summary MACCs should be interpreted in the same manner as the MACCs in Sections 2 and 3 of this report. The labels associated with each bar on the MACCs indicate the sum of the marginal abatement, in tCO_2e, for all bars to the left of the label line[54]. Estimates of the proportion of the customer abatement potential that is associated with cost effective measures for each individual bar as well as RNG abatement potential are provided in the tables that follow each exhibit. Also included in the supporting tables is the average cost data, by end use for customer abatement, and by feedstock category for RNG abatement, used to create the MACCs.

[53] The model results for achievable abatement potential within this timeframe are driven by measure-level achievable adoption curves developed in the 2016 CPS.
[54] For example, if the first bar represents a marginal abatement of 5 tCO_2e, the second bar represents 40 tCO_2e and the third bar represents 15 tCO_2e the label on the right edge of the third bar would read 60 tCO_2e.

Exhibit 17 Summary MACC Including Customer Conservation Measures and RNG Potential for Minimum LTCPF

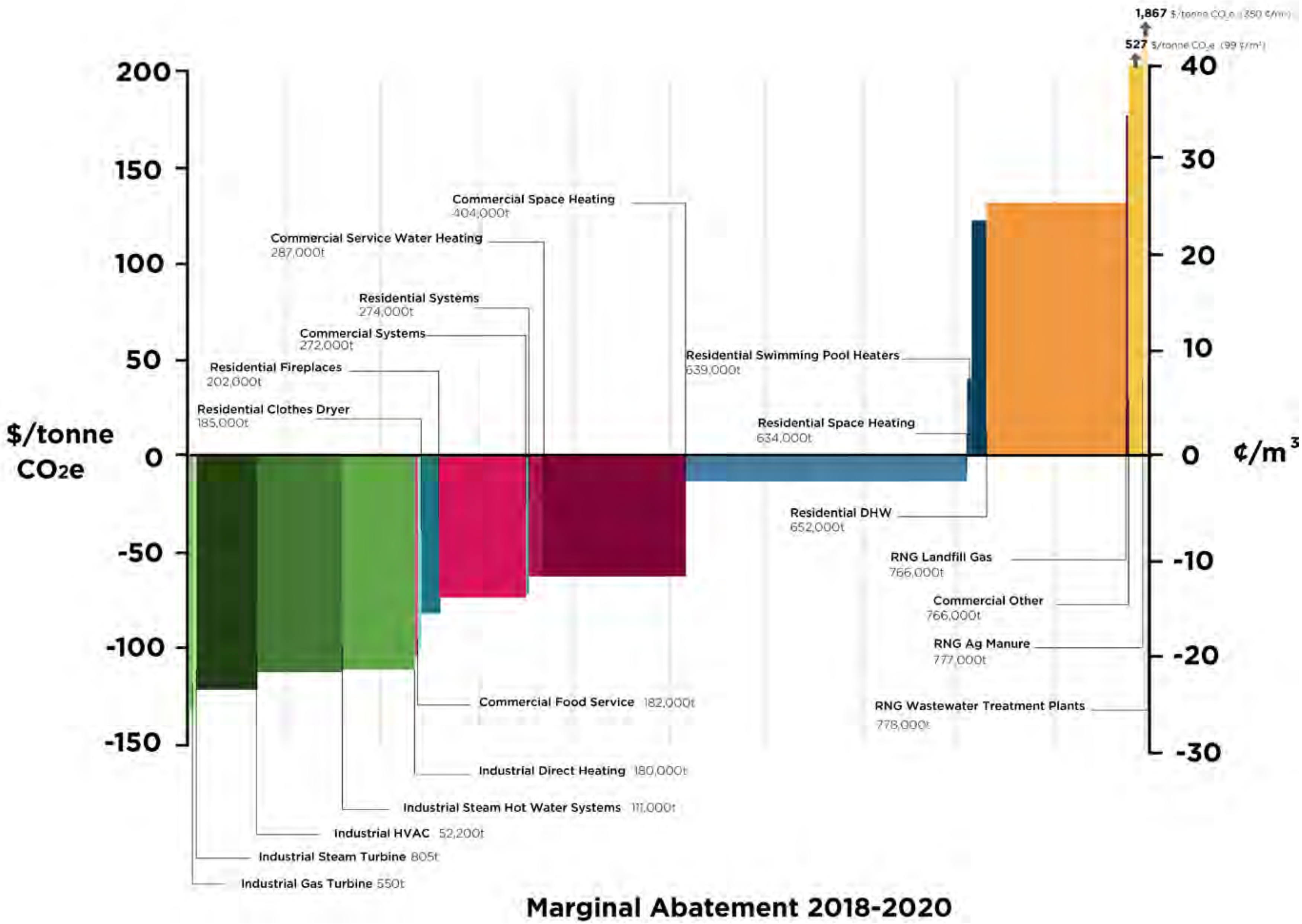

Table 25 Summary MACC Including Customer Conservation Measures and RNG Potential for Minimum LTCPF, Average Cost and Abatement Results

Customer Abatement End Use of RNG Category	Average $/tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Industrial Gas Turbine	-130	-24	550	0.3	100%
Industrial Steam Turbine	-130	-24	250	0.1	100%
Industrial HVAC	-122	-23	51,400	27	100%
Industrial Steam Hot Water System	-112	-21	58,600	31	100%
Industrial Direct Heating	-111	-21	69,700	37	100%
Commercial Food Service	-105	-20	1,040	0.6	100%
Residential Clothes Dryers	-100	-19	3,830	2	97%
Residential Fireplaces	-83	-16	16,200	8.7	100%
Commercial Systems	-75	-14	70,100	37	86%
Residential Systems	-72	-13	1,850	1	100%
Commercial Service Water Heating	-62	-12	13,400	7	96%
Commercial Space Heating	-62	-12	117,000	63	94%
Residential Space Heating	13	2	230,000	122	64%
Residential Swimming Pool Heaters	40	8	5,480	3	74%
Residential Domestic Hot Water	127	24	12,900	7	57%
RNG Landfill Gas	133	25	114,000	61	0%
Commercial Other	176	33	3	0.002	0%
RNG Ag Manure	527	99	11,200	6	0%
RNG Wastewater Treatment Plants	1,867	350	800	0.4	0%
values may not sum to total due to rounding			**778,000**	**415**	

Exhibit 18 Summary MACC Including Customer Conservation Measures and RNG Potential for Maximum LTCPF

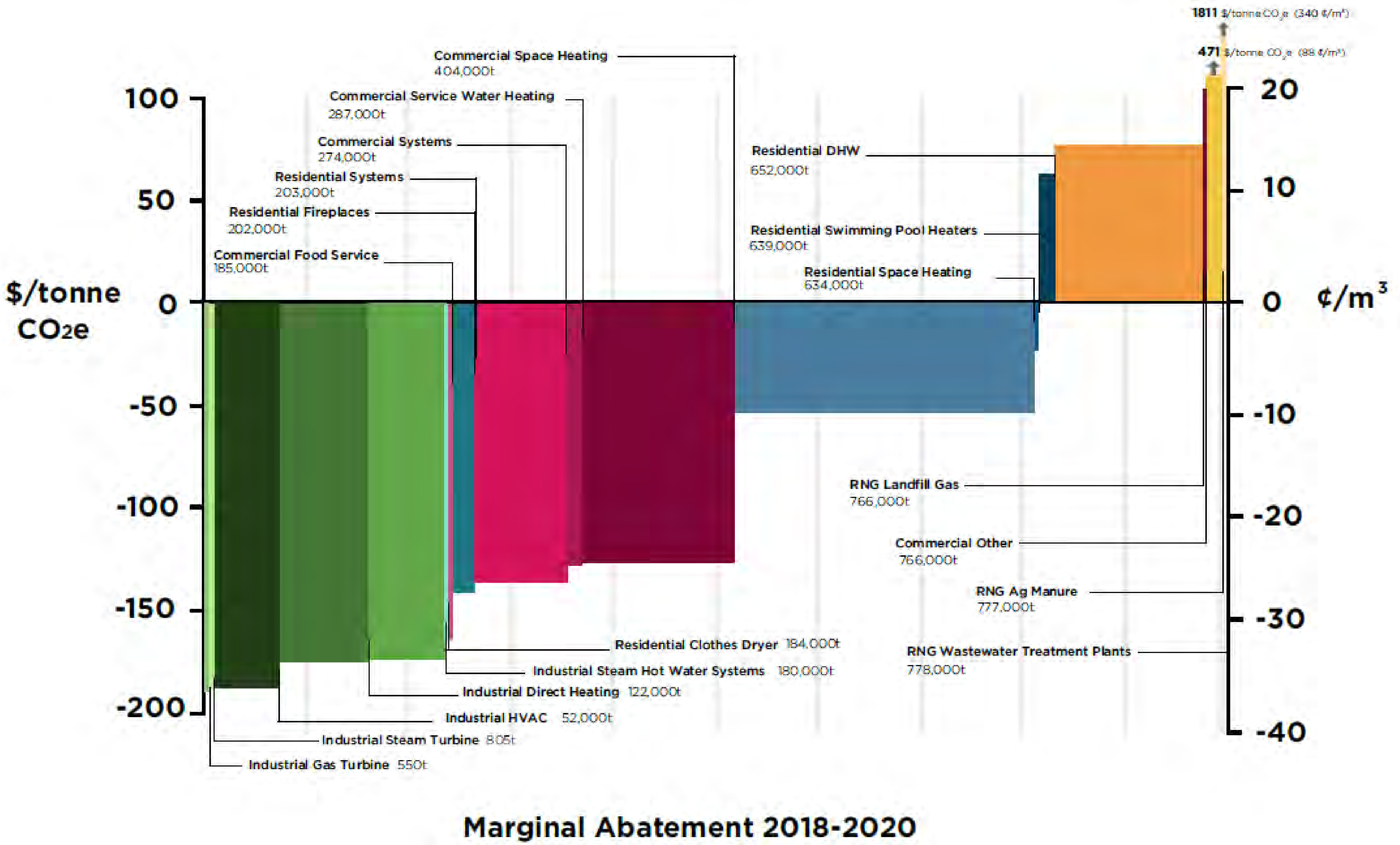

Table 26 Summary MACC Including Customer Conservation Measures and RNG Potential for Maximum LTCPF, Average Cost and Abatement Results

Customer Abatement End Use of RNG Category	Average $/tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Industrial Gas Turbine	-186	-35	550	0.3	100%
Industrial Steam Turbine	-186	-35	250	0.1	100%
Industrial HVAC	-184	-34	51,400	27	100%
Industrial Direct Heating	-176	-33	69,700	37	100%
Industrial Steam Hot Water System	-175	-33	58,600	31	100%
Residential Clothes Dryers	-166	-31	3,830	2	98%
Commercial Food Service	-165	-31	1,040	0.6	100%
Residential Fireplaces	-143	-27	16,200	8.7	100%
Residential Systems	-143	-27	1,850	1	100%
Commercial Systems	-137	-26	70,100	37	100%
Commercial Service Water Heating	-127	-24	13,400	7	96%
Commercial Space Heating	-127	-24	117,000	63	97%
Residential Space Heating	-54	-10	230,000	122	76%
Residential Swimming Pool Heaters	-22	-4	5,480	3	74%
Residential Domestic Hot Water	63	12	12,900	7	57%
RNG Landfill Gas	77	14	114,000	61	0%
Commercial Other	106	20	3	0.002	0%
RNG Ag Manure	471	88	11,200	6	0%
RNG Wastewater Treatment Plants	1,811	340	800	0.4	0%
values may not sum to total due to rounding			**778,000**	**415**	

Exhibit 19 Summary MACC Including Customer Conservation Measures and RNG Potential for Mid-Range LTCPF

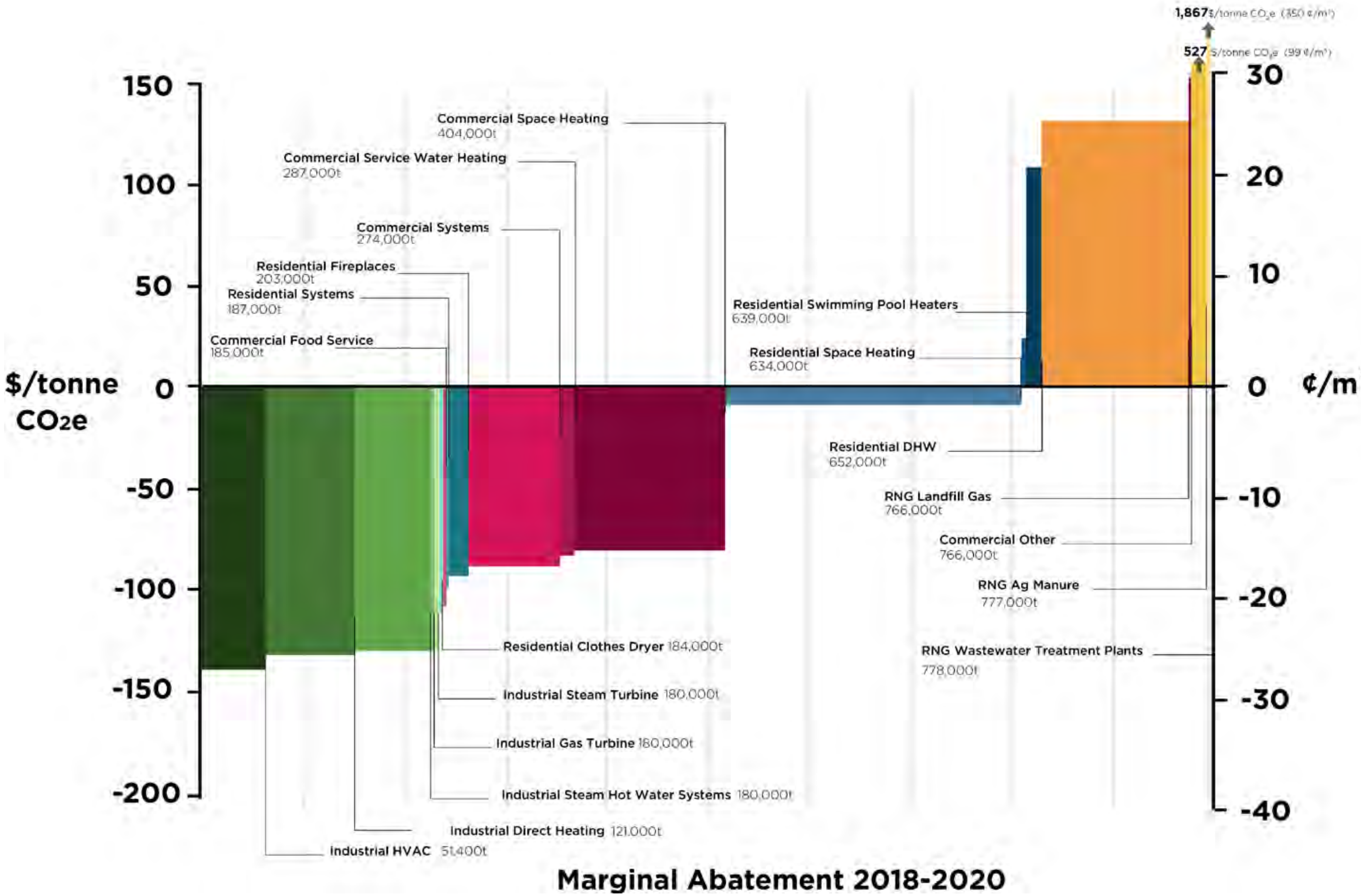

Table 27 Summary MACC Including Customer Conservation Measures and RNG Potential for Mid-Range LTCPF, Average Cost and Abatement Results

Customer Abatement End Use of RNG Category	Average $/tCO_2e$	Average ¢/m^3	Estimated 2018-2020 Abatement (tCO_2e)	Estimated 2018-2020 Abatement (million m^3)	Estimated Cost Effective Abatement (%)
Industrial HVAC	-139	-26	51,400	27	100%
Industrial Direct Heating	-132	-25	69,700	37	100%
Industrial Steam Hot Water System	-131	-25	58,600	31	100%
Industrial Gas Turbine	-130	-24	550	0.3	100%
Industrial Steam Turbine	-130	-24	250	0.1	100%
Residential Clothes Dryers	-123	-23	3,830	2	98%
Commercial Food Service	-119	-22	1,040	0.6	100%
Residential Systems	-97	-18	1,850	1	100%
Residential Fireplaces	-94	-18	16,200	8.7	100%
Commercial Systems	-88	-16	70,100	37	86%
Commercial Service Water Heating	-83	-16	13,400	7	96%
Commercial Space Heating	-83	-15	117,000	63	96%
Residential Space Heating	-7	-1	230,000	122	65%
Residential Swimming Pool Heaters	24	5	5,480	3	74%
Residential Domestic Hot Water	108	20	12,900	7	57%
RNG Landfill Gas	133	25	114,000	61	0%
Commercial Other	151	28	3	0.002	0%
RNG Ag Manure	527	99	11,200	6	0%
RNG Wastewater Treatment Plants	1,867	350	800	0.4	0%
values may not sum to total due to rounding			**778,000**	**415**	

6. Recommendations

The development of a province-wide MACC for Ontario is expected to be conducted on a three-year cycle. The purpose of this section is to identify ways to enhance the next MACC study, both by capturing some of the successful features of this exercise and by improving on other aspects.

6.1 Successes to Retain

Features of the current study that ICF found greatly assisted the work include the following:

- The TAG was dedicated to producing a good study in a timely manner, and provided review and constructive feedback (during and after the TAG meetings) that the consultants found extremely valuable. It was important that the group represented a variety of perspectives.

6.2 Recommended Improvements

Aspects of the current study that could be improved in the next study include the following:

- The next study should have a longer timeframe for completion. In particular, this extended period would allow for more detailed review and more flexibility for the contractor to make modelling changes and/or MACC illustration changes in response to feedback.
- Subsequent studies and any updates to this study should account for the impacts of the Ontario government's CCAP, once details of the Plan are made public. CCAP is expected to underpin new programs and policies designed to reduce provincial emissions through allocation of revenues from the cap and trade program.
- Subsequent studies might consider presenting costs on the MACC from the perspective of society or the customer as well as the utilities. Although the utility perspective makes sense for the analysis done here, the cost consequences for the customer are also relevant to the OEB (i.e., costs borne by the customer for the activity and those passed along from the utility). While a number of the initiatives may look very attractive from the utility point of view, the OEB's consumer protection mandate involves evaluating and optimizing customer impacts in addition to overall ratepayer impacts.
- In the CPS model, assumptions for the industrial sector are defined by subsector, e.g., chemical facilities. Although the natural gas volumes representing the consumption of emitters that are independently 'covered' by the cap and trade program were removed from the model for this MACC study, no revisions were made to market penetration rates for industrial conservation measures[55]. Given more time, market penetration rates that might be more reflective of non-LFEs should be developed and used to model the industrial sector.

[55] The model uses an average for all sizes of industrial facilities, and therefore ignores any potential differences in energy consumption or conservation opportunities between smaller and larger facilities within a given sub-sector. This approach is consistent with the approach that was used in the 2016 CPS, where average market penetration rates were used for both LFEs and non-LFEs, as there was not enough data available to support producing two separate sets of inputs.

- For MACC end uses (bars on the MACC) resulting in a relatively large proportion of the abatement potential for a given sector, consideration should be given to sub-dividing the end use category in subsequent studies. For example, the residential space heating end use category could be sub-divided into measures associated with building envelope and all other space heating measures in order to present more granular data where possible.
- Ontario is a vast province and more detailed, locally relevant feedstock availability and cost data would significantly improve the RNG abatement estimates presented in this study. Subsequent studies should incorporate an expansion of the scope of study for RNG to include renewable hydrogen and forest residue feedstocks, as well as more detailed consideration of waste management assumptions, e.g., inclusion of waste tipping fees.
- Subsequent studies and any updates to this study should account for the impacts of the Federal government's Clean Fuel Standard proposal.
- Once the Ontario offset program is established to support the cap and trade program, and the final protocols are available, the RNG cost estimates presented in Section 3 of this study could be re-assessed. Consideration of the improved economics associated with the ability to generate offsets will reduce the cost of the resource for a proportion of the RNG. Note: at this time, the RNG MACCs in Section 3.4 do not include stacking of environmental benefits[56].
- Future studies may consider inclusion of facility abatement options based on the utilities' facility emissions analyses, which are expected to be available at the time of the next MACC.

[56] Given the various economic sectors that are impacted by RNG development and consumption as a fuel (natural gas distribution or transportation applications), it can be difficult to assign GHG reductions to one program or another. Further complicating the issue, the GHG reductions or environmental attributes may apply to different programs. In some cases, these attributes can be combined or stacked. For the sake of simplicity, we assumed only the reductions attributable to displacing fossil natural gas.

Appendix A Air Source Heat Pumps

Air source heat pumps (ASHPs) are a residential and commercial heating and cooling technology which are technologically similar to central air conditioners (CACs). In cooling mode, ASHPs are identical to CACs; CACs intake air from indoors, remove its heat using a compressor/condenser, and transfer the heat outside. When in heating mode, this process works in reverse; ASHPs intake air from outdoors, remove the heat using a compressor, and push the heat through a duct system in the same fashion as a furnace. ASHPs can also be "ductless," comprising an outdoor unit and one or more indoor units which intake and disburse the cool or warm air. When using multiple units, ductless ASHPs can also transfer heat from a warm part of the house to a colder one (e.g. second floor to the basement).

Of relevance to Ontario, at lower temperatures the heating process becomes less efficient, to the point where all ASHPs require backup resistance heating coils when temperatures are extremely low. ASHP technology has developed significantly over the last 5 years with more efficient and lower cost units and better cold climate solutions that can be 20-30% more efficient than resistance electric even at temperatures in the -20 °C range.

ASHPs have a significant energy efficiency benefit. However, they are considered distinctly from the Customer Abatement measures (discussed in Section 2 of this report) as the technology is electric powered and therefore the measure is fundamentally a fuel switch measure (natural gas to electric). Further, some natural gas conservation measures include electricity co-benefits as avoided costs and some add cost due to increased electrical consumption. However, in the latter example the electricity burdens are typically immaterial. The ASHP measure reduces natural gas consumption, however, the increased cost of electricity will be material and a key factor in cost effectiveness. This measure must be thought through from the perspective of the benefit to the residential energy consumer as opposed to the natural gas rate payer.

The GHG abatement potential is driven by the amount of energy required to fire the heating / cooling system and the GHG intensity of the energy (natural gas vs electric). The ASHP requires less energy on an annual basis than conventional heating / cooling technology and natural gas consumed in the home is more GHG intensive (~0.2 tCO_2/MWh) than Ontario's electricity system (0.05 tCO_2/MWh[57]). As such, the technology has GHG abatement potential.

However, the appropriateness and cost effectiveness of this technology is driven by capital cost (conventional heating / cooling versus ASHP), avoided cost of energy (natural gas), and, unlike pure energy efficiency measures, the significant added cost of electrical energy must be considered. As the technology costs have become close to equivalent, the measures' cost effectiveness is predominantly driven by the energy cost spread between natural gas and electricity. As depicted in the analysis below the delivered cost of electricity in Ontario, at ~$140/MWh (IESO Ontario Planning Outlook, September 2016), versus that of natural gas, at ~$30/MWh-equivalent, challenges the cost effectiveness of ASHPs in Ontario. Given Ontario's

[57] This is the average GHG intensity of the Ontario electricity grid. The GHG intensity of Ontario's grid varies significantly depending on time of day and time of year – the GHG intensity that determines the emissions or avoided emissions associated with incremental electricity demand is the marginal emission factor, which in Ontario varies from 0 t/MWh when non-emitting resources are on the margin to approximately 0.4 t/MWh when natural gas-fired generators are on the margin.

capacity mix, it is important to note that natural gas-fired electricity (0.4 tCO_2/MWh) has a higher GHG intensity than when natural gas is consumed in the building as a result of the loss of efficiency in converting thermal to electrical energy as well as minor energy loss in electricity transmission.

The analysis below is not intended to illustrate all ASHP applications nor get into significant detail on the electric grid supply or cost of electricity (current or forward). Key forward assumptions on cost of electricity are taken from the IESO's Ontario Planning Outlook (September 2016). Additionally,

- Capital costs include equipment purchase, installation, and a cost to upgrade amperage service for all-electric ASHP
- Annual costs are based on current gas and electricity rate structures and assumptions of time of use/seasonality
- ASHP application in the existing home is considered distinctly from the new home
- Full system lifetime is 15 years; no discount rate is applied to calculate lifetime costs
- Emission factor of 0.418 t/MWh for natural gas-fired electricity (based on 45% conversion efficiency and 5% T&D losses); emission factor of 0 t/MWh for zero-carbon electricity
- Per home lifetime costs do **not** include an impact on electricity rates as a result of any new electricity generation capacity required to meet a winter peaking load
- Assumptions related to ASHP capital cost are intended to illustrate cost over the 2018-2020 timeframe

Table 28 Assessment of Abatement Cost Associated with Residential ASHPs – Capital Cost Assumptions

Type of Home:	Existing Homes				New Homes			
Scenario:	Base Case	ASHP	ASHP + HPWH	Integrated ASHP + NG	Base Case	ASHP	ASHP + HPWH	Integrated ASHP + NG
Source of household heat	Natural Gas Furnace	ASHP (electric backup)	ASHP (electric backup)	ASHP with Auxiliary NG Furnace	Natural Gas Furnace	ASHP (electric backup)	ASHP (electric backup)	ASHP with Auxiliary NG Furnace
Source of household cooling	Electric A/C	ASHP	ASHP	ASHP	Electric A/C	ASHP	ASHP	ASHP
Heating/Cooling System Capital Costs	$9,000	$7,000	$7,000	$8,000	$9,000	$6,000	$6,000	$7,000
Source of household hot water	NG Storage	NG Storage	Heat Pump (HPWH)	NG Storage	NG Storage	NG Storage	Heat Pump (HPWH)	NG Storage
Hot Water System Capital Costs	$1,500	$1,500	$2,250	$1,500	$1,500	$1,500	$2,250	$1,500
Average Cost of Amperage Upgrade	$0	$2,000	$2,000	$0	$0	$0	$0	$0
Total Capital	$10,500	$10,500	$11,250	$9,500	$10,500	$7,500	$8,250	$8,500

Costs								

The table above illustrates the capital costs associated with different home heating technology deployments. Overall we have been conservative on the price of the ASHP technology (so as not to overestimate the cost) and we have assumed a standard ASHP technology deployment rather than a cold climate ASHP that would come with improved performance and higher cost. The base case represents the conventional gas fired furnace and hot water, and electric driven A/C. The ASHP scenario replaces the conventional heating and cooling with an ASHP (hot water remains natural gas storage tank type). The ASHP + HPWH is a full electrification scenario that also assumes that hot water is provided via an electric heat pump water heater, a stand-alone unit which is not connected to the ASHP. The integrated solution ASHP + NG assumes a natural gas fired furnace is also available and deployed to meet cold day heating requirements when the ASHP performance degrades to a low efficiency (low coefficient of performance, or COP).

The results illustrate that in most scenarios there is little delta in capital cost between the base case and the ASHP solutions.

The following table provides the assumed heating and cooling efficiencies that were used for this illustrative analysis (on an annual basis) for each scenario.

Table 29 Assessment of Abatement Cost Associated with Residential ASHPs – Annual Performance Assumptions

Scenario:	Base Case[58]	ASHP	ASHP + HPWH	Integrated ASHP + NG
Source of household heat	Natural Gas Furnace	ASHP (electric backup)	ASHP (electric backup)	ASHP with Auxiliary NG Furnace
Annual heating efficiency (% or COP)	95%	2.1	2.1	ASHP: 2.3 NG Furnace: 95% (Aux. meets 25% of annual heat demand)
Source of household cooling	Electric A/C	ASHP	ASHP	ASHP
Annual cooling efficiency (COP)	4	5	5	5
Source of household hot water	NG Storage	NG Storage	Heat Pump (HPWH)	NG Storage
Annual water heating efficiency (% or COP)	67%	67%	2.34	67%

In addition, the following assumptions were made with regard to peak day demand and performance:

- Peak demand at temperature of -26°C
- Furnace input rate of 54,200 BTU/h for an existing home and 40,000 BTU/h for a new home at peak design conditions

[58] These reflect typical efficiencies for new equipment, based on the current Ontario Building Code – they do not reflect the efficiencies of the currently installed stock of equipment in Ontario (which are lower)

- Blended COP of 1 for all-electric air source heat pump (ASHP) at peak day design conditions (includes contribution of electric resistance heating to overall heat pump performance)
- COP of 1.63 at operating peak of integrated ASHP, which occurs just above a switch-over temperature of -8°C (zero power draw on Ontario's peak design day, because the system would be running on natural gas on the coldest peak design day)
- Water heating peak based on an average daily hot water usage profile, where 10% of total daily energy consumption occurs in the peak hour
- Heating profile over the peak design day based on typical variation of temperature over a cold day (based on all days under 0°C in CWEC[59] data)

Based on the above assumptions, the following table illustrates the results of the GHG abatement potential and cost ($/t$CO_2$e) analysis. Annual operating costs for the ASHP technology deployment scenarios will be up to $1,000/yr higher per home than that of the base case as a result of the high cost of electric energy in Ontario relative to natural gas.

Table 30 Assessment of Abatement Cost Associated with Residential ASHPs – The Existing Home

Type of home:		Existing Homes		
Scenario:		ASHP	ASHP + HPWH	Integrated ASHP + NG
Capital Costs (delta vs NG Base Case)		$0	+$750	-$1,000
Annual Energy Costs (delta vs NG Base Case)		+$930/yr	+$1,000/yr	+$600/yr
Total Measure Spend (= Capital Cost + Lifetime Energy Costs)		$14,000	$16,000	$7,900
Annual Emissions from NG		0.82 tCO_2e/yr	0 tCO_2e/yr	1.6 tCO_2e/yr
Incremental Annual Emission (Reduction=negative)	Gas-Fired Elec.	0.14 tCO_2e/yr	0.09 tCO_2e/yr	-0.19 tCO_2e/yr
	Zero-Carbon Elec.	-3.5 tCO_2e/yr	-4.3 tCO_2e/yr	-2.7 tCO_2e/yr
Incremental Emissions over Measure Life (15 yrs)	Gas-Fired Elec.	2.1 tCO_2e	1.3 tCO_2e	-2.8 tCO_2e
	Zero-Carbon Elec.	-52 tCO_2e	-65 tCO_2e	-40 tCO_2e
Incremental Electricity Consumption		+8,700 kWh/yr	+11,000 kWh/yr	+5,900 kWh/yr
Incremental Natural Gas Consumption		-1,900m^3/yr	-2,300m^3/yr	-1,400m^3/yr
Lifetime Cost of Emission Reduction	Gas-Fired Elec.	$-6,600 / t$CO_2$e	$-12,000 / t$CO_2$e	$2,800 / t$CO_2$e
	Zero-Carbon Elec.	$270 / t$CO_2$e	$240 / t$CO_2$e	$200 / t$CO_2$e

Assuming a non-emitting source of electricity, emissions can be reduced by up to 4.3 tCO_2e/home/yr for the typical single family home in Ontario. The cost of abatement would be up to $270/t$CO_2$e and $200/t$CO_2$e where an integrated ASHP and NG furnace is deployed. The

[59] Canadian Weather Year for Energy Calculation (CWEC)

text in red illustrates an increase in emissions where the incremental electric load is met with natural gas-fired electricity instead of non-emitting generation[60].

Within the new home the ASHP applications are more cost effective due to lower capital cost and operating costs associated with cost of energy. As such, emissions can be reduced by up to 3.3 tCO_2e/home/yr and at between \$130 to \$180/tCO_2e.

Table 31 Assessment of Abatement Cost Associated with Residential ASHPs – The New Home

Type of home:		New Homes		
Scenario:		ASHP	ASHP + HPWH	Integrated ASHP + NG
Capital Costs (delta vs NG Base Case)		-\$3,000	-\$2,250	-\$2,000
Annual Energy Costs (delta vs NG Base Case)		\$650/yr	\$570/yr	\$410/yr
Total Measure Spend (= Capital Cost + Lifetime Energy Costs)		\$6,700	\$6,300	\$4,200
Annual Emissions from NG		0.82 tCO_2e/yr	0 tCO_2e/yr	1.4 tCO_2e/yr
Incremental Annual Emissions (Reduction=negative)	Gas-Fired Elec.	0.08 tCO_2e/yr	-0.03 tCO_2e/yr	-0.15 tCO_2e/yr
	Zero-Carbon Elec.	-2.5 tCO_2e/yr	-3.3 tCO_2e/yr	-1.9 tCO_2e/yr
Incremental Emissions over Measure Life (15 yrs)	Gas-Fired Elec.	1.2 tCO_2e	-0.51 tCO_2e	-2.3 tCO_2e
	Zero-Carbon Elec.	-37 tCO_2e	-49 tCO_2e	-28 tCO_2e
Electricity Consumption		+6,100 kWh/yr	+7,800 kWh/yr	+4,100 kWh/yr
Natural Gas Consumption		-1,300m^3/yr	-1,800m^3/yr	-1,000m^3/yr
Lifetime Cost of Emission Reduction	Gas-Fired Elec.	\$-5,500 / tCO_2e	\$12,000 / tCO_2e	\$1,900 / tCO_2e
	Zero-Carbon Elec.	\$180 / tCO_2e	\$130 / tCO_2e	\$150 / tCO_2e

The integrated ASHP + NG solution could minimize the need for incremental winter peaking capacity and electric system transmission and distribution upgrades were the measure taken to an economy-wide scale. Rather than the full-electric air source heat pump (ASHP) exclusively, this option leverages ASHP efficiency for spring, fall and most winter days and integrated natural gas fired technology for extreme cold periods. This option could reduce GHG emissions by ~60% versus a home that currently heats with natural gas alone.

Assessment of commercial ASHPs was not carried out. However, the following should be considered related to commercial application.

- Commercial application of the ASHP is technically feasible and shown to be economic in markets with a more favorable energy price delta between natural gas and electricity
- ASHP units can be scaled (2-100 tons) to meet the higher demand load of larger buildings such as care homes, schools, offices, hospitals, community and public buildings

[60] A natural gas furnace is less GHG-intensive than a standard ASHP powered by electricity from gas-fired generators at low temperatures – the ASHP has a higher end point efficiency in the home, but that can be outweighed by the loss of energy in converting thermal to electrical energy at the generator as well as minor energy losses in electricity transmission which combine to determine the system efficiency

- Larger three phase models incorporate twin or quadruple compressors for multiple stages of power
- Due to the variety of building types and sizes within Ontario a simple illustration of technical and cost effectiveness is not relevant as they are in the less diverse residential sector
- Similarly, little pricing information is available in the public domain due to issues related to applicability
- For the purposes of this study we suggest that costs in the range of \$100/tCO_2 to \$250/tCO_2 provide a reasonable range depending size of building and heating/cooling demand

Concluding comments

While ASHPs have recently reached levels of performance that make them a viable alternative to electric resistance heat in Ontario's climate, they are not yet a cost effective alternative to natural gas furnaces in residential or commercial settings. At current price/performance ratios, and given existing shares of natural gas on the electricity grid, ASHPs have both higher capital and operating costs, and may increase emissions if the marginal electricity generation is supplied mainly by natural gas. If electricity were carbon-free, it would require a carbon price above \$200/tCO_2e for the existing home and \$130/tCO_2e for the new home for the lifetime cost to be equivalent (at current retail electricity prices).

This analysis assumes no improvements in ASHP technology over the study timeframe (through 2020 and 2028). Further focus on the cold climate ASHP would be warranted as the technology matures, were the prices for these to come into comparison with conventional technology.

The abatement costs associated with ASHPs presented in the above are illustrative and based on several simplifying assumptions. The following context should be considered with regard to residential and commercial applications and the overall objective of this analysis.

- Programmatic costs associated with the delivery of an ASHP deployment project are **not** included in the above analysis
- ASHP technology cost and efficiency are likely to improve throughout the 2018-2028 period
- The cost of electric energy to the rate payer is a key input to cost of abatement – \$/kWh and rate structure are relevant
- The proliferation of ASHP deployment will drive the Ontario electric system to a winter peaking from summer peaking region, and require the addition of considerably more peak reliable capacity – potentially adding to system cost
- The GHG intensity (tCO_2e/MWh) of the electrical system's winter peak supply is critical to determining abatement potential and cost
- Where winter peaking capacity is met by natural gas fired generation, total GHG emissions are likely to increase (along with demand for natural gas)
- Where winter peaking capacity is met by natural gas fired generation and existing capacity, the cost per marginal demand for electricity to the system could be significantly lower than \$140/MWh
- The electrical distribution system infrastructure and behind the meter technology in the home will need to be re-thought to accommodate +14kW peak load attributed to an ASHP (in parallel with other issues like home charging for EVs)
- Dedication of cap and trade proceeds of sale of allowance to the ASHP could improve utility program or end user cost effectiveness

Appendix B RNG Results Disaggregated by Feedstock Cost Category

This appendix contains Canadian national RNG potential results disaggregated by feedstock cost category.

Exhibit 20 below presents the national RNG potential by 2020, by feedstock cost category. RNG potential from nine out of the possible 19 RNG feedstock LCOE categories is estimated to become available by 2020[61], as detailed in Table 32. An illustrative 'cost effectiveness' line has been included in Exhibit 20. The line represents the cost of an allowance in 2020 plus the commodity price of fossil-derived natural gas. The line is equivalent to zero-line in Exhibit 15 and Exhibit 16 in Section 3.

Exhibit 20 Canadian RNG Potential by 2020

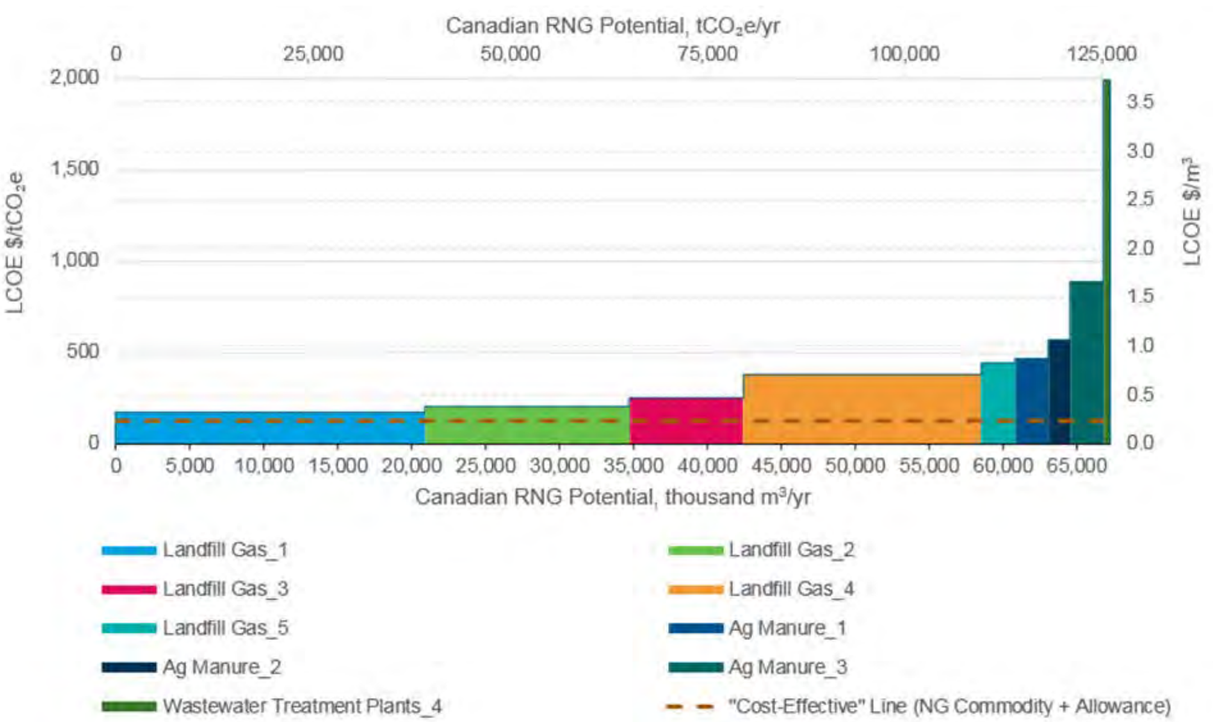

Table 32 Canadian RNG Potential by 2020, LCOE and Potential Results

RNG Feedstock Category	LCOE $/tCO_2e$	LCOE ¢/m³	Estimated Potential by 2020 (tCO_2e)	Estimated Potential by 2020 (million m³)
Landfill Gas Category 1	175	33	39,200	21
Landfill Gas Category 2	201	38	25,900	14

[61] The potential by 2020 is based on the potential deployment s-curve starting in 2018 and reaching full deployment potential by 2028. The underlying principle of this assumption is that the initial investments will be modest over the first 5-7 years (2018-2024), but that deployment in the out-years ramps up.

RNG Feedstock Category	LCOE $/tCO_2e$	LCOE ¢/m³	Estimated Potential by 2020 (tCO_2e)	Estimated Potential by 2020 (million m³)
Landfill Gas Category 3	248	46	14,500	7.7
Landfill Gas Category 4	381	71	30,100	16
Landfill Gas Category 5	438	82	4,340	2.3
Ag Manure Category 1	466	87	4,210	2.3
Ag Manure Category 2	566	106	2,810	1.5
Ag Manure Category 3	888	166	4,210	2.3
Wastewater Treatment Category 4	1,990	373	800	0.4
**values may not sum to total due to rounding*			**126,000**	**67**

Exhibit 21 presents national RNG potential by 2028, by feedstock cost category. All of the national potential described in Table 33 is illustrated here in $/tCO_2e$ and $/m³.

Exhibit 21 Canadian RNG Potential by 2028

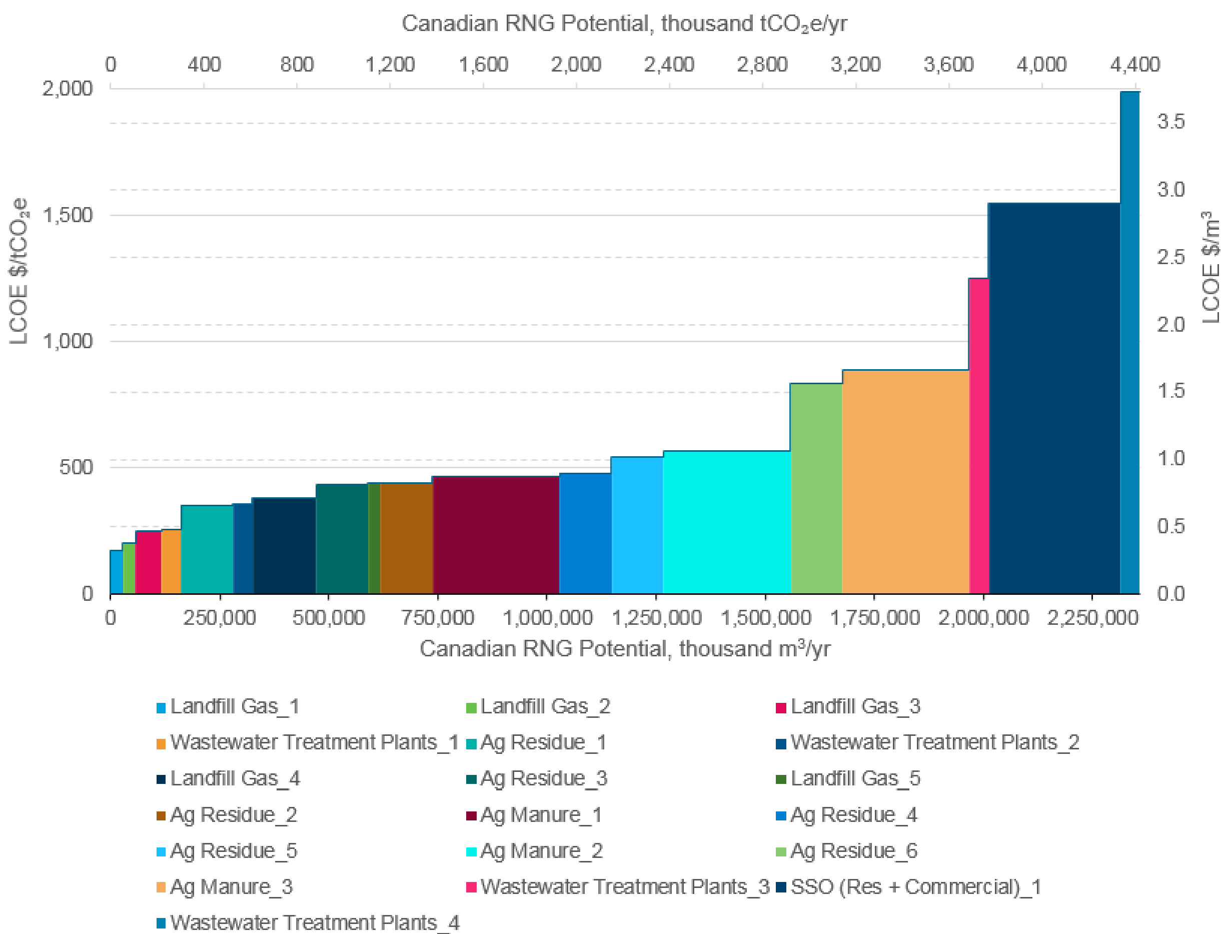

Table 33 Canadian RNG Potential by 2028, LCOE and Potential Results

RNG Feedstock Category	LCOE $/tCO_2e$	LCOE ¢/m³	Estimated Potential by 2028 (tCO_2e)	Estimated Potential by 2028 (million m³)
Landfill Gas Category 1	175	33	54,400	29
Landfill Gas Category 2	201	38	54,400	29
Landfill Gas Category 3	248	46	109,000	58
Wastewater Treatment Category 1	257	48	84,400	45
Ag Residue Category 1	355	66	223,000	119

RNG Feedstock Category	LCOE $/tCO_2e$	LCOE ¢/m^3	Estimated Potential by 2028 (tCO_2e)	Estimated Potential by 2028 (million m^3)
Wastewater Treatment Category 2	357	67	84,400	45
Landfill Gas Category 4	381	71	272,000	145
Ag Residue Category 3	432	81	223,000	119
Landfill Gas Category 5	438	82	54,400	29
Ag Residue Category 2	443	83	223,000	119
Ag Manure Category 1	466	87	546,000	291
Ag Residue Category 4	478	90	223,000	119
Ag Residue Category 5	540	101	223,000	119
Ag Manure Category 2	566	106	546,000	291
Ag Residue Category 6	835	157	223,000	119
Ag Manure Category 3	888	166	546,000	291
Wastewater Treatment Category 3	1,250	234	84,400	45
SSO (Residential & Commercial)	1,550	290	562,000	300
Wastewater Treatment Category 4	1,990	373	84,400	45
**values may not sum to total due to rounding*			**4,420,000**	**2,360**

If the scope of the feedstock sourcing is confined to Ontario, the RNG potential is significantly reduced from the results presented in Exhibit 20 and Exhibit 21. RNG development in Ontario could benefit immensely from better province-specific analytics and potential assessments.