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Activity 4.2.3 Marginal Abatement Cost Curve (MACC) Analysis Report

Ankara 2020

CFCU – Central Finance & Contracts Unit

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Abbreviations and Acronyms

AC	Air Conditioner
BAU	Business-As-Usual
CCGT	Combined Cycle Gas Turbine
CH_4	Methane
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
ELC	Electricity
EPS	Expanded Polystyrene
EU	European Union
EV	Electric vehicle
GHG	Greenhouse Gas
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
LCDTR	Technical Assistance for Developed Analytical Basis for Formulating Strategies and Actions towards Low Carbon Development
LED	Light-Emitting Diode
LH	Long haul
MACC	Marginal Abatement Cost Curve
MoEU	Ministry of Environmental and Urbanization
MSW	Municipal Solid Waste
N_2O	Nitrous oxide
NCCAP	National Climate Change Action Plan
NCCS	National Climate Change Strategy
NDC	Nationally Determined Contribution
SH	Small haul
TIMES	The Integrated MARKAL-EFOM System
TURKSTAT	Turkish Statistical Institute
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
XPS	Extruded Polystyrene

1. Introduction

This report is prepared under Activity 4.2 of the European Union (EU)-funded project "***Technical Assistance for Developed Analytical Basis for Formulating Strategies and Actions towards Low Carbon Development"***.

The **overall objective of the project** is to reduce anthropogenic greenhouse gas (GHG) emissions in Turkey to contribute to the global efforts to mitigate climate change in line with scientific evidence.

Specific project's objective is increasing national and local capacity to prepare for medium- and long-term climate action towards climate-resilient low-carbon development, which will gradually align with the European Union (EU) climate policy and legislation by providing an analytical basis to support the realization of low carbon in the long-term, focusing on cost-effective climate change mitigation actions related to ***buildings, waste, transportation and agriculture sectors*** (National Climate Change Action Plan - NCCAP)[1].

The purpose of the project will be realized through the achievement of four distinct yet highly ***interconnected results***:

- Result 1/ (Component 1): Review of existing strategies in relation to climate change.
- Result 2/ (Component 2): Preparation of regulatory and sectoral impact assessments for EU climate acquis.
- Result 3/ (Component 3): Determination of the costs and emission mitigation potential of the actions specified within the buildings, waste, transport, and agriculture sectors of the NCCAP.
- Result 4/ (Component 4): Developing an analytical basis for possible strategies and actions ensuring green growth in the long term.

The objective of Component 4 is to develop a solid, reliable, and sustainable institutional capacity, and analytical approach supported by modelling tools to ensure long-term low carbon pathways for Turkey. Component 4 covers GHG scenario development for buildings, waste, transport, and agriculture sectors, and it aims to determine carbon mitigation actions with climate, growth, and energy security perspectives, which will provide significant benefit to Turkey.

[1] Republic of Turkey National Climate Change Action Plan (2011-2023), Ankara, 2011

Activity 4.2 is focused on the identification of carbon mitigation activities entailing significant benefits to Turkey with a perspective to reconcile climate, growth, and energy security in the selected sectors.

The objective of this activity is to provide a list of the most promising GHG mitigation actions for agriculture, buildings, transport, and waste sectors together with MACC analysis. Another main objective is to provide list and description of the recommended sectoral long term GHG mitigation options.

Major outputs under Activity 4.2:

- The most promising GHG mitigation actions report
- Sectoral long-term GHG mitigation options report
- Marginal abatement cost curve (MACC) analysis report

This report focused on the marginal abatement cost analysis for agriculture, buildings, transport, and waste sectors. In this study MAC curves for four sectors have been developed using model-derived MAC approach. In this respect models representing agriculture, buildings, transport and waste sectors build upon on TIMES framework has been deployed. In that respect, reference cases developed for Activities 3.1, 3.2 and 4.1 has been used as baseline for the MAC curve developments. No further description of baseline results will be discussed within the report; in case of need one should refer to the reports for the respective activities.

Key ***project stakeholders and target groups*** include:

- Ministry of Environment and Urbanization – primary project Beneficiary
- Ministry of Transport and Infrastructure
- Ministry of Agriculture and Forestry
- Ministry of Energy and Natural Resources
- Turkish Statistical Institute (TurkStat)
- Local-level governmental institutions
- Other governmental agencies
- NGOs and the private sector — with a focus on the key sectors of building, transport, waste, and agriculture
- Academic and research institutions

Implementation of the project is ***managed by an international consortium*** led by Human Dynamics (Austria), and the consortium also includes AESA (Belgium) and Regional Environmental Centre (REC- Hungary and Turkey). All three consulting companies have extensive track records of working on climate change-related issues, and significant experience of project implementation in Turkey.

This report consists of seven chapters. Following the introduction provided in Chapter 1 of the report, Chapters 2-6 provides the MAC analysis results for the agriculture, buildings, transport and waste sectors, respectively. Chapter 7 provides general conclusions.

2. Definition of the Marginal Abatement Cost Curve

A marginal abatement cost curve (MACC) is defined as a graph that indicates the cost, associated with the last (the marginal cost) of emission abatement for varying amounts of emission reduction. Therefore, a baseline with no CO_2 constraint has to be defined in order to assess the marginal abatement cost against this baseline development.

There are two types MAC curves that can be classified namely expert-based and model based. Typical representation of both types is given in Figure 1**Error! Reference source not found.**. Expert-based MAC curves, assess the cost and reduction potential of each potential measure based on the evaluation of educated opinions of experts. Model derived curves are based on the calculation of various top-down or bottom-up models.

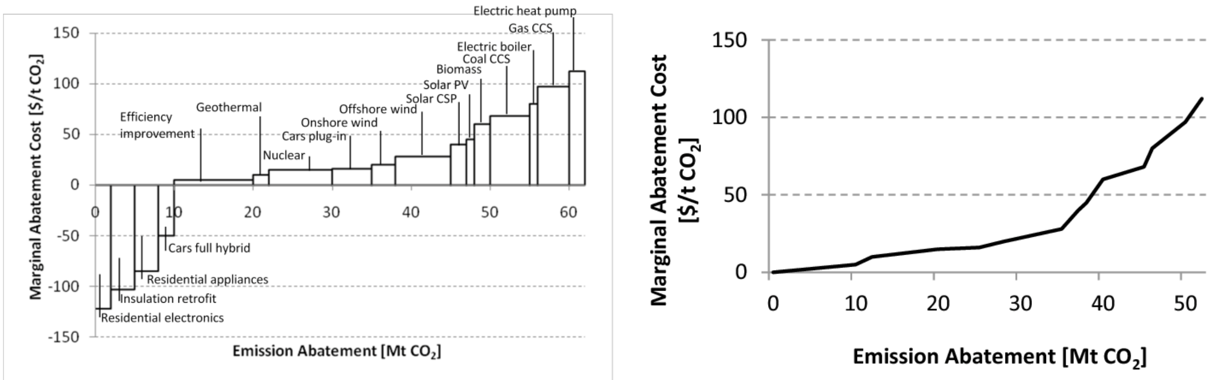

Figure 1. Examples for an expert-based (left) and model-derived MAC curve (right)[2].

MACCs make easier to see the total cost associated with a desired mitigation level. Even-though concept of MAC curves are very useful with in the process of decision making around the policy makers due to the simple representation of the cost related to emission mitigation, one should consider the possible disadvantages of the MAC approach that can limit the benefits of use[3]. As a summary advantages and disadvantages of MAC curve approach is summarized in Table 1.

[2] Source: Kesicki, Fabian. "Marginal abatement cost curves for policy making–expert-based vs. model-derived curves." Energy Institute, University College London (2010): 1-8.

[3] Kesicki, F., & Ekins, P. (2012). Marginal abatement cost curves: a call for caution. Climate Policy, 12(2), 219-236.

Table 1. Advantages and disadvantages of MAC curve approach[4]

Advantages	Disadvantages
• Express reduction cost for any given total reduction amount • Give the total cost necessary for the abatement quantity. • Allow the calculation of average abatement cost.	• Limited to one point in time (for a stationary single year approach) • No consideration of uncertainty • No representation of time dependency • Limited information regarding the assumptions • Lack of side effects / benefits of options.

Expert based approach of building MAC curves is based on experts' opinion and calculations for baseline development of CO_2 emissions. Then iteratively the emission reduction potential and the corresponding cost of each measure is calculated. Based on ranking process of the measures from cheapest to most expensive to represent the cost of realizing incremental levels of emission reduction. The advantageous and disadvantages of expert-based MAC curves can be seen in Table 2.

Table 2. Strengths and weaknesses of expert-based MAC curve

Strengths	Weaknesses
• Extensive detail level • Possibility to take into account technology specific market distortions • Easy understanding of technology specific abatement curves	• Behavioural factors problems • Multiple abatement measures interactions cannot be captured • Baseline consistency issues • Time based / intertemporal interactions omitted • Simplified technological structure • No consideration of macro-economic feedbacks

[4] Adopted from Kesicki, Fabian. "Marginal abatement cost curves for policy making–expert-based vs. model-derived curves." Energy Institute, University College London (2010): 1-8.

As used in this study, model derived MAC curves use energy models to derive the cost and potential for emission mitigation. A number of models can be deployed for this purpose, however, the most common way classifying the models deployed is economy-oriented top-down models and engineering –oriented bottom-up models. Abatement curves are generated by the CO_2 price resulting from the runs with different emission cap levels.

Bottom-up energy models, like TIMES model deployed in this study, are partial equilibrium models representing the single sector of interest representing the energy system with its all commodities, technologies and policies. A general comparison of strengths and weaknesses of model derived MAC curves can be found in Table 3.

Table 3. Strength and weaknesses of model-based MAC curves[5]

Strengths	Weaknesses
Bottom-up	**Bottom-up**
▪ Explicit representation of techs with significant detail level ▪ Detailed follow up depreciation of techs	▪ No macroeconomic feedbacks ▪ Risk of penny-switching ▪ Poor handling of rebound effect
Top-down	**Top-down**
▪ Macroeconomic feedbacks and costs considered	▪ Model lacks technological detail ▪ Simple approach for depreciation
Both	
▪ Interactions between measures included ▪ Emission pathways are consistent ▪ Intertemporal interactions incorporated ▪ Possibility to represent uncertainty under special cases ▪ Possible to incorporate behavioural effects ▪ Comparably quick generation ▪ Assumption of rational agent, disregarding market friction etc.	

In this study MAC curves for four sectors have been developed using model-derived MAC approach. In this respect models representing buildings sector, transport sector,

[5] Adopted from Kesicki, Fabian. "Marginal abatement cost curves for policy making–expert-based vs. model-derived curves." Energy Institute, University College London (2010): 1-8.

waste sector and agriculture sector build upon on TIMES framework has been deployed. Based on this realization, reference cases developed for activity 3.1, 3.1 and 4.1 has been used as baseline for the MAC curve developments. No further description of baseline results will be discussed within the report; in case of need one should refer to the reports for the respective activities.

For the development MAC curves, series of scenarios has been designed to explore the model space in terms of CO_2 abatement options, entering and exiting technologies as well as their respective costs. The scenarios have been designed to reflect abatement levels to comply with INDC targets. Scenarios are basically setup for 1% incremental reduction from the baseline emission trajectory initiating from 2030 to 2050 for each scenario setup/step for each respective year. This way MAC curves have been designed to show the efforts level with respect to national targets.

Since the emission accounting standard for UNFCCC does not account for the end sector related electricity consumption related emission, this standard was misleading for the analysis. In this respect, need for accounting electricity emissions has risen. Since then, original model structure has been modified to account for electricity consumption related emissions. Within this project, since the electricity sector modelling has been out of the scope of the study, the results of a previous modelling work has been used to feed in the electricity emission intensities to the respective models of interest in the study; transport and buildings sector. Emission intensities implemented within the models are displayed in Table 4.

Table 4. Electricity emission intensities implemented within the model runs (tonneCO_2 per MWh)[6]

	Reference (Ref_BauElc)	High Abatement Ambition (Ref_LowElc)
2015	0.46	0.46
2018	0.46	0.46
2020	0.40	0.28
2023	0.36	0.25
2025	0.40	0.25
2030	0.53	0.37

6 Source: Author's previous work under different projects

Each scenario has a code name systematic such that first three letter represents sector, next three letter represents electricity sector emission abatement ambition level if exists for the sector, next three letter is “MAC” representing MAC curve related scenario setup and last two digits emission restriction level. For example, “TRN_REF_MAC_04” represent transportation sector MAC scenario design where emission abatement ambition is reference level and 4% reduction from the baseline trajectory is imposed for the model run. A maximum of 21% abatement level compared to baseline is considered to be maximum level of emission abatement ambition and a total of 21 emission cap scenarios have been implemented for every sector/ambition level. Baseline emission levels for the sectors are given in Table 5. In that respect 1% reduction for building sector corresponds to 1.465 and 1.77 million to CO_2 for Low and Reference electricity intensity based scenarios for 2030 respectively. Regarding agriculture sector it correspond to 0.5 million tonne CO_2 while regarding Waste sector it corresponds to 0.15 million tonne CO_2 abatement. Lastly, 1% reduction for transportation under low and reference electricity emission intensity corresponds to 1.25 and 1.253 million tonne CO_2 respectively.

Table 5. Baseline emission trajectories including electricity consumption related emissions (ktonne CO_2e where appropriate)

Baselines	Description	2015	2020	2025	2030	2035	2040	2045	2050
RSD_HIGH _BASE	Residential Sector – Low Electricity Intensity Base	103,955	104,613	111,155	146,511	158,680	167,344	174,365	180,878
RSD_REF_ BASE	Residential Sector-Reference Electricity Intensity	103,955	121,918	135,886	177,039	192,288	203,117	211,652	219,407
AGR_BASE	Agriculture Sector	42,690	45,731	48,063	50,326	52,258	54,976	56,997	59,716
TRN_HIGH_ BASE	Transportation Sector- Low Electricity Intensity Base	74,523	103,073	115,596	125,065	133,504	142,776	150,800	158,446
TRN_REF_ BASE	Transportation Sector-Reference Electricity Intensity	74,523	103,201	115,773	125,286	133,755	143,048	151,093	158,760
WST_BASE	Waste Sector	12,326	14,702	14,365	15,630	16,607	17,519	18,411	19,237

Various types of cost definitions exist within the literature. As in the reporting process we will report many different type costs having a common understanding is important to clearly express the results. Average cost of abatement up to a certain level of mitigation is calculated by dividing the change of total system cost between the baseline and emission mitigation scenario runs to change of emission reduced between respective cases. Marginal cost of abatement is the change of total system cost per unit of extra emission to be abated. From a practical point of view, it is the cost of next unit of emission to be abated. In terms of it is the derivative of objective function with respect to emission change. And the value is only correct for a range of Ɛ (epsilon). Besides, another cost that will be reported is the incremental cost of abatement; discrete version of marginal cost of abatement. Practically, instead of the derivative operation, total system cost change between two consecutive scenarios are divided by emission change between two consecutive scenarios. In that respect, a representative marginal abatement cost is generated for a real-life representative emission abatement.

As the last word, one should remember that developed MAC curves are model based, since then model results include the impact current technology stock levels, remaining life of current and the future invested technologies, thus a stock management problem is inherent within the problem. In other words, depreciation of the capital is not continuous and uniform. Thus, model results inherent the friction caused by this fact, creating non-smooth MAC curves. Beside, interactions of different measures are also inherent with in the results leading to cost discontinuities as well as spikes with in the curves.

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3. Marginal Abatement Cost Curves for the Agriculture Sector

In this section of the study MAC curves of the agriculture sector has been presented. In general, average cost of mitigation reaches $100 per tonne CO_{2e} limit for 13% reduction level while marginal cost abatement hits that limit much early, 10% reduction limit. For low level of mitigation manure management strategies, while mid-level mitigation deploys biomethanization and fat supplement for beef cattle. For higher levels of abatement, fat supplement for dairy cows becomes the dominant tool of the strategy. Figure 2 displays the average and marginal cost abatement for the agriculture sector.

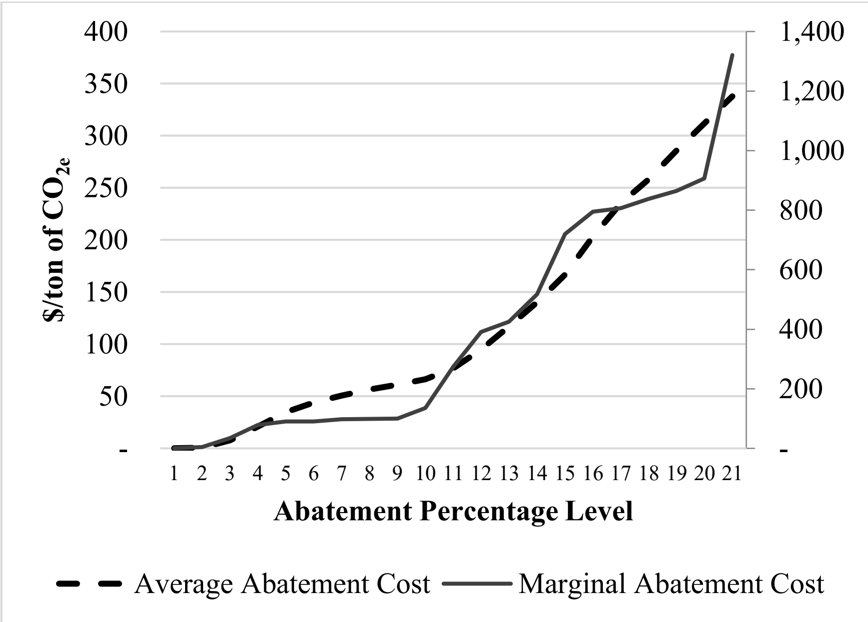

Figure 2. Average (left axis) and Marginal (right axis) abatement cost curves for agriculture sector[7]

Table 6 presents the marginal and abatement cost for the respective abatement levels. As can be seen, emission abatement levels over 9% (4.5 million tonne CO_2) leads to 100 USD cost of abatement on the margin while average cost reaches over 66 USD per ton. 10% or higher levels of abatement leads 3-digit cost figures on the margin around 20% reduction levels while average cost of abatement increases in a fast manner reaching to 300 USD levels at the end of scale. Besides, under 10 USD cost level 3% (1.5 million tonne CO_2) reduction can be reached showing an opportunity for emission reduction with a little effort.

[7] Source: Authors original study

Table 6. Marginal and Average abatement cost levels for respective abatement levels for agriculture sector (\$/tonne CO_{2e})[8]

Emission Abatement Level	Marginal Abatement Cost	Average Abatement Cost
1%	0.4	0.1
2%	4.2	0.6
3%	34.1	7.8
4%	78.1	20.8
5%	90.4	34.7
6%	90.5	43.8
7%	97.5	50.6
8%	99.3	56.5
9%	99.5	61.2
10%	135.6	66.2
11%	273.7	76.8
12%	390.7	94.7
13%	425.0	116.8
14%	518.2	140.2
15%	719.7	166.6
16%	794.9	203.1
17%	806.2	234.9
18%	837.9	258.1
19%	864.6	285.8
20%	906.3	311.7
21%	1,320.8	337.8

As mentioned before incremental cost of abatement represent the cost difference between two emission abatement levels (higher level of abatement with respect to prior level). Figure 3 displays the incremental cost of abatement within the agriculture sector. Due to the way of it is accounted it is more representative then the marginal cost of abatement due to the modelling framework deployed. Also this way of analysis reveals the interactions between the various emission mitigation pathways, creating an important piece of information for the future use.

[8] Authors original study

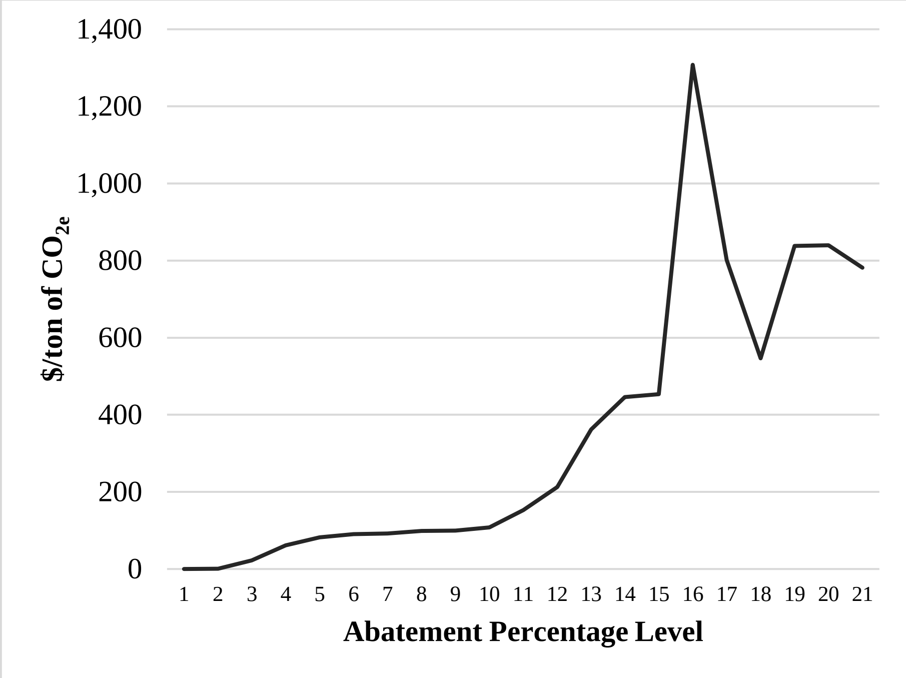

Figure 3. Incremental cost of abatement with respect to prior emission reduction level for agriculture sector[9]

Incremental abatement cost increases, spikes-up, from 15% to 16% abatement level then decreases back to expected levels as in Figure 2. This is due to the structural change switching from one chain of emission abatement technology to another one creating a capacity management problem which increases the cost of incremental abatement cost from 15% reduction level to 16%. Higher levels of abatement targets restructures the supply chains removing the problems. In that respect, one should be cautious about the possibility of market friction / capacity management problems within the sector over for medium-high abatement levels which points out a need for a stressful decisions that need to be made with conflicting outcomes. The reasons behind can be seen more clearly within Table 7.

[9] Authors original study

Table 7. List of technologies to be invested in and to be abandoned out of the sector between each abatement level and the corresponding incremental cost of abatement for agriculture sector[10]

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_{2e})
Base-1	Deep bedding for Cattle Manure Daily Spread for Cattle Manure Pasture for Cattle Manure Anaerobic Lagoon for Other Manure Daily Spread for Other Manure	Anaerobic Lagoon for Cattle Manure Deep bedding for Other Manure Pasture for Other Manure Solid Storage for Other Manure	0.11
1-2	CCGT Anaerobic Digestion for Cattle Manure Anaerobic Lagoon for Cattle Manure Pasture for Cattle Manure Anaerobic Digestion for Other Manure Anaerobic Lagoon for Other Manure	Composting for Cattle Manure Deep bedding for Cattle Manure Solid Storage for Cattle Manure Deep bedding for Other Manure Pasture for Other Manure Solid Storage for Other Manure	1.11
2-3	Crop Production with Optimal N Fertilizer Use CCGT Anaerobic Digestion for Cattle Manure Anaerobic Lagoon for Cattle Manure Pasture for Cattle Manure Anaerobic Lagoon for Other Manure Composting for Other Manure	Existing Crop Production Synthetic Fertilizer to N Composting for Cattle Manure Solid Storage for Cattle Manure Deep bedding for Other Manure Pasture for Other Manure Solid Storage for Other Manure	22.32
3-4	Beef Cattle with Fat Supplement Crop Production with Optimal N Fertilizer Use CCGT Anaerobic Digestion for Cattle Manure Deep bedding for Cattle Manure Anaerobic Digestion for Other Manure Anaerobic Lagoon for Other Manure Deep bedding for Other Manure	Beef Cattle Base Existing Crop Production Synthetic Fertilizer to N Anaerobic Lagoon for Cattle Manure Composting for Cattle Manure Pasture for Cattle Manure Solid Storage for Cattle Manure Daily Spread for Other Manure Pasture for Other Manure Solid Storage for Other Manure	61.51
4-5	Beef Cattle with Fat Supplement CCGT Anaerobic Digestion for Cattle Manure Anaerobic Lagoon for Other Manure	Beef Cattle Base Anaerobic Lagoon for Cattle Manure Composting for Cattle Manure Deep bedding for Cattle Manure Pasture for Cattle Manure Solid Storage for Cattle Manure Pasture for Other Manure	81.89
5-6	Beef Cattle with Fat Supplement	Beef Cattle Base	90.46
6-7	Beef Cattle with Fat Supplement	Beef Cattle Base	92.10
7-8	Beef Cattle with Fat Supplement	Beef Cattle Base	98.88
8-9	Beef Cattle with Fat Supplement	Beef Cattle Base	99.39
9-10	Beef Cattle with Fat Supplement CCGT Anaerobic Digestion for Cattle Manure	Beef Cattle Base Anaerobic Lagoon for Cattle Manure Composting for Cattle Manure	108.30

[10] Authors original study

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_{2e})
	Anaerobic Lagoon for Other Manure Composting for Other Manure Daily Spread for Other Manure Solid Storage for Other Manure	Deep bedding for Cattle Manure Pasture for Cattle Manure Solid Storage for Cattle Manure Anaerobic Digestion for Other Manure Pasture for Other Manure	
10-11	Beef Cattle with Fat Supplement Dairy Cow with Fat Supplement CCGT Anaerobic Digestion for Cattle Manure Anaerobic Lagoon for Other Manure Daily Spread for Other Manure Solid Storage for Other Manure	Beef Cattle Base Dairy Cow Base Anaerobic Lagoon for Cattle Manure Composting for Cattle Manure Deep bedding for Cattle Manure Pasture for Cattle Manure Solid Storage for Cattle Manure Anaerobic Digestion for Other Manure Composting for Other Manure Pasture for Other Manure	152.49
11-12	Beef Cattle with Fat Supplement Dairy Cow with Fat Supplement CCGT Anaerobic Digestion for Cattle Manure Anaerobic Lagoon for Other Manure Deep bedding for Other Manure	Beef Cattle Base Dairy Cow Base Anaerobic Lagoon for Cattle Manure Composting for Cattle Manure Deep bedding for Cattle Manure Pasture for Cattle Manure Solid Storage for Cattle Manure Pasture for Other Manure	212.55
12-13	Beef Cattle with Fat Supplement Dairy Cow with Fat Supplement CCGT Anaerobic Digestion for Cattle Manure Anaerobic Lagoon for Other Manure Deep bedding for Other Manure Solid Storage for Other Manure	Beef Cattle Base Dairy Cow Base Anaerobic Lagoon for Cattle Manure Composting for Cattle Manure Deep bedding for Cattle Manure Pasture for Cattle Manure Solid Storage for Cattle Manure Daily Spread for Other Manure Pasture for Other Manure	362.13
13-14	Beef Cattle with Fat Supplement Dairy Cow with Fat Supplement CCGT Anaerobic Digestion for Cattle Manure Deep bedding for Other Manure	Beef Cattle Base Dairy Cow Base Anaerobic Lagoon for Cattle Manure Composting for Cattle Manure Deep bedding for Cattle Manure Pasture for Cattle Manure Solid Storage for Cattle Manure Pasture for Other Manure	446.24
14-15	Beef Cattle with Fat Supplement Dairy Cow with Fat Supplement CCGT Anaerobic Digestion for Cattle Manure Composting for Cattle Manure Deep bedding for Other Manure Solid Storage for Other Manure	Beef Cattle Base Dairy Cow Base Anaerobic Lagoon for Cattle Manure Deep bedding for Cattle Manure Pasture for Cattle Manure Solid Storage for Cattle Manure Anaerobic Digestion for Other Manure Anaerobic Lagoon for Other Manure	453.07

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_{2e})
		Pasture for Other Manure	
15-16	Beef Cattle Base Dairy Cow with Fat Supplement CCGT Anaerobic Digestion for Cattle Manure Composting for Cattle Manure	Beef Cattle with Fat Supplement Dairy Cow Base Pasture for Cattle Manure Solid Storage for Cattle Manure	1307.78
16-17	Beef Cattle with Fat Supplement Dairy Cow with Fat Supplement	Dairy Cow Base	801.24
17-18	Beef Cattle with Fat Supplement Dairy Cow with Fat Supplement	Beef Cattle Base Dairy Cow Base	546.45
18-19	Beef Cattle with Fat Supplement Dairy Cow with Fat Supplement	Dairy Cow Base	838.29
19-20	Dairy Cow with Fat Supplement CCGT Anaerobic Digestion for Cattle Manure Deep bedding for Other Manure	Dairy Cow Base Composting for Cattle Manure Pasture for Cattle Manure Solid Storage for Cattle Manure Pasture for Other Manure	839.84
20-21	Beef Cattle with Fat Supplement Dairy Cow with Fat Supplement CCGT Anaerobic Digestion for Cattle Manure Deep bedding for Other Manure	Beef Cattle Base Dairy Cow Base Anaerobic Lagoon for Cattle Manure Composting for Cattle Manure Deep bedding for Cattle Manure Pasture for Cattle Manure Solid Storage for Cattle Manure Pasture for Other Manure	781.57

Table 7 displays the entering technologies and abandoned technologies and resulting cost of abatement. In other words, considering constant demand for the sector in terms meat, egg, milk and other relevant sub demand items, total production/process is shifted from abandoned technologies sets to the entering ones with a balance. The level of shift is depended on the cap limit that has imposed as pointed out step section. Thus abandoned technologies are partially abandoned to the limit where the emission cap is met. Given this facts incremental abatement cost change depends on the technology it replace and the impact on the rest of the sector supply chains. In this respect Table 7 points out the mix technologies that is preferred over the mix of technologies left over. However, the level technologies that is entering and exiting is not comparable due the different units used in terms of capacity and activity e.g. milk production, meat production, manure management etc. In that respect, Figure 4. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – entering technologies for agriculture sector until 11% reduction Figure 4, Figure 5, Figure 6 and Figure 7 displays the corresponding abatement impacts of technologies for the given level of prices on their horizontal axis. Figure 4 displays the entering technologies mixes for the reduction levels from 1% to 11% while Figure 5 displays the abandoned technologies for the same reduction levels. Figure 6 displays the entering technologies mixes for the reduction levels from 12% to 21% while and Figure 7 displays the abandoned technologies for the same reduction levels.

Overall, manure management opens up an opportunity window for nearly 1% reduction for nearly no cost of abatement. However, starting from 2% reduction levels CCGT and coupled with becomes an important part of mitigation action coupled with anaerobic digestion process. Beef cattle feeding with fat supplements as well as structuring manure management away from the conventional methods to low emitting ones is observed e.g. deep bedding. Until 15% reduction beef cattle-based emission reduction is the focus of the technology structuring while above this limit strategy shifts due to the limit reached by this strategy; opening up dairy cow-based emission mitigation measures for the upcoming reduction. This shift point reflects a potential market barrier problem due to the structure of the sector while even after this critical shift abatement costs are always higher than the beef cattle-based levels. Overall, market structure is dynamic and interactions of the measures are dominant as it can be seen in Figure 4, Figure 5, Figure 6 and Figure 7.

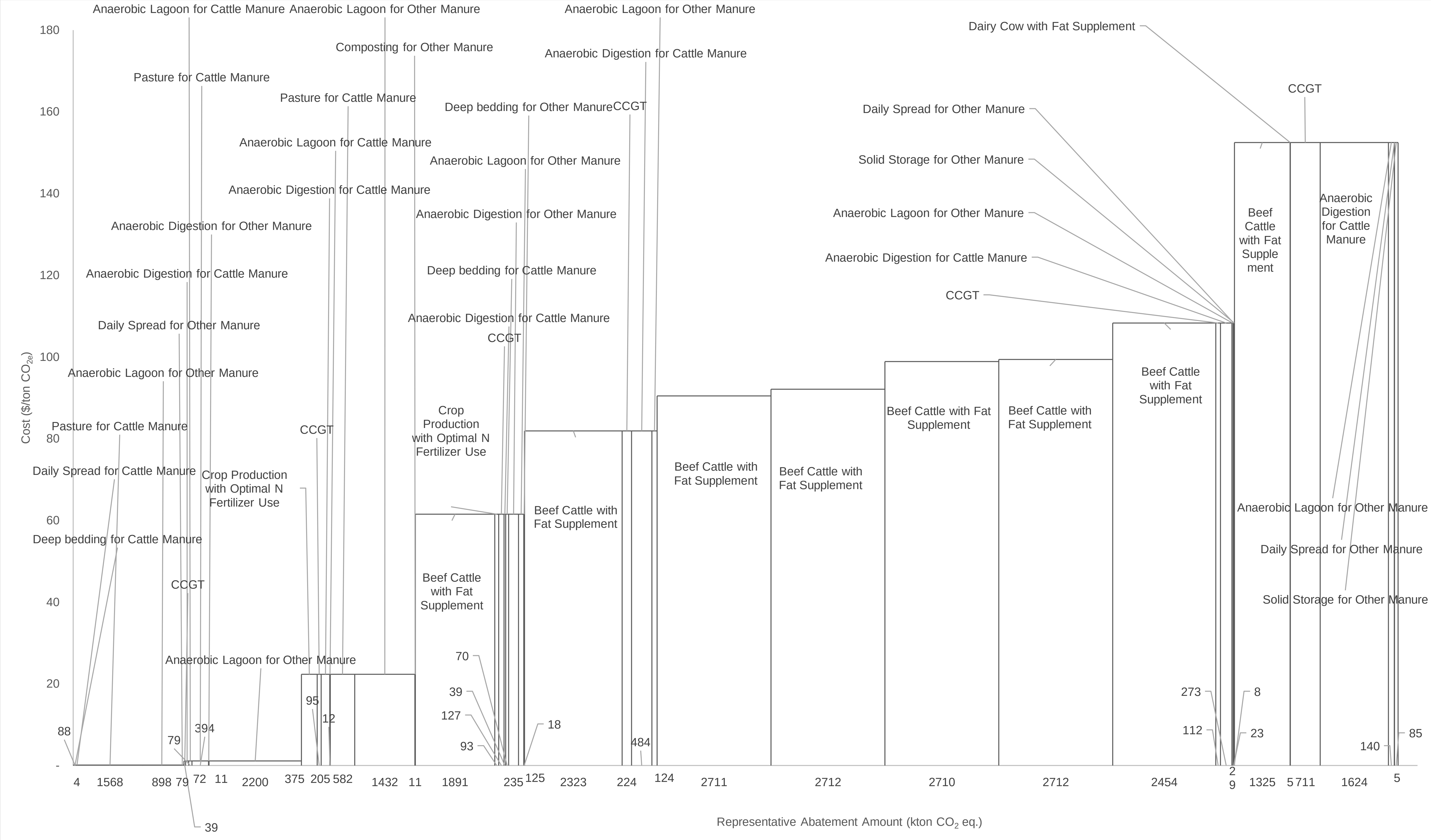

Figure 4. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – entering technologies for agriculture sector until 11% reduction

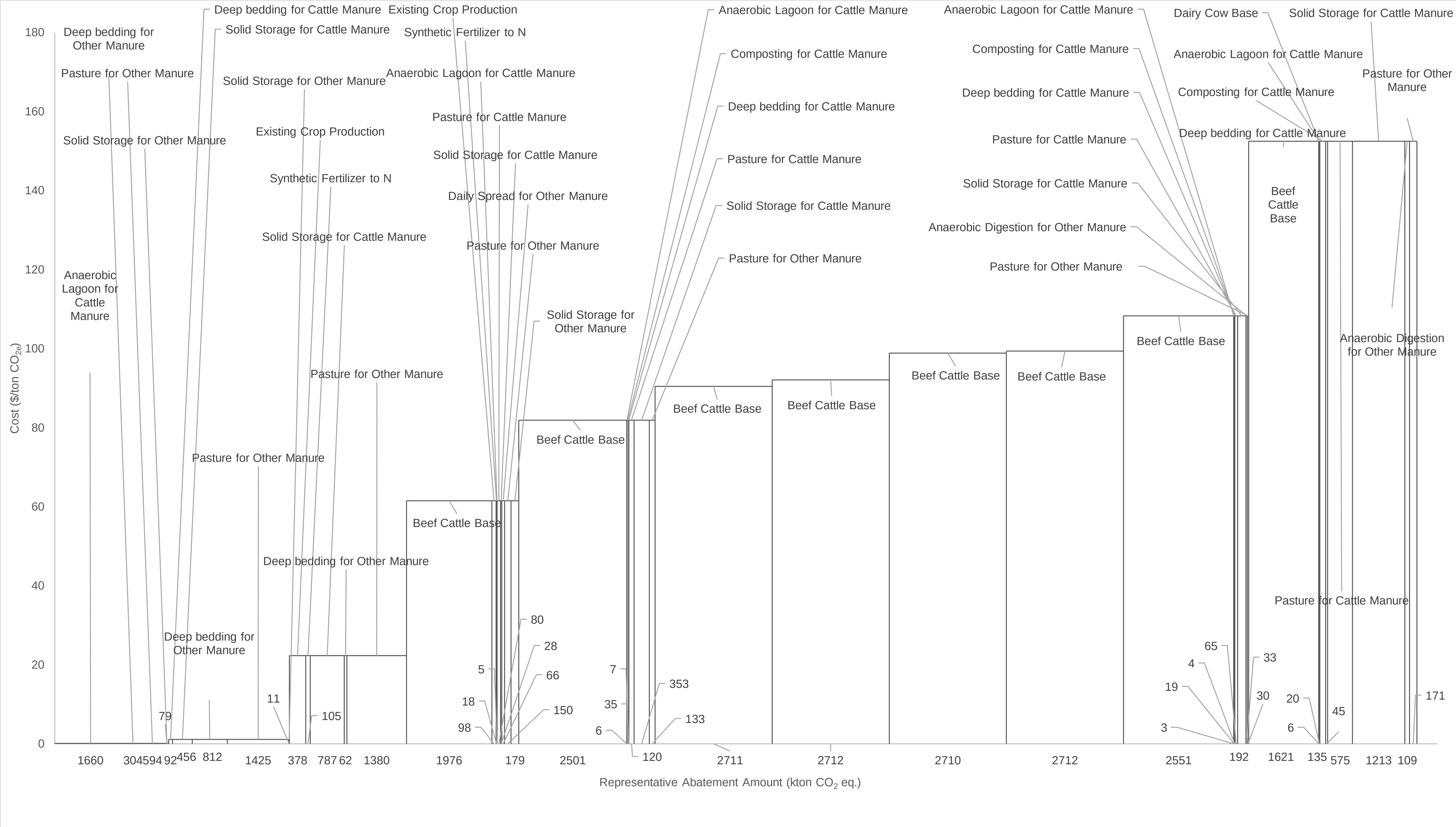

Figure 5. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – abandoned technologies for agriculture sector until 11% reduction

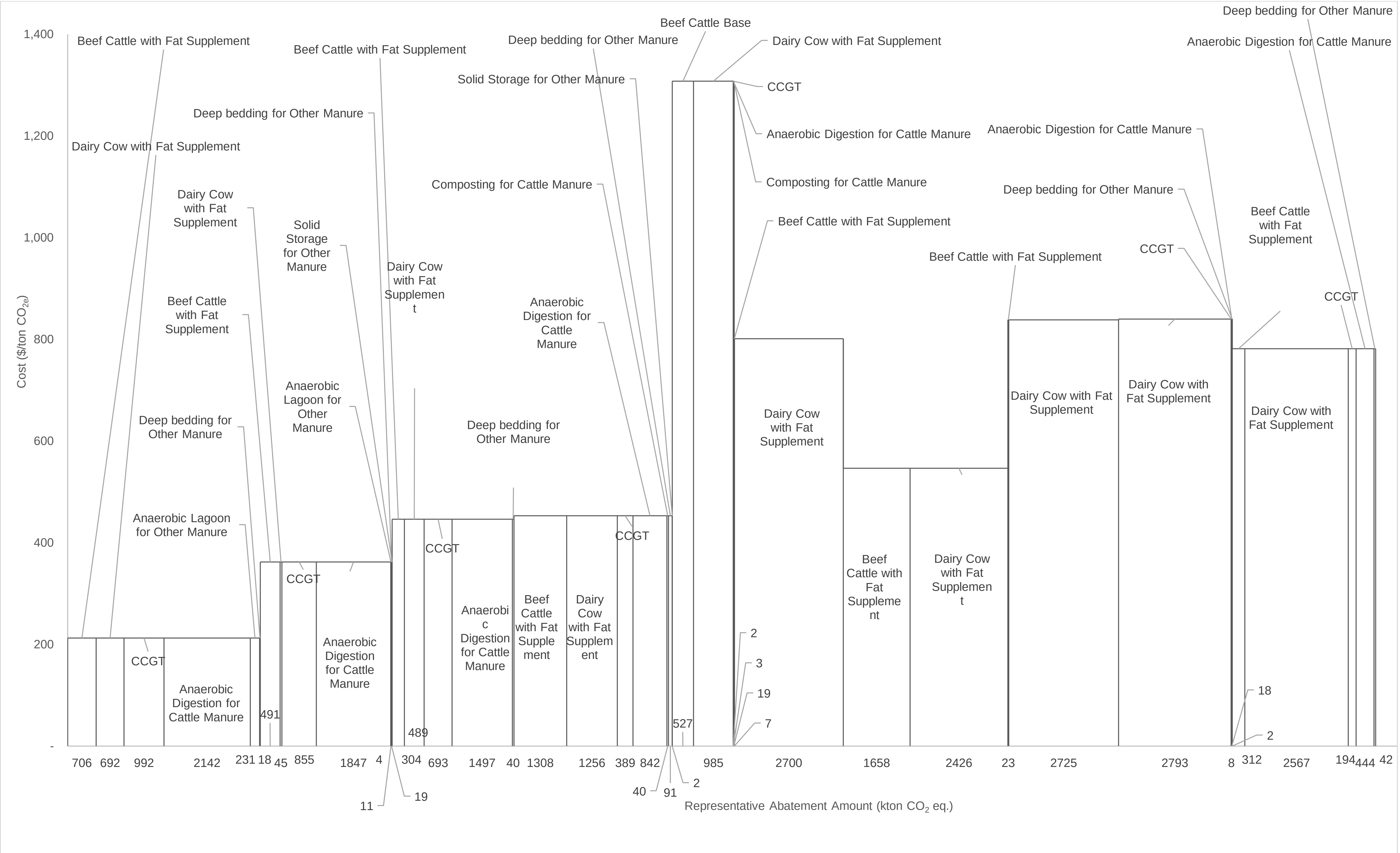

Figure 6. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – entering technologies for agriculture sector starting from 11% to 21% reduction

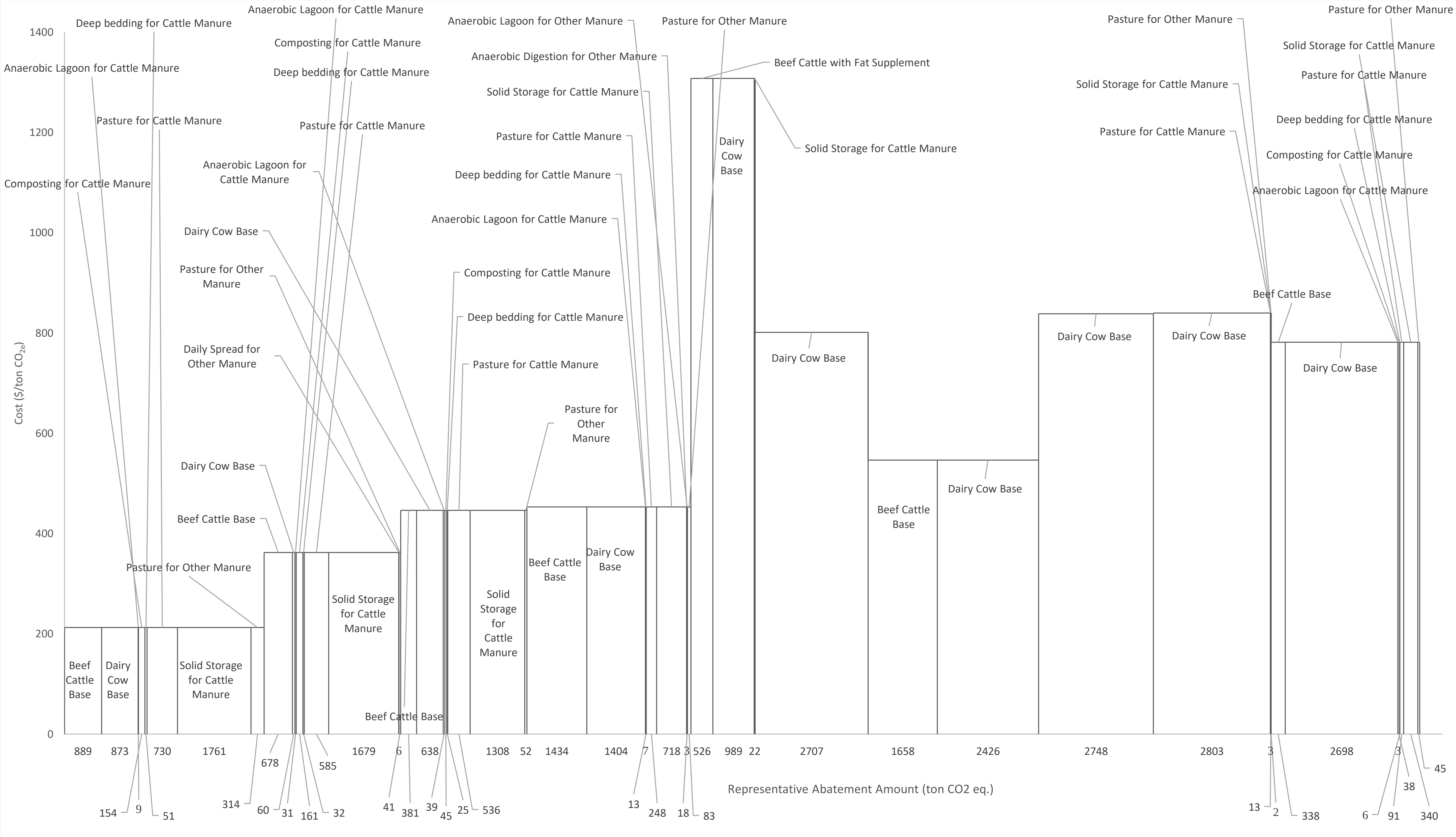

Figure 7 Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – abandoned technologies for agriculture sector starting from 11% to 21% reduction

4. Marginal Abatement Cost Curves for the Buildings Sector

Regarding the building sector, emission intensity of the electricity becomes a critical factor for setting up optimum cost strategies and resulting costs deviates significantly. Average abatement cost for reference electricity emission intensity average cost of abatement starts from $8 range increases up to $60 per tonne CO_2. However, for low electricity emission intensity case cost increases up $150 per tonne CO_2. For reference case, more efficient equipment deployment is the focus of technology structure while for low electricity emission intensity case insulation and the electrified high-tech equipment becomes the essence of the strategy.

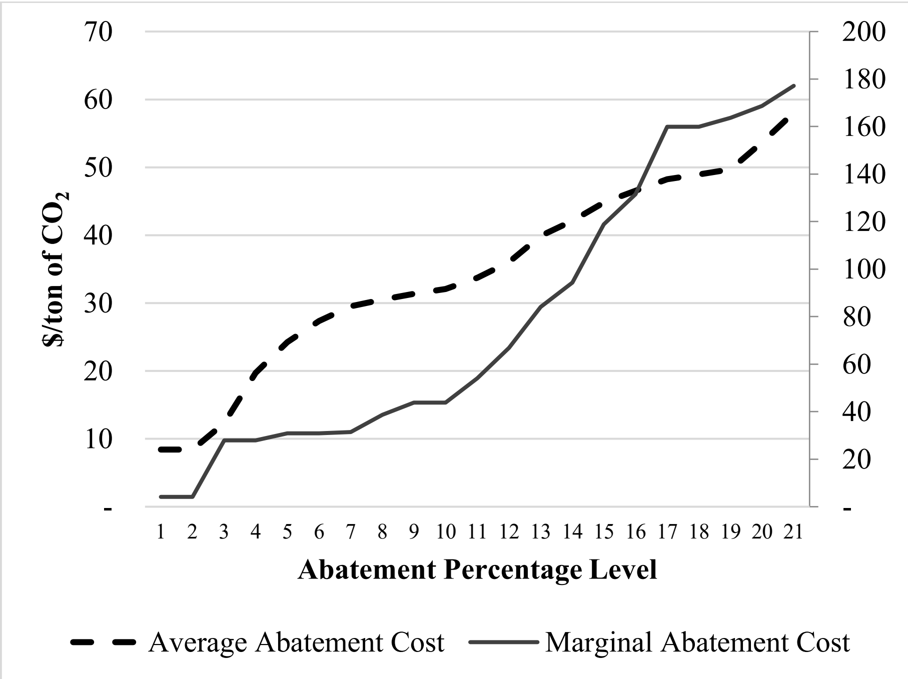

Figure 8. Average (left axis) and Marginal (right axis) abatement cost curves for building sector for reference level electricity emission intensity

Figure 8 displays the marginal and average cost of abatement for reference electricity intensity case. Marginal cost of abatement ranges up to 180 USD per tonne of abatement as the abatement level increases up to 21%. Average cost of abatement reaches up to 60 USD per tonne CO_2 abated. Marginal cost of abatement stays around 30 USD till 7% reduction level (12.39 million tons of CO_2 for 2030) which is attractive. After this point both marginal and average abatement cost curves become steeper for further reduction. However, these outcomes are only true for a reference electricity emission intensity, in which reference emission trajectory relatively higher than the alternative case.

Figure 9 displays the marginal and average cost of abatement for low electricity intensity case. In comparison with Figure 8, significant cost increase is seen. This due to the fact that cleaner/less emission intensity base line eliminates many inexpensive emission abatement options that are not cleaner to compensate clean electricity emission intensity levels before hand, and thus leaving more expensive options for mitigation. This fact can be seen by comparing Table 9 and Table 10 in detail. Marginal cost of abatement levels up from 180 USD to 300 USD while more dramatic impact is observed for the average abatement cost; increase from 60 USD to 140 USD per tonne CO_2. This points out a steeper structure of marginal abatement curve penetrating to average abatement costs.

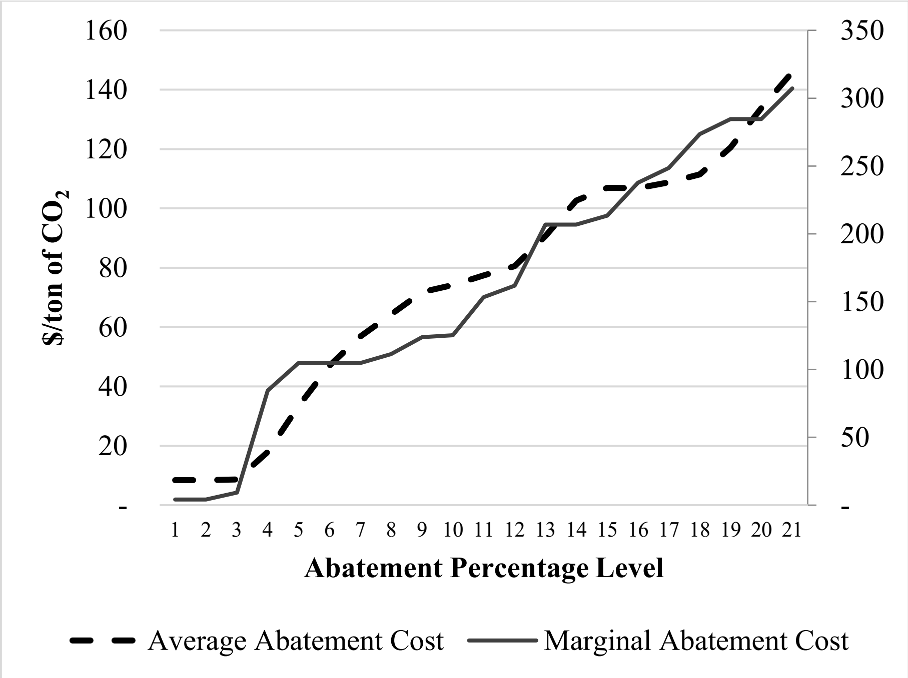

Figure 9. Average (left axis) and Marginal (right axis) abatement cost curves for building sector for low level electricity emission intensity

Table 8 displays the marginal and average cost of abatement for both cases for ease of comparison. As a quick example 100 USD per tonne CO_2 marginal abatement cost level corresponds to 14% reduction (24.78 million tonne CO_2) with 42.1 USD average abatement cost while same cost under low electricity emission intensity case sector can reach up to 7% reduction (10.26 million tonne CO_2) with an average cost of reduction 56 USD. However, an interesting remark, for low level emission abatement levels, up to 3%, low electricity emission intensity case points out a advantageous structure.

Table 8. Marginal and Average abatement cost levels for respective abatement levels for building sector for reference and low electricity emission intensity cases ($/tonne CO_2)

	Ref_BauElc		Ref_LowElc	
Emission Abatement Level	Marginal Abatement Cost	Average Abatement Cost	Marginal Abatement Cost	Average Abatement Cost
1%	4.1	8.4	4.1	8.4
2%	4.1	8.4	4.1	8.4
3%	27.9	12.3	9.2	8.6
4%	27.9	19.7	84.4	17.9
5%	31.0	24.2	104.7	33.4
6%	31.0	27.4	104.7	47.1
7%	31.5	29.5	104.7	56.8
8%	38.7	30.5	111.3	64.2
9%	43.8	31.4	123.8	71.8
10%	43.8	32.1	125.2	74.1
11%	54.1	33.7	153.4	77.4
12%	66.9	36.0	161.8	80.6
13%	84.1	39.9	206.9	90.6
14%	94.3	42.1	206.9	102.6
15%	118.9	44.8	213.3	107.0
16%	131.5	46.5	237.7	106.8
17%	159.9	48.3	248.5	108.7
18%	159.9	48.9	273.5	111.5
19%	163.6	49.7	284.6	120.5
20%	168.7	53.7	284.6	133.7
21%	177.1	58.0	307.2	145.9

Figure 10 displays the incremental cost of abatement within the residential sector under reference electricity emission intensity. Due to the way of it is accounted it is more representative than the marginal cost of abatement due to the modelling framework deployed. Also, this way of analysis reveals the interactions between the various emission mitigation pathways, creating an important piece of information for the future use. Table 9 displays the newly deployed and abandoned technologies under the reference electricity emission intensity case with respect to previous abatement level.

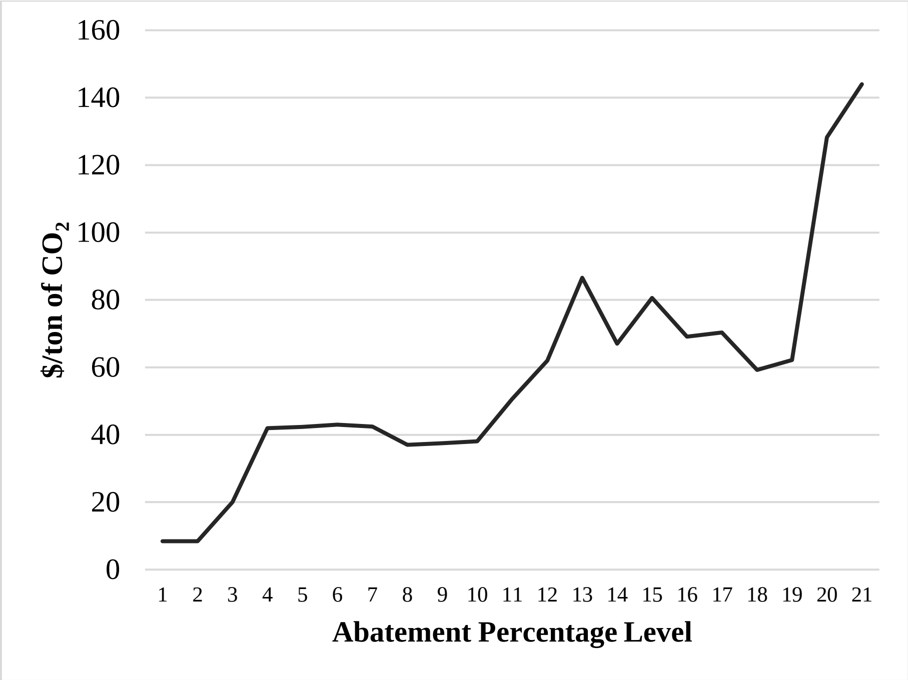

Figure 10. Incremental cost of abatement with respect to prior emission reduction level for building sector under reference electricity emission intensity

Up to 10 USD levels, main strategy for mitigation is to replace coal based commercial stoves with the natural gas condensing furnaces. Incremental cost structure points out that a plateau of 40 USD exists between 4% and 10% reduction levels. In this part of the curve electric water heaters are replaced by less emission intensive natural gas hermetic geysers. Starting from 10% level significant abatement cost increases lie ahead due to the mostly more capital-intensive technologies deployed such as more efficient central air conditioners. After 15% reduction levels switch between a nearly flat pricing parts can be seen till 18% reduction level, where switch between similar technology types but better efficiency levels are observed. 19% and higher levels require insulation coupled with removal of natural gas geysers substituted with the natural gas combined boiler mostly for central infrastructure.

Table 9. List of technologies to be invested in and to be abandoned out of the sector between each abatement level and the corresponding incremental cost of abatement for building sector under reference electricity emission intensity

Step	Entering Technologies	Left Technologies	Cost of Abatement ($ / tonne CO_2)
Base-1	Com. New Condensing Natural Gas Furnace	Com. Base Coal Stove	8.42
1-2	Com. New Condensing Natural Gas Furnace	Com. Base Coal Stove	8.42
2-3	Com. New Condensing Natural Gas Furnace Base A++ Class Dryer Base A+ LED Base NGA Hermetic Geyser	Com. Base Coal Stove Base A+ Class Dryer Base A Class Fluorescent Base Electric Water Heater Geyser	20.07
3-4	Com. New Condensing Natural Gas Furnace Base NGA Hermetic Geyser	Com. Base Coal Stove Base Electric Water Heater Geyser	41.95
4-5	Com. New Condensing Natural Gas Furnace Base A++ Class Dryer Base NGA Hermetic Geyser	Com. Base Coal Stove Base A+ Class Dryer Base Electric Water Heater Geyser	42.38
5-6	Base NGA Hermetic Geyser	Base Electric Water Heater Geyser	43.01
6-7	Base NGA Hermetic Geyser	Base Electric Water Heater Geyser	42.47
7-8	Base A++ Class Dryer Base NGA Hermetic Geyser	Base A+ Class Dryer Base A Class Fluorescent Base Electric Water Heater Geyser	37.04
8-9	Base A Class Fluorescent Base A+ LED Base NGA Hermetic Geyser	Base Electric Water Heater Geyser	37.49
9-10	Base NGA Hermetic Geyser	Base Electric Water Heater Geyser	38.02
10-11	Com. Base Central AC ELC cooler Base NGA Hermetic Geyser	Com. Base Room AC ELC cooler Base A Class Fluorescent Base Electric Water Heater Geyser	50.61
11-12	Base N.Gas Condensing Combined Boiler Base NGA Hermetic Geyser	Base Electric Water Heater Geyser	62.00
12-13	Com. Base A++ LED Com. Base Central AC ELC cooler Base A Class Fluorescent New N. Gas Condensing Boiler Base N.Gas Condensing Combined Boiler	Com. Base A+ LED Com. Base Room AC ELC cooler Base Solid Fuel Boiler Base Electric Water Heater Geyser Base NGA Hermetic Geyser	86.54
13-14	Com. Base Central AC ELC cooler New N. Gas Condensing Boiler Base NGA Hermetic Geyser	Com. Base Room AC ELC cooler Base Solid Fuel Boiler Base Electric Water Heater Geyser	67.05
14-15		Com. Base A++ Class Refrigerator Base N.Gas Condensing Boiler	80.60

Step	Entering Technologies	Left Technologies	Cost of Abatement ($ / tonne CO_2)
	Com. New A++++ Class Refrigerator New N. Gas Condensing Boiler Base NGA Hermetic Geyser	Base Solid Fuel Boiler Base Electric Water Heater Geyser	
15-16	Base N.Gas Condensing Combined Boiler	Com. Base Room AC ELC cooler New N. Gas Condensing Boiler Base Solid Fuel Boiler Base Electric Water Heater Geyser Base NGA Hermetic Geyser	69.10
16-17	Com. Base A++ LED Com. Base Central AC ELC cooler Com. New Condensing Natural Gas Furnace Com. Base Liquid Gas Furnace Base Air-conditioner (ASHP) - More Efficient New N. Gas Condensing Boiler Base NGA Hermetic Geyser	Com. Base A+ LED Com. Base Room AC ELC cooler Com. Base Electric Radiant Base A Class Fluorescent Base Air-conditioner (ASHP) - Less Efficient Base N.Gas Condensing Combined Boiler Base Solid Fuel Boiler Base Electric Water Heater Geyser	70.32
17-18	Com. New Condensing Natural Gas Furnace Com. Base Liquid Gas Furnace New N. Gas Condensing Boiler	Com. Base Electric Radiant Base Solid Fuel Boiler	59.23
18-19	Com. New Condensing Natural Gas Furnace Com. Base Liquid Gas Furnace Base N.Gas Condensing Combined Boiler	Com. Base Electric Radiant New N. Gas Condensing Boiler Base Solid Fuel Boiler Base NGA Hermetic Geyser	62.22
19-20	Com. New Condensing Natural Gas Furnace Com. Base Liquid Gas Furnace 8 cm wall insulation (XPS/EPS) + 16 cm roof insulation (XPS) for old buildings upgraded Base N.Gas Condensing Combined Boiler	Com. Base Electric Radiant New N. Gas Condensing Boiler Base Solid Fuel Boiler Base NGA Hermetic Geyser	128.27
20-21	Com. New A++++ Class Refrigerator 8 cm wall insulation (XPS/EPS) + 16 cm roof insulation (XPS) for old buildings upgraded Base N.Gas Condensing Combined Boiler	Com. Base A++ Class Refrigerator New N. Gas Condensing Boiler Base Solid Fuel Boiler Base NGA Hermetic Geyser	143.99

Figure 11 displays the incremental cost of abatement for the buildings under low electricity emission intensity case. Cost levels are higher than the previous case as expected. The spikes between reduction levels 12% and 16% as well as 18% and 21%. These are the critical points that shape the marginal and average cost figures and underlying investment pattern is very important indeed.

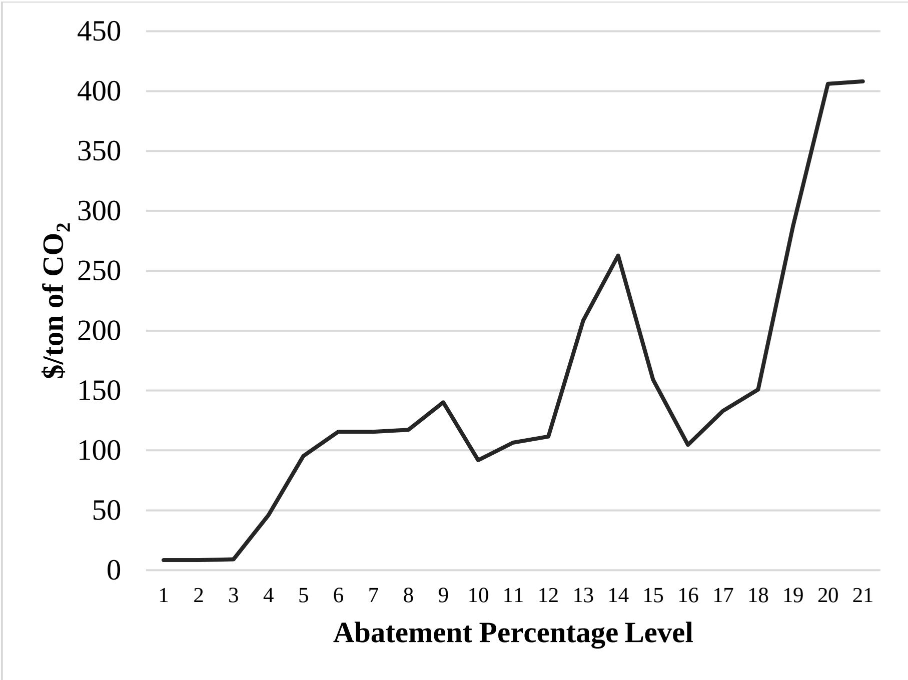

Figure 11. Incremental cost of abatement with respect to prior emission reduction level for building sector under low electricity emission intensity

Table 10 displays the entering and abandoned technologies under low electricity emission intensity respective emission caps and corresponding cost of abatement. As can be seen starting from 13% reduction levels insulation for old buildings gets into the picture which is good for energy efficiency improvements. However, removing solid fuel boilers, electric water geysers and natural water geysers at the same of insulation due cap limit increases the abatement costs significantly. Second spike initiates from the insulation implementation to the new buildings due to increased cap limits starting from 19% cap limits. From that point abatement costs becomes very high to consider.

Table 10. List of technologies to be invested in and to be abandoned out of the sector between each abatement level and the corresponding incremental cost of abatement for building sector under low electricity emission intensity

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_2)
Base-1	Com. New Condensing Natural Gas Furnace	Com. Base Coal Stove	8.4
1-2	Com. New Condensing Natural Gas Furnace	Com. Base Coal Stove	8.4
2-3	Com. New Condensing Natural Gas Furnace Base A++ Class Dryer	Com. Base Coal Stove Base A+ Class Dryer	9.0
3-4	Com. Base Central AC ELC cooler Com. New Condensing Natural Gas Furnace Base A++ Class Dryer Base A+ LED New N. Gas Condensing Boiler	Com. Base Room AC ELC cooler Com. Base Coal Stove Base A+ Class Dryer Base A Class Fluorescent Base Solid Fuel Boiler	45.8

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_2)
4-5	Com. Base Central AC ELC cooler New N. Gas Condensing Boiler Base N. Gas Condensing Combined Boiler	Com. Base Room AC ELC cooler Base A Class Fluorescent Base Electric Water Heater Geyser Base Solid Fuel Boiler	95.2
5-6	New N. Gas Condensing Boiler Base N. Gas Condensing Combined Boiler	Base Electric Water Heater Geyser Base Solid Fuel Boiler	115.6
6-7	New N. Gas Condensing Boiler Base N. Gas Condensing Combined Boiler	Base Electric Water Heater Geyser Base Solid Fuel Boiler	115.6
7-8	Base NGA Hermetic Geyser New N. Gas Condensing Boiler Base N. Gas Condensing Combined Boiler	Base Electric Water Heater Geyser Base Solid Fuel Boiler	117.3
8-9	Com. Base Central AC ELC cooler Base NGA Hermetic Geyser Base N. Gas Condensing Combined Boiler	Com. Base Room AC ELC cooler Base Electric Water Heater Geyser New N. Gas Condensing Boiler Base Solid Fuel Boiler	140.3
9-10	Com. New Condensing Natural Gas Furnace New N. Gas Condensing Boiler Base N. Gas Condensing Combined Boiler	Com. Base Lignite Furnace Base Electric Water Heater Geyser Base Solid Fuel Boiler	91.9
10-11	Com. Base A++ LED Com. New A++++ Class Refrigerator Com. New Condensing Natural Gas Furnace New N. Gas Condensing Boiler Base N. Gas Condensing Combined Boiler	Com. Base A+ LED Com. Base A++ Class Refrigerator Com. Base Lignite Furnace Base Electric Water Heater Geyser Base N. Gas Condensing Boiler Base Solid Fuel Boiler	106.5
11-12	Com. New A++++ Class Refrigerator Com. Base Lignite Furnace Base N. Gas Condensing Combined Boiler	Com. Base A++ Class Refrigerator Com. New Condensing Natural Gas Furnace Base Electric Water Heater Geyser Base NGA Hermetic Geyser New N. Gas Condensing Boiler Base Solid Fuel Boiler	111.6
12-13	Com. Base A++ LED Com. New Condensing Natural Gas Furnace 8 cm wall insulation (XPS/EPS) + 16 cm roof insulation (XPS) for old buildings upgraded Base Air-conditioner (ASHP) - More Efficient Base N. Gas Condensing Combined Boiler	Com. Base A+ LED Com. Base Lignite Furnace Base Electric Water Heater Geyser Base NGA Hermetic Geyser Base Air-conditioner (ASHP)- Less Efficient New N. Gas Condensing Boiler Base Solid Fuel Boiler	208.4
13-14	8 cm wall insulation (XPS/EPS) + 16 cm roof insulation (XPS) for old buildings upgraded Base NGA Hermetic Geyser Base N. Gas Condensing Combined Boiler	Base Electric Water Heater Geyser New N. Gas Condensing Boiler Base Solid Fuel Boiler	262.6
14-15	8 cm wall insulation (XPS/EPS) + 16 cm roof insulation (XPS) for old buildings upgraded Base NGA Hermetic Geyser Base N. Gas Condensing Combined Boiler	Base Electric Water Heater Geyser New N. Gas Condensing Boiler Base Solid Fuel Boiler	159.2
15-16	Com. Base A++ LED Com. New Condensing Natural Gas Furnace	Com. Base A+ LED Base Electric Water Heater Geyser	104.6

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_2)
	Com. Base Lignite Furnace Base Air-conditioner (ASHP) - More Efficient Base N. Gas Condensing Combined Boiler	Base Air-conditioner (ASHP)- Less Efficient New N. Gas Condensing Boiler Base Solid Fuel Boiler	
16-17	Com. New A++++ Class Refrigerator Com. New Condensing Natural Gas Furnace Com. Base Lignite Furnace 8 cm wall insulation (XPS/EPS) + 16 cm roof insulation (XPS) for old buildings upgraded Base A Class Fluorescent New N. Gas Condensing Boiler Base N. Gas Condensing Combined Boiler	Com. Base A++ Class Refrigerator Base Electric Water Heater Geyser Base Solid Fuel Boiler	133.0
17-18	Com. Base A++ LED Com. New A++++ Class Refrigerator Com. New Condensing Natural Gas Furnace 8 cm wall insulation (XPS/EPS) + 16 cm roof insulation (XPS) for old buildings upgraded Base Air-conditioner (ASHP) - More Efficient Base N. Gas Condensing Combined Boiler	Com. Base A+ LED Com. Base A++ Class Refrigerator Base Electric Water Heater Geyser Base Air-conditioner (ASHP)- Less Efficient New N. Gas Condensing Boiler Base Solid Fuel Boiler	150.9
18-19	Com. New A++++ Class Refrigerator Com. New Condensing Natural Gas Furnace 4 cm wall insulation (XPS/EPS) + 8 cm roof insulation (XPS) for new buildings upgraded 8 cm wall insulation (XPS/EPS) + 16 cm roof insulation (XPS) for old buildings upgraded Base NGA Hermetic Geyser Base N. Gas Condensing Combined Boiler	Com. Base A++ Class Refrigerator Base Electric Water Heater Geyser New N. Gas Condensing Boiler	287.4
19-20	4 cm wall insulation (XPS/EPS) + 8 cm roof insulation (XPS) for new buildings upgraded 8 cm wall insulation (XPS/EPS) + 16 cm roof insulation (XPS) for old buildings upgraded Base NGA Hermetic Geyser	Base Electric Water Heater Geyser New N. Gas Condensing Boiler Base N. Gas Condensing Combined Boiler	406.0
20-21	Com. New Electric Heat Pump 4 cm wall insulation (XPS/EPS) + 8 cm roof insulation (XPS) for new buildings upgraded 8 cm wall insulation (XPS/EPS) + 16 cm roof insulation (XPS) for old buildings upgraded Base NGA Hermetic Geyser	Com. Base Central AC ELC cooler Base Electric Water Heater Geyser New N. Gas Condensing Boiler Base N. Gas Condensing Combined Boiler	408.1

Figure 12, Figure 13, Figure 14 and Figure 15 displays entering and abandoned technologies on an expert based representation of a MAC curve by dividing emission cap limits in to two piece, 1% to 11% and 11% to 21% for the ease of readability.

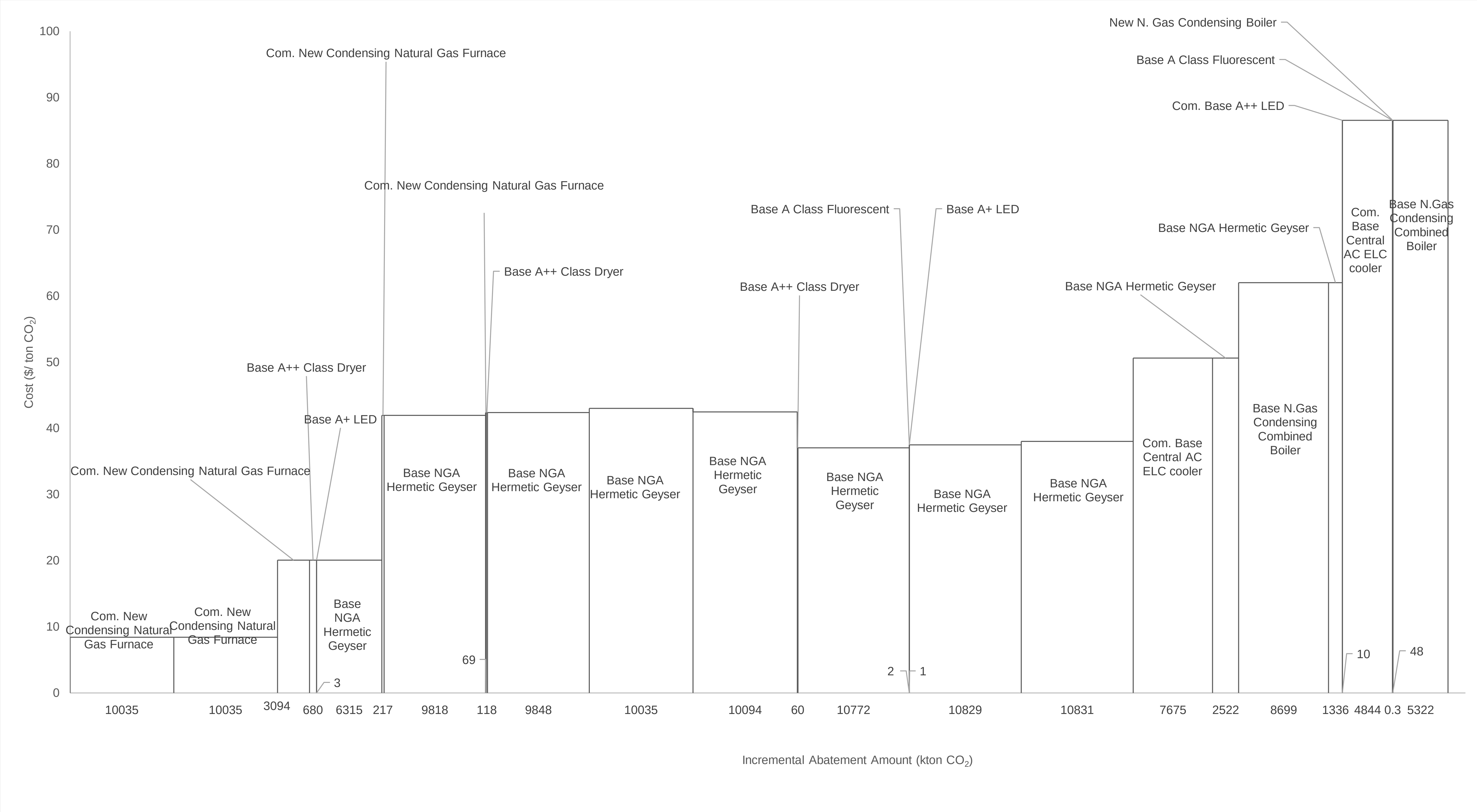

Figure 12. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – entering technologies for building sector starting until 11% reduction for reference electricity emission intensity

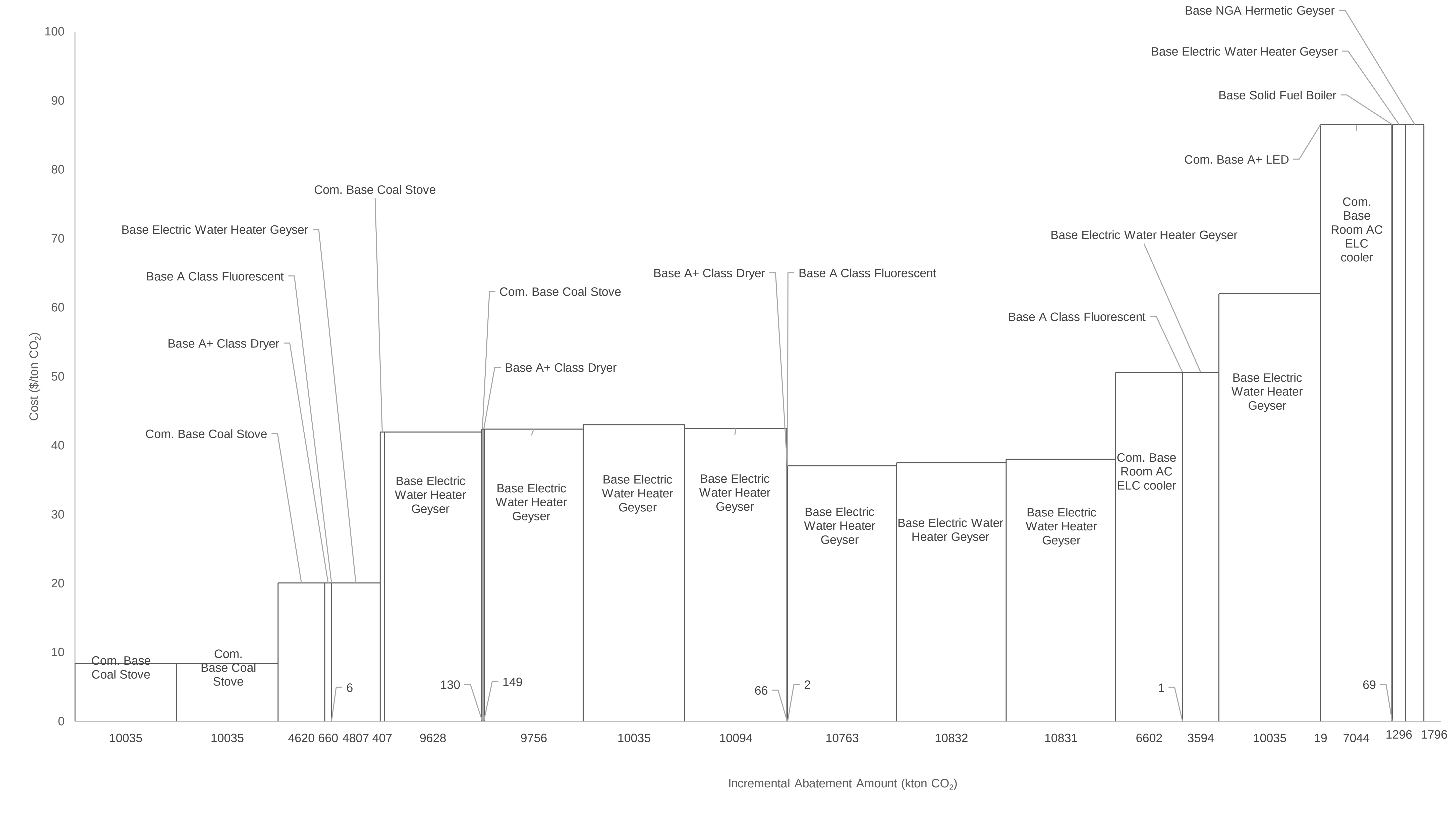

Figure 13. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – abandoned technologies for building sector starting until 11% reduction for reference electricity emission intensity

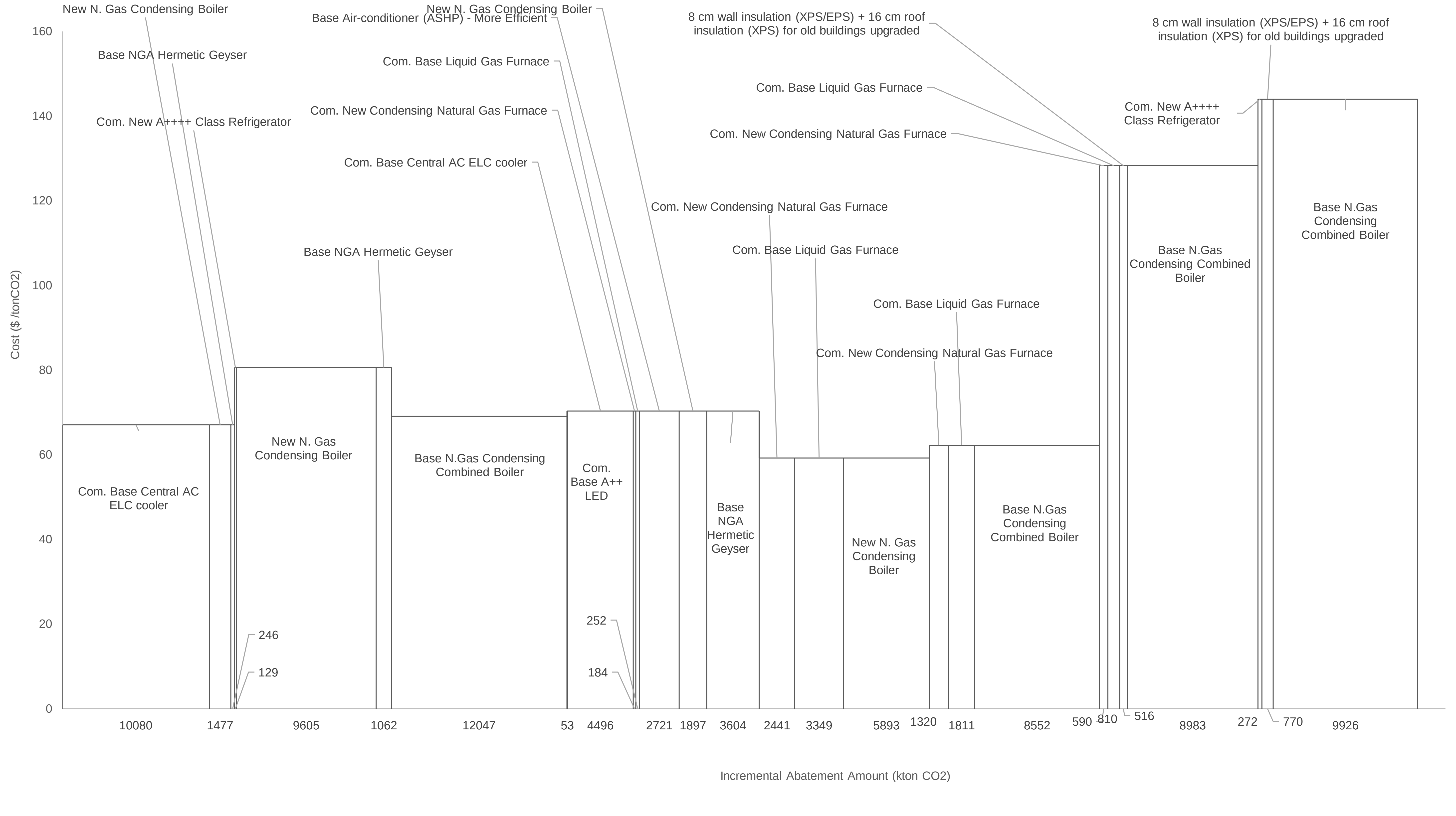

Figure 14. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – entering technologies for building sector starting from 11% to 21% reduction for reference electricity emission intensity

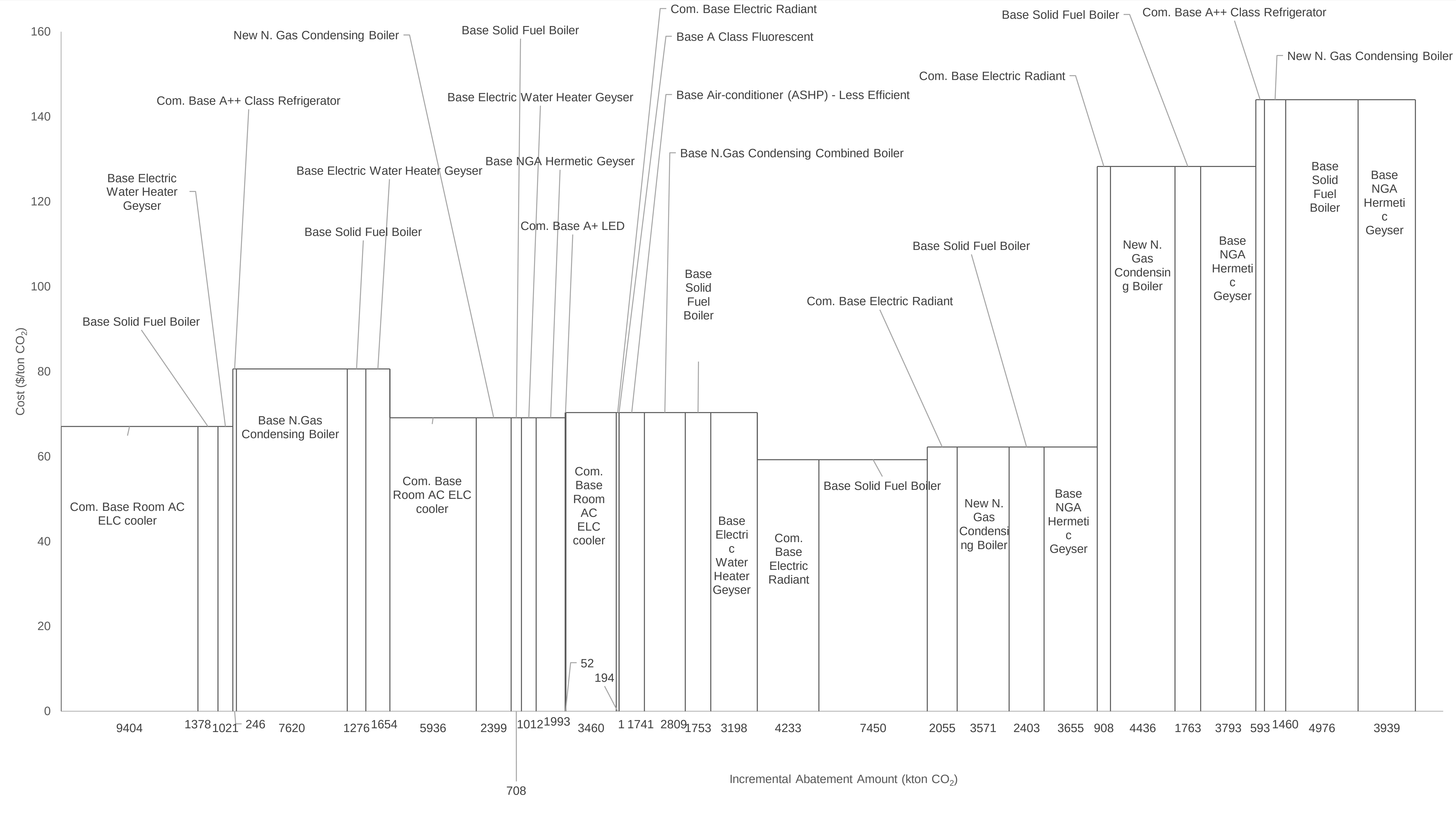

Figure 15. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – abandoned technologies for building sector starting from 11% to 21% reduction for reference electricity emission intensity

5. Marginal Abatement Cost Curves for the Transport Sector

Regarding the transport sector emission intensity changes the way that the vehicle technology park is going to be formed. For reference level case, marginal abatement from electricity fuelled vehicles is relatively low, thus low emission intensity fuels (eg. E85) becomes the basis for the energy mix at the low-level abatement. However, for higher level EVs comes into play short distance travels for both passenger and cargo trips. For low electricity emission intensity case, EV kicks in the market much sooner while driving both average and marginal cost levels lower levels. Cost difference between the two cases are so significant that it becomes a critical question how the future of electricity sector is going to be.

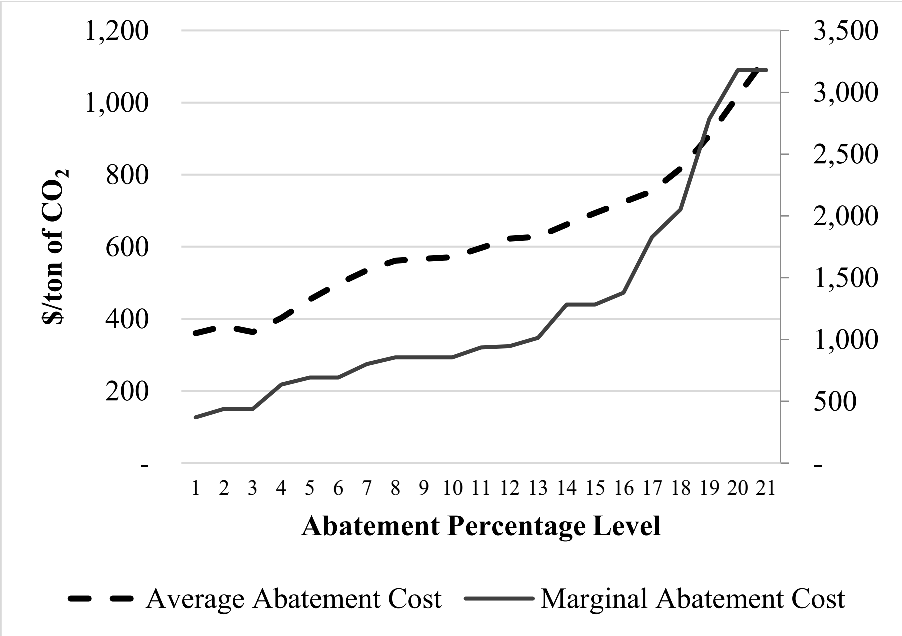

Figure 16. Average (left axis) and Marginal (right axis) abatement cost curves for the transport sector for reference level electricity emission intensity

Figure 16 and Figure 17 displays the marginal and average abatement cost curves for the transportation sector under reference and low-level electricity emission intensity levels respectively. For the reference emission intensity case average costs range up to 1000 USD while marginal costs can reach over 3000 USD. Even for 1% reduction (1.25 million tonne CO_2 by 2030) cost of abatement is very close 400 USD level. Accordingly, such an emission intensity of electricity, marginal cost of abatement of the EVs is not so attractive at all.

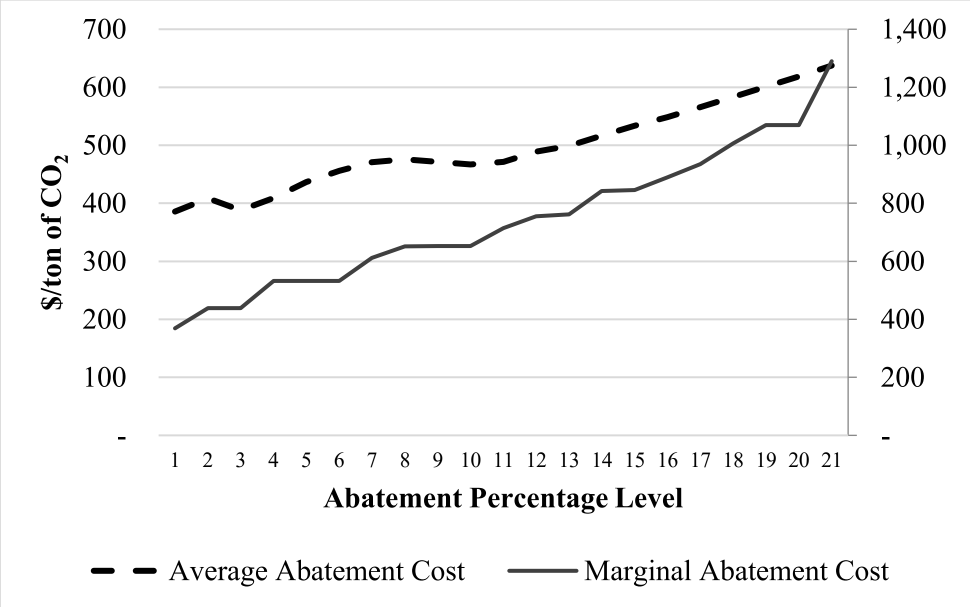

Figure 17. Average (left axis) and Marginal (right axis) abatement cost curves for transport sector for low level electricity emission intensity

However, under low electricity emission intensity cost of abatement both in terms marginal and average drops significantly. Average cost abatement varies up to 600 USD while marginal cost peaks up to 1200 USD per tonne CO_2. This level of difference highlights the importance of electricity sector emission intensity on the transportation sector abatement policies. Table 11 displays this phenomenon more clearly.

Table 11. Marginal and Average abatement cost levels for respective abatement levels for transport sector for reference and low electricity emission intensity cases ($/tonne CO_2)

	Ref_BauElc		Ref_LowElc	
Emission Abatement Level	Marginal Abatement Cost	Average Abatement Cost	Marginal Abatement Cost	Average Abatement Cost
1%	370.1	360.2	369.0	385.7
2%	439.5	379.4	438.5	408.5
3%	439.5	363.6	438.5	387.9
4%	635.7	402.6	532.7	408.8
5%	691.4	453.9	532.7	436.9
6%	691.4	497.6	532.7	455.8
7%	800.1	535.0	611.6	470.8
8%	855.5	561.4	651.1	475.9
9%	855.5	566.9	652.6	471.4
10%	855.5	571.2	652.6	466.8
11%	935.5	596.5	714.9	471.4
12%	947.2	622.8	755.2	489.2
13%	1,012.4	628.2	761.7	498.7
14%	1,281.4	661.6	842.0	516.9
15%	1,281.4	693.9	845.9	534.0
16%	1,379.3	723.9	889.8	548.5

17%	1,827.8	753.5	935.0	565.9
18%	2,051.8	816.6	1,006.8	583.5
19%	2,783.6	908.0	1,069.1	600.8
20%	3,179.2	1,018.4	1,069.1	618.6
21%	3,179.2	1,125.5	1,289.7	637.4

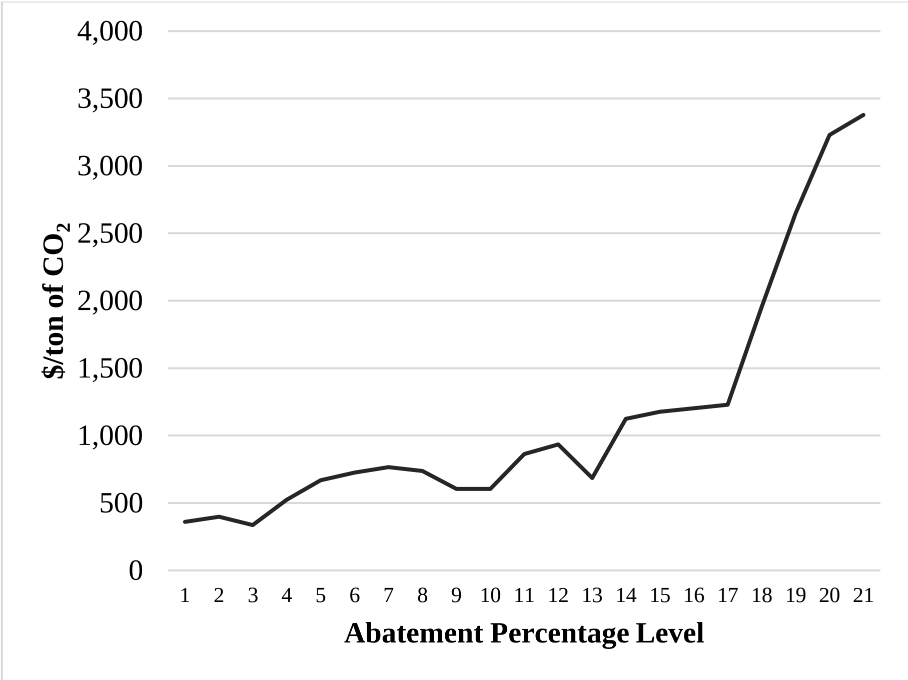

Figure 18. Incremental cost of abatement with respect to prior emission reduction level for transport sector under reference electricity emission intensity

Figure 18 displays the incremental abatement cost structure and Table 12 depicts the entering and abandoned technologies for the reference case. Up to 3% reduction main strategy is the use of biofuels instead of diesel fuels for the long-haul use. As the reduction level increases CNG for long haul transportation, E85 for short haul transportation, EVs of small trucks regarding short hauls are deployed. Through the 21% level of reduction use of hybrid trucks and buses becomes inevitable coupled with advanced diesel vehicles. Cost increase after 17% reduction level is significant, showing how hard it is to achieve the target.

Table 12. List of technologies to be invested in and to be abandoned out of the sector between each abatement level and the corresponding incremental cost of abatement for transport sector under reference electricity emission intensity

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_2)
Base-1	Small Truck/ Minibus E85 LH Improved	Small Truck/ Minibus Diesel LH Improved	360
1-2	Small Truck/ Minibus E85 LH Improved	Small Truck/ Minibus Diesel LH Improved	398
2-3	Small Truck/ Minibus E85 LH Improved	Small Truck/ Minibus Diesel LH Improved	337
3-4	Bus CNG SH Improved Truck Hybrid Diesel SH Improved Small Truck/ Minibus E85 LH Improved Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Bus Diesel SH Improved Truck Diesel SH Existing Small Truck/ Minibus Diesel LH Improved Small Truck/ Minibus Diesel SH Improved	525
4-5	Truck Hybrid Diesel SH Improved Small Truck/ Minibus E85 LH Improved Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Truck Diesel SH Existing Small Truck/ Minibus Diesel LH Improved Small Truck/ Minibus Diesel SH Improved	669
5-6	Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Small Truck/ Minibus Diesel SH Improved	725
6-7	Truck Hybrid Diesel SH Improved Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Truck Diesel SH Base Small Truck/ Minibus Diesel SH Improved	767
7-8	Truck Hybrid Diesel SH Improved Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Truck Diesel SH Base Small Truck/ Minibus Diesel SH Improved	738
8-9	Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Small Truck/ Minibus Diesel SH Improved	605
9-10	Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Small Truck/ Minibus Diesel SH Improved	605
10-11	Bus CNG SH Improved Small Truck/ Minibus E85 LH Improved Small Truck/ Minibus Battery EV SH Advanced	Bus Diesel SH Improved Small Truck/ Minibus Diesel LH Base Small Truck/ Minibus Diesel LH Existing Small Truck/ Minibus Diesel SH Improved Small Truck/ Minibus Battery EV SH Improved	863
11-12	Bus CNG SH Improved Small Truck/ Minibus E85 LH Improved Small Truck/ Minibus Battery EV SH Advanced	Bus Diesel SH Improved Small Truck/ Minibus Diesel LH Base Small Truck/ Minibus Diesel SH Improved Small Truck/ Minibus Battery EV SH Improved	934
12-13	Bus CNG SH Improved Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Bus Diesel SH Improved Small Truck/ Minibus Diesel SH Improved	685
13-14	Bus CNG SH Improved Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Bus Diesel SH Existing Bus Diesel SH Improved Small Truck/ Minibus Diesel SH Existing Small Truck/ Minibus Diesel SH Improved	1124
14-15	Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Small Truck/ Minibus Diesel SH Existing Small Truck/ Minibus Diesel SH Improved	1178

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_2)
15-16	Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Small Truck/ Minibus Diesel SH Base Small Truck/ Minibus Diesel SH Existing Small Truck/ Minibus Diesel SH Improved	1203
16-17	Bus CNG SH Base Bus CNG SH Improved Truck Hybrid Diesel SH Improved Small Truck/ Minibus E85 LH Improved Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Bus Diesel SH Base Bus Diesel SH Improved Truck Diesel SH Base Small Truck/ Minibus Diesel LH Base Small Truck/ Minibus Diesel SH Base Small Truck/ Minibus Diesel SH Improved	1228
17-18	Bus CNG SH Improved Bus Hybrid Diesel SH Improved Small Truck/ Minibus E85 LH Improved Small Truck/ Minibus Battery EV SH Improved	Bus Diesel SH Improved Small Truck/ Minibus Diesel LH Base Small Truck/ Minibus Diesel SH Base Small Truck/ Minibus Battery EV SH Advanced	1952
18-19	Bus Hybrid Diesel SH Improved Small Truck/ Minibus Battery EV SH Advanced Small Truck/ Minibus Battery EV SH Improved	Bus CNG SH Improved Small Truck/ Minibus Diesel SH Base	2647
19-20	Small Truck/ Minibus Diesel SH Base Small Truck/ Minibus Battery EV SH Advanced	Small Truck/ Minibus Battery EV SH Improved	3229
20-21	Small Truck/ Minibus Diesel SH Base Small Truck/ Minibus Battery EV SH Advanced	Small Truck/ Minibus Battery EV SH Improved	3378

Figure 19 displays the incremental abatement cost curve for the low electricity emission intensity case. Compared to the reference case cost are much lower due the emission intensity of electric vehicles eliminating the need for advanced diesel vehicles for the abatement targets.

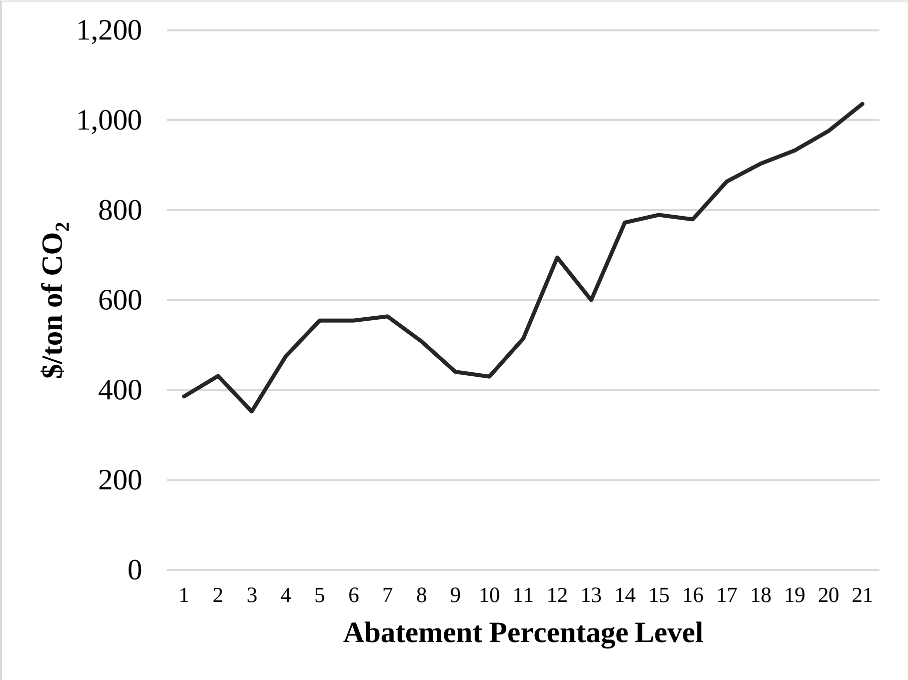

Figure 19. Incremental cost of abatement with respect to prior emission reduction level for transport sector under low electricity emission intensity

Figure 20, Figure 21, Figure 22 and Figure 23 displays the expert based representation of the reference electricity emission intensity incremental abatement cost curves, pointing out the necessary simultaneous entering and abandoned technologies for each emission cap level, corresponding costs and emission abatement shares.

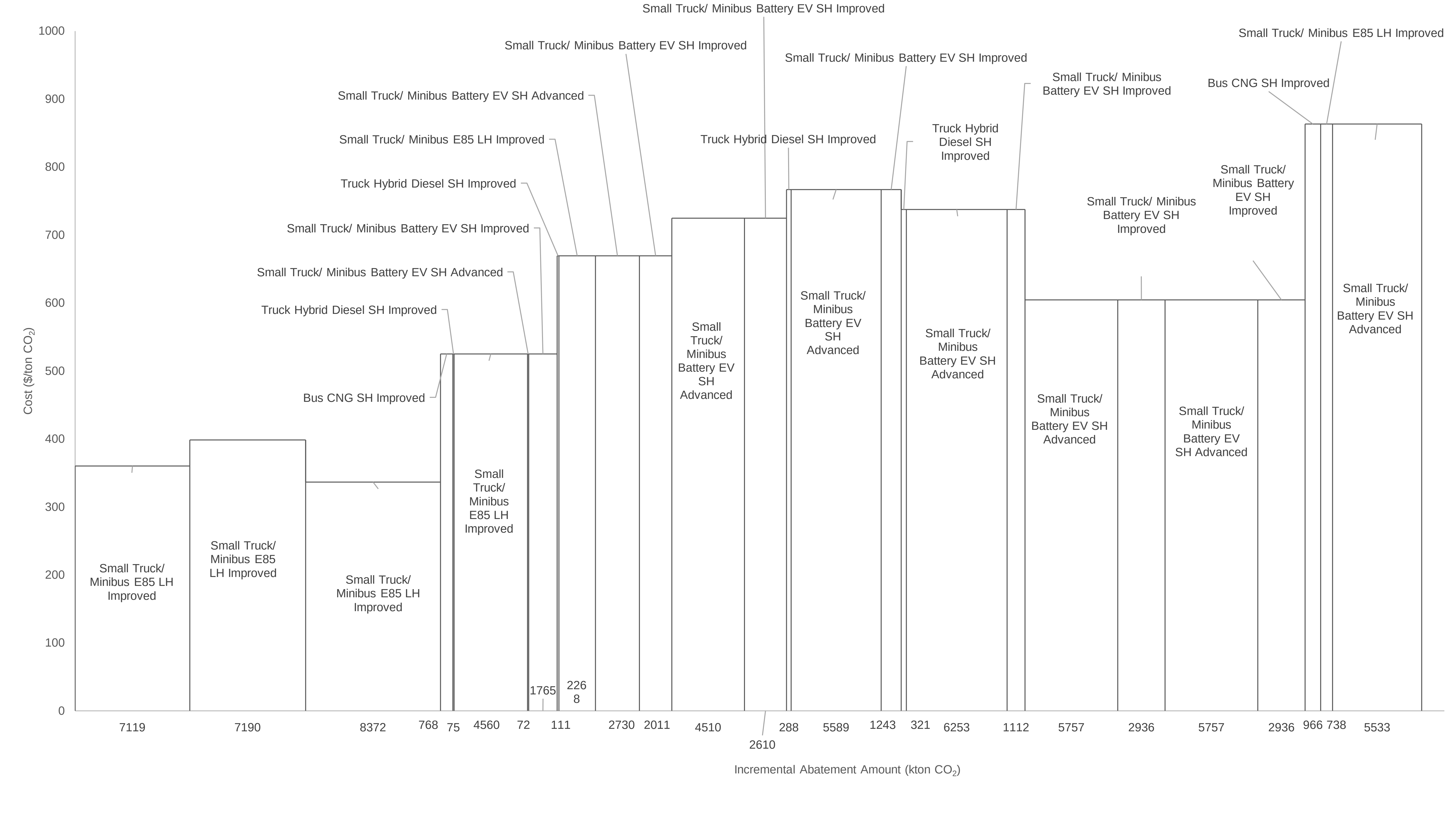

Figure 20. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – entering technologies for the transport sector until 11% reduction for reference electricity emission intensity

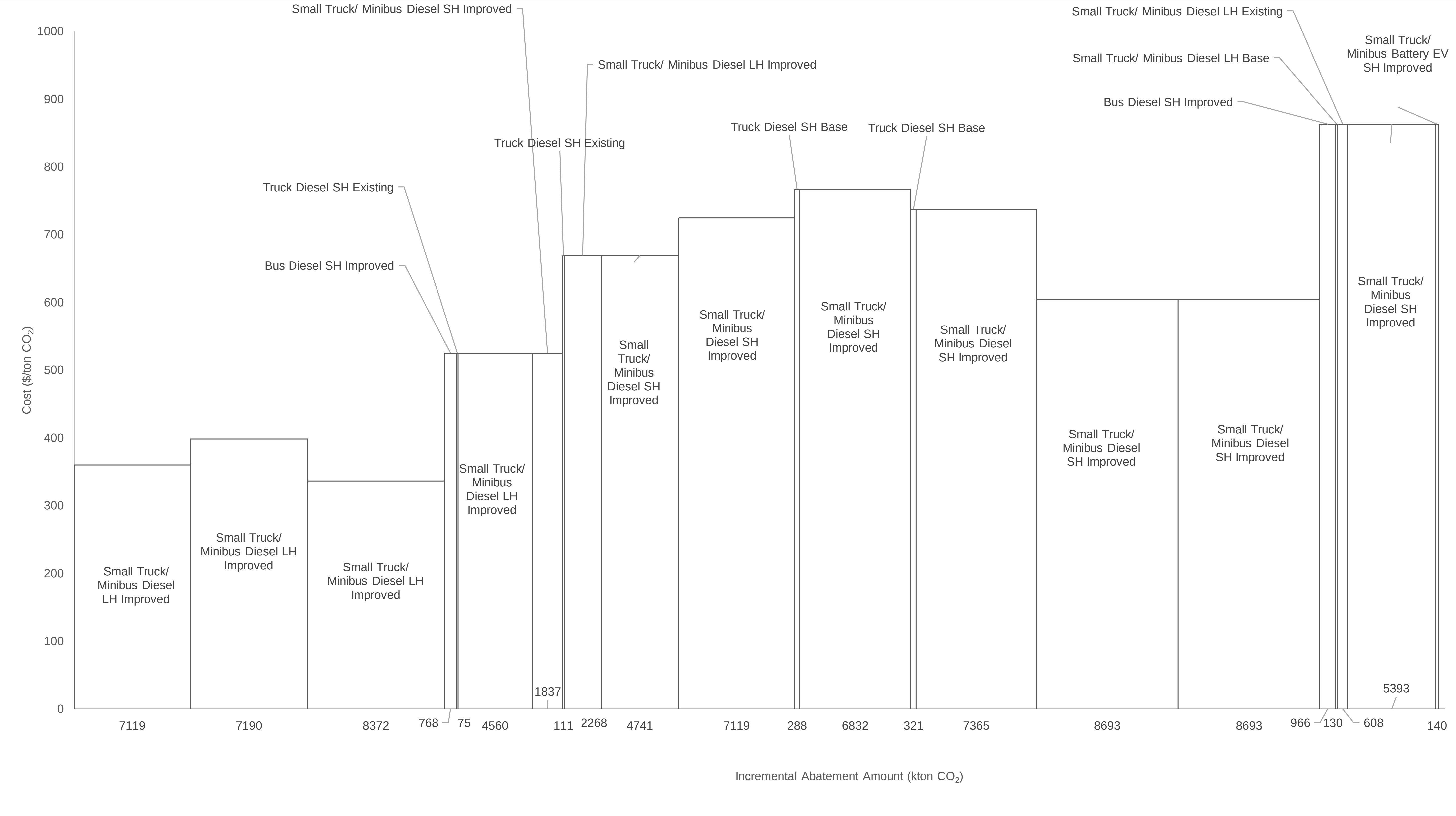

Figure 21. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – abandoned technologies for the transport sector until 11% reduction for reference electricity emission intensity

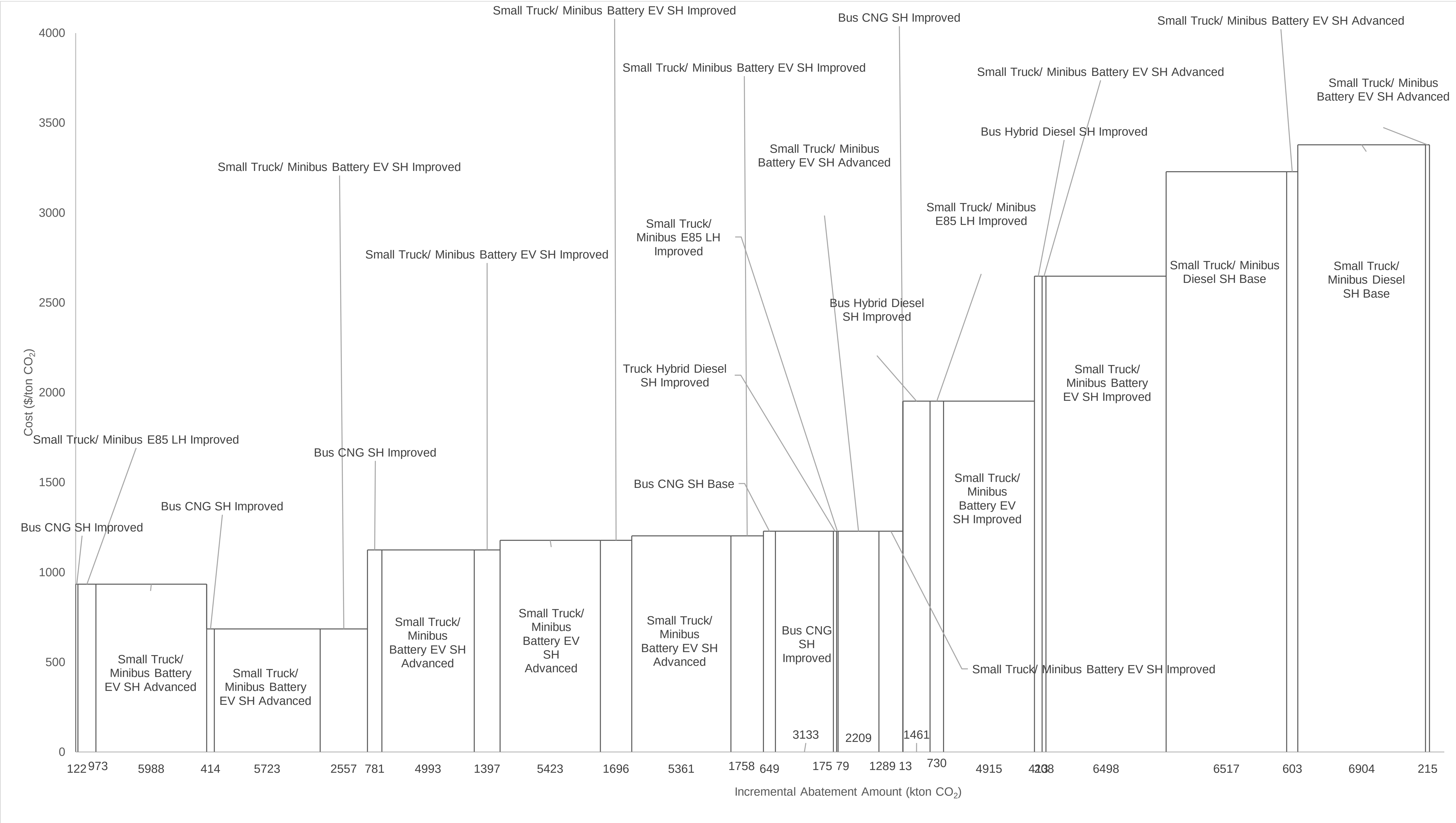

Figure 22. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – entering technologies for the transport sector starting from 11% to 21% reduction for reference electricity emission intensity

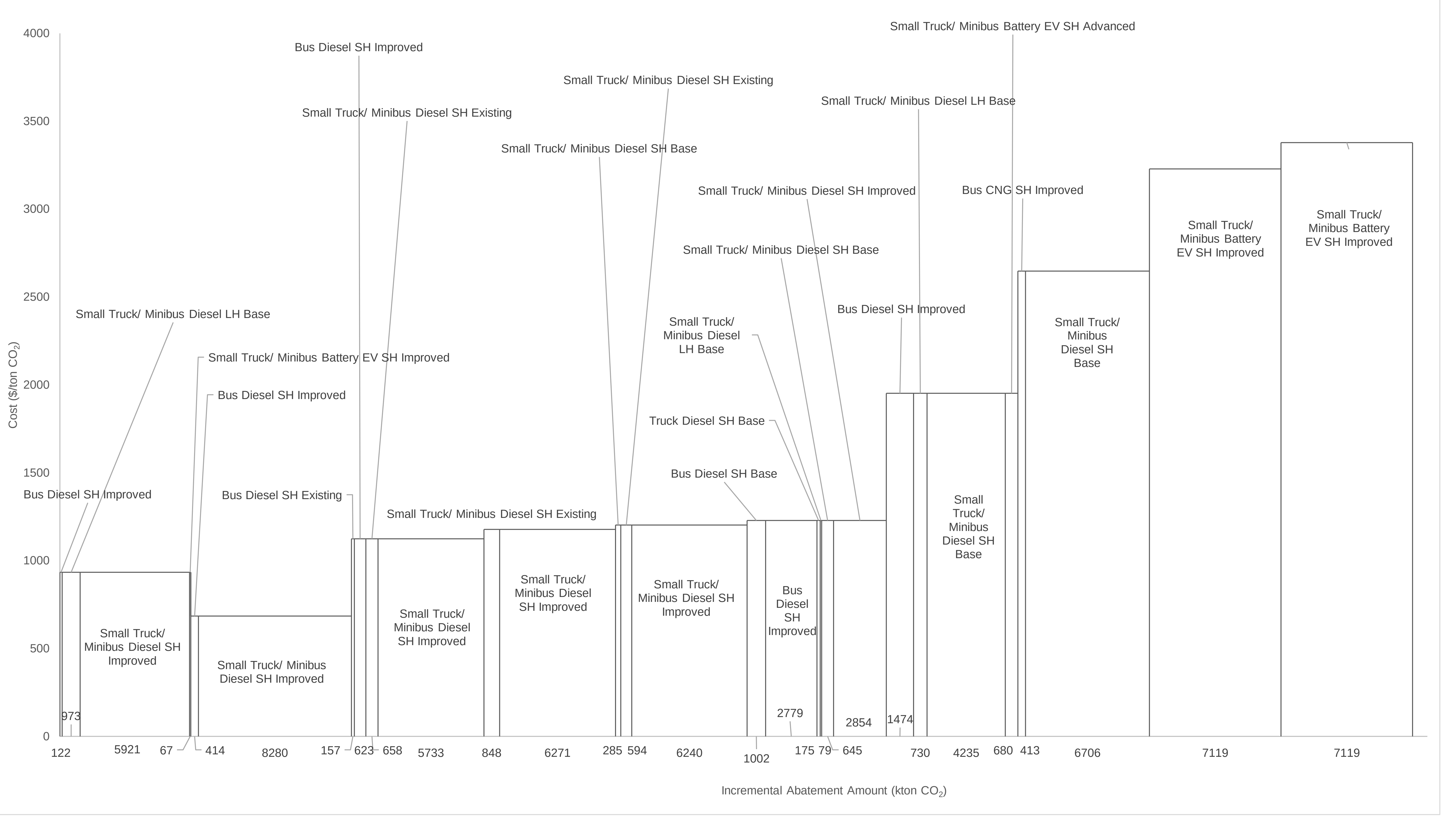

Figure 23. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – abandoned technologies for the transport sector starting from 11% to 21% reduction for reference electricity emission intensity

6. Marginal Abatement Cost Curves for the Waste Sector

Waste sector emission mitigation depends on the level of the recycling penetration. Based on the supply assumptions inherent with in the base scenario, it is clear that emission mitigation should be based on separation of organic waste from the overall waste and processed via bio-methanization and gasification to initiate methane formation under controlled environment. However, electricity production is not the direct way as it seems; flaring of the gas collected should be considered as the model results suggest to minimize the cost of mitigation. Range of average cost of abatement is found to be in between \$100 - \$120 per tonne CO_{2e}. Marginal cost is higher, however incremental cost changes point out \$120 per tonne level as an important level for the abatement.

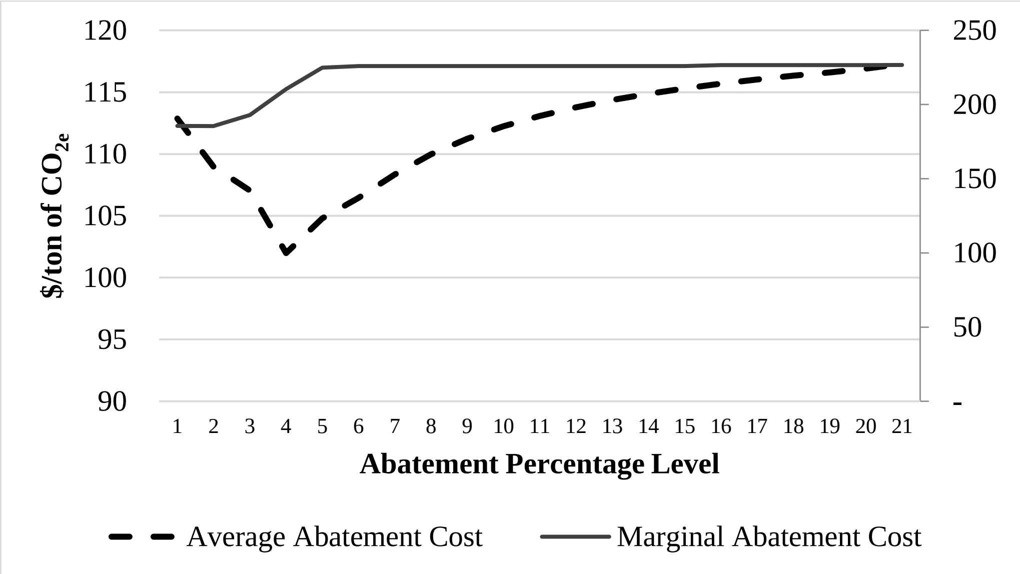

Figure 24. Average (left axis) and Marginal (right axis) abatement cost curves for the waste sector

Figure 24 displays the average and marginal cost of abatement and Table 13 depicts cost of abatement for the specific cap levels. On average, cost of abatement is around 100 and 120 USD range per tonne of CO_{2e} abatement. As the figures suggest emission mitigation supply is very limited and the variations around these numbers are related to new technologies that is used for certain levels of abatement.

Table 13. Marginal and Average abatement cost levels for respective abatement levels for the waste sector ($/tonne CO_{2e})

Emission Abatement Level	Marginal Abatement Cost	Average Abatement Cost
1%	185.6	112.9
2%	185.5	109.0
3%	193.0	107.0
4%	210.4	102.0
5%	224.8	104.8
6%	225.9	106.4
7%	225.9	108.3
8%	225.9	110.0
9%	225.9	111.2
10%	225.9	112.3
11%	225.9	113.1
12%	225.9	113.8
13%	225.9	114.4
14%	225.9	114.9
15%	225.9	115.3
16%	226.5	115.7
17%	226.5	116.0
18%	226.5	116.3
19%	226.5	116.6
20%	226.5	116.9
21%	226.7	117.3

As can be seen from Table 14, entering technologies and abandoned technologies are nearly uniform for each step abatement. This leads to a very close approximation of cost of abatement 120 USD / tonne CO_{2e}. Figure 25 displays this fact and shows the nature of abatement cost.

Table 14. List of technologies to be invested in and to be abandoned out of the sector between each abatement level and the corresponding incremental cost of abatement for the waste sector

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_2)
Base-1	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill Wild Dumpsites	112.9
1-2	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	105.2
2-3	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	103.2
3-4	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening Gasification MSW Flare	Sanitary Landfill	86.8
4-5	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening Gasification MSW Flare	Sanitary Landfill	116.2
5-6	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Gasification Sanitary Landfill	114.1
6-7	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	119.6
7-8	CCGT Biodrying Biomethanization	Sanitary Landfill	121.4

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_2)
	MSW Mechanical Sorting Screening MSW Flare		
8-9	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	121.4
9-10	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	121.4
10-11	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	121.4
11-12	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	121.4
12-13	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	121.4
13-14	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	121.4
14-15	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	121.4
15-16	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	121.4
16-17	CCGT	Sanitary Landfill	121.5

Step	Entering Technologies	Left Technologies	Cost of Abatement ($/tonne CO_2)
	Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare		
17-18	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	121.5
18-19	CCGT Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	Sanitary Landfill	121.5
19-20	Gas Turbine Biodrying Biomethanization MSW Mechanical Sorting Screening MSW Flare	CCGT Sanitary Landfill	122.9
20-21	Gas Turbine Biodrying Biomethanization MSW Mechanical Sorting Screening	CCGT Sanitary Landfill MSW Flare	124.5

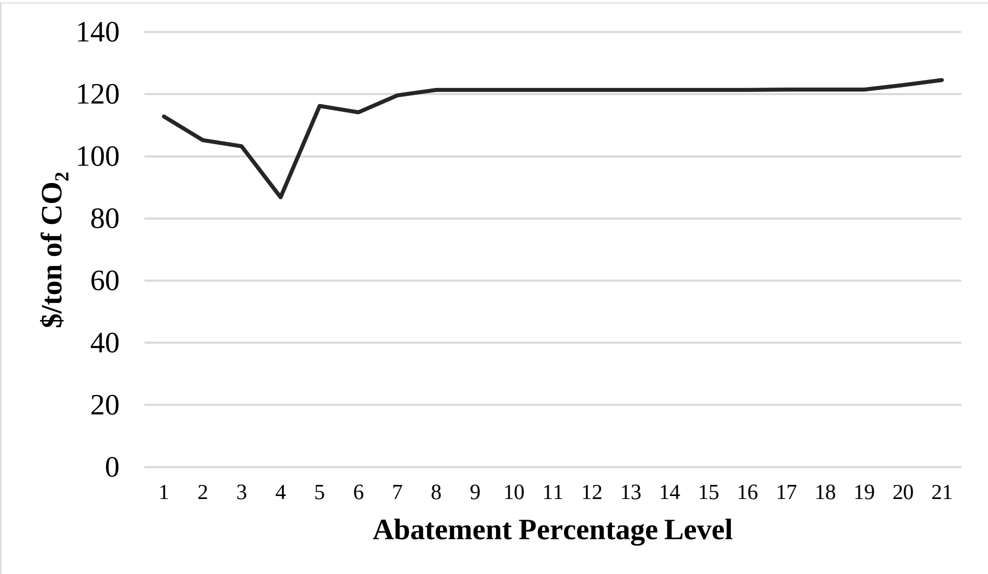

Figure 25. Incremental cost of abatement with respect to prior emission reduction level for the waste sector

Figure 26 and Figure 27 displays the nature of technologies that are entering the supply chain of waste processing. Since the only exiting technology is the sanitary land fill no expert based representation of the abandoned technologies is given. In that respect flaring activities should be considered as an easy way out for reducing GHGs where the scale of gas collected does not permit economical electricity generation.

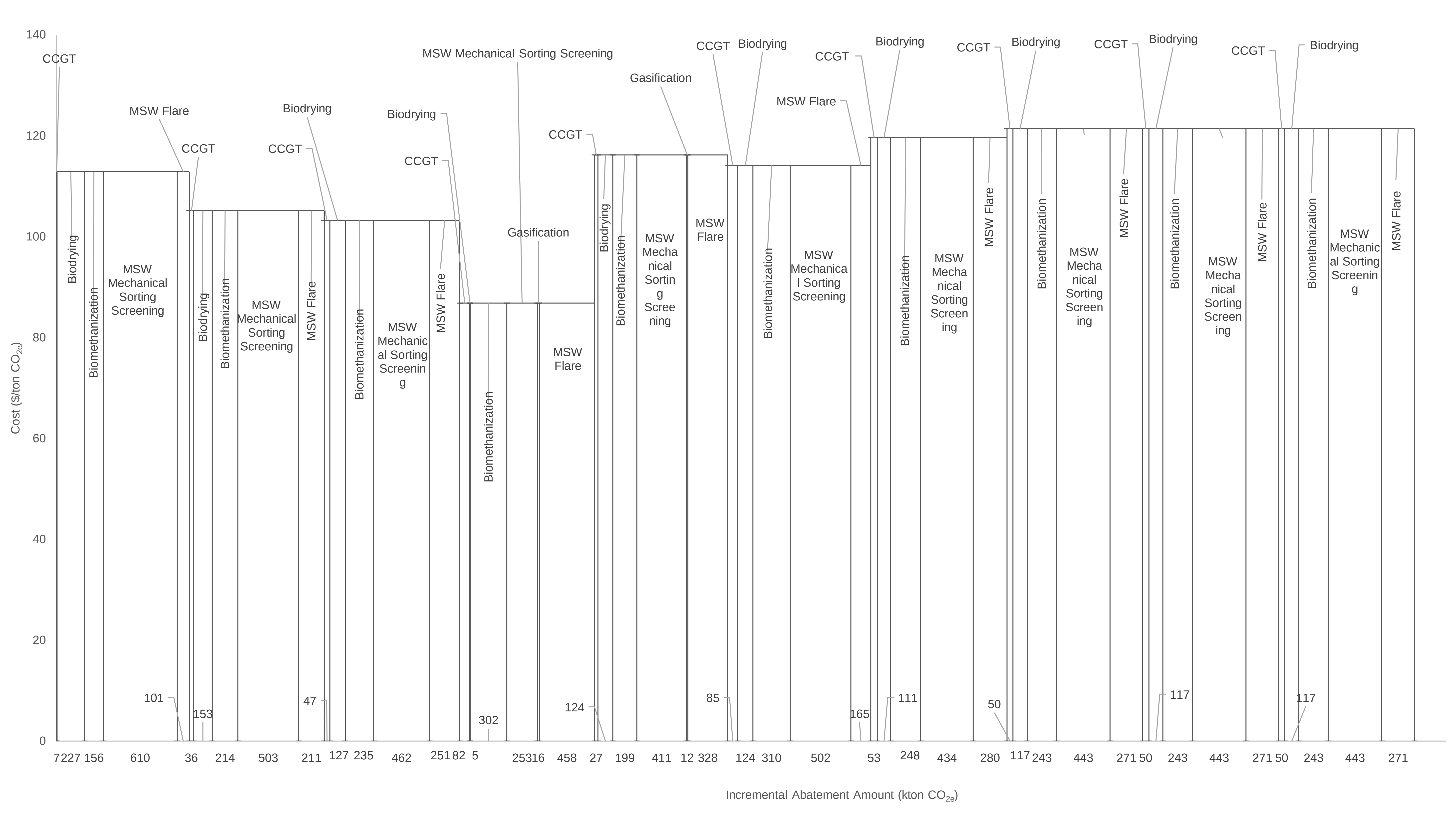

Figure 26. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – entering technologies for the waste sector up to 11% reduction level

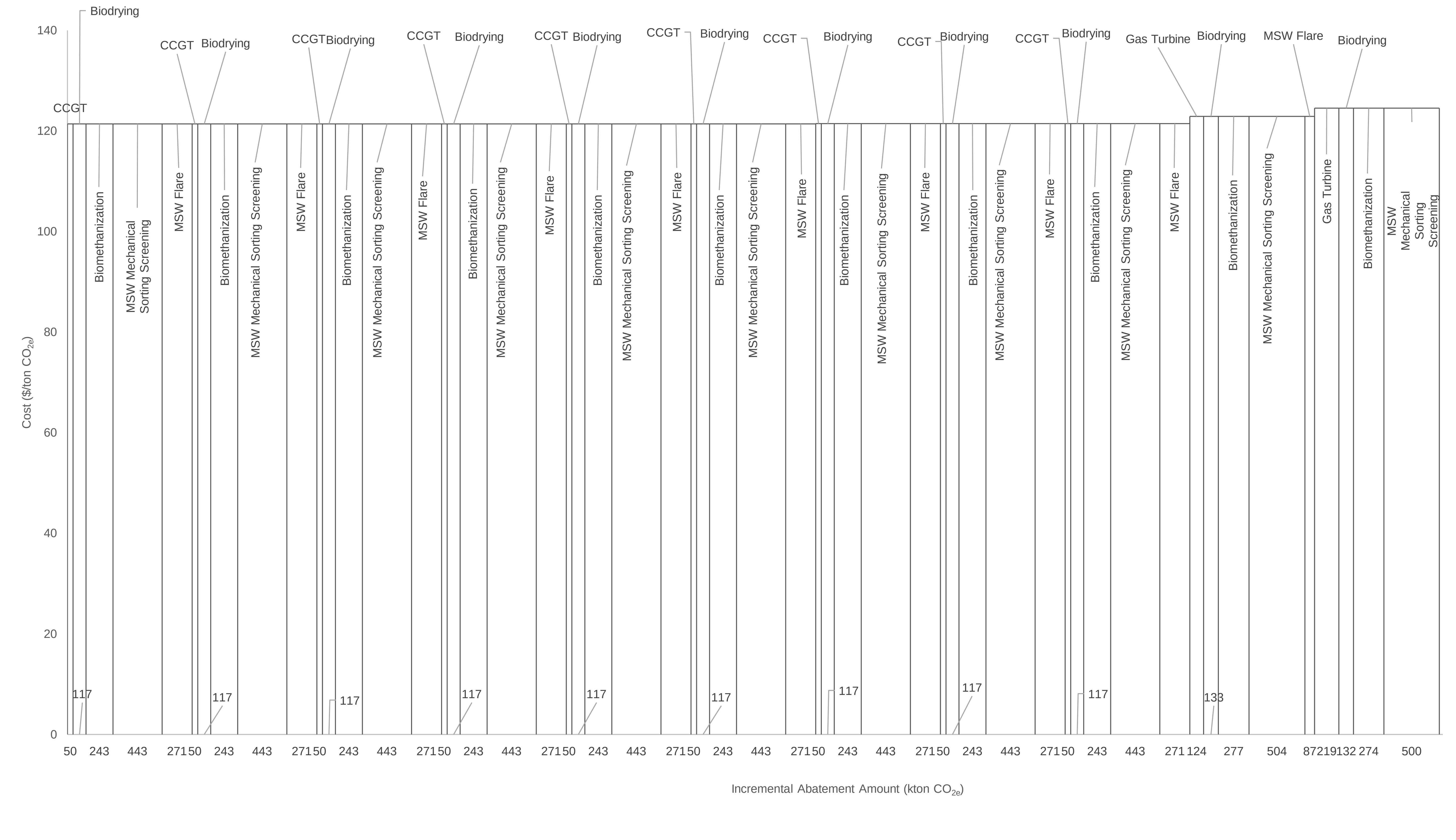

Figure 27. Expert based representation of the MAC curve with the corresponding incremental abatement cost levels and abatement impact – entering technologies for the waste sector over 11% up to 21% reduction level.

7. General Conclusion

Overall, regarding the emission abatement cost curves for the four sector studied in this study it can be said that cost of mitigation does not depend on just sectoral decision made within but the inputs from other sector really have big impact on the cost of abatement. Especially electricity sector will play a key role in this regard. Waste sector points out a flat abatement curve both in terms of marginal and incremental even if for the average cases; pointing out a limiting factor of scale of the waste sources and the logistics of the waste while price of electricity is a very critical influencer on the formation of the sector. The transport sector is the most expensive sector to initiate mitigation especially without a clean electricity sector. Residential sector points out potential for abatement and the opportunity for low cost of abatement based on electricity sector emission intensity. Agriculture sector, points out easy mitigation for low levels of abatement while how the cost can skyrocket in case of higher abatement levels is very interesting to see.

This publication is prepared with financial contribution of the European Union and the Republic of Turkey. Only the consortium led by the Hulla & Co Human Dynamics KG is solely responsible for the contents of this publication, and such contents do not reflect the opinions and the attitude of the European Union.