

How Do We Prioritize the GHG Mitigation Options?

Development of a Marginal Abatement Cost Curve
for the Building Sector in Armenia and Georgia

Govinda Timilsina

Anna Sikharulidze

Eduard Karapoghosyan

Suren Shatvoryan



WORLD BANK GROUP

Development Research Group
Environment and Energy Team
June 2016

Abstract

Armenia and Georgia are taking the climate change agenda seriously and contributing to efforts for mitigating global climate change through various ways, including preparation of low-carbon development strategies for their future economic growth. The improvement of energy efficiency is one of the key elements of the low-carbon development strategies. This study develops a methodology to estimate a marginal abatement cost curve for energy efficiency measures and applies it to the building sector in both countries.

The study finds that among the various energy efficiency measures considered, the replacement of energy inefficient lightbulbs (incandescent lamps) with efficient lightbulbs is the most cost-effective measure in saving energy and reducing greenhouse gas emissions from the building sector. Most energy efficiency improvement options considered in the study would produce net economic benefits even if the value of reduced carbon is not taken into account.

This paper is a product of the Environment and Energy Team, Development Research Group. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at <http://econ.worldbank.org>. The authors may be contacted at gtimilsina@worldbank.org.

The Policy Research Working Paper Series disseminates the findings of work in progress to encourage the exchange of ideas about development issues. An objective of the series is to get the findings out quickly, even if the presentations are less than fully polished. The papers carry the names of the authors and should be cited accordingly. The findings, interpretations, and conclusions expressed in this paper are entirely those of the authors. They do not necessarily represent the views of the International Bank for Reconstruction and Development/World Bank and its affiliated organizations, or those of the Executive Directors of the World Bank or the governments they represent.

How Do We Prioritize the GHG Mitigation Options? Development of a Marginal Abatement Cost Curve for the Building Sector in Armenia and Georgia¹

Govinda Timilsina, Anna Sikharulidze, Eduard Karapoghosyan and Suren Shatvoryan²

Key Words: Energy efficiency, Climate change mitigation, Marginal abatement cost curve, building sector, Georgia

JEL Classification: Q48, Q54

¹ The authors would like to thank Marina Shvangiradze, Dana Kenney, Adrien Vogt-Schilb and Mike Toman for their valuable comments and suggestions. The views and interpretations are of authors and should not be attributed to the World Bank Group. Financial support from the Knowledge for Change (KCP) Trust Fund of the World Bank is acknowledged.

² . Govinda Timilsina is the corresponding author and a Senior Economist at Development Research Group, World Bank, Washington, DC (e-mail: gtimilsina@worldbank.org), Anna Sikharulidze is Technical Manager at Sustainable Development Centre Remissa, Tbilisi, Georgia, Eduard Karapoghosyan was Senior Scientific Researcher at Energy Strategy Center of the Scientific Research Institute of Energy, Yerevan, Armenia during the course of this study and Suren Shatvoryan is Research Manager at Energy Strategy Center of the Scientific Research Institute of Energy, Yerevan, Armenia.

1. Introduction

Armenia and Georgia are small countries in the Caucasus region located between the Black Sea, Russia, Turkey, Azerbaijan and Iran thereby connecting Eastern Europe to Western Asia. Both countries are currently developing low carbon strategies³ for their economic development while promoting economic growth and prosperity. The strategies aim to reduce the growth of greenhouse gas (GHG) emissions. The low carbon strategies are also important because both countries depend on imports for their oil and gas supply. Both countries submitted their Intended Nationally Determined Contributions (INDCs)⁴ in response to the decision made by the UNFCCC in its 19th Conference of Parties in Warsaw, Poland in 2013 (UNFCCC, 2013). The Paris Agreement reached at the 19th Conference of Parties in Paris in December 2015 (UNFCCC, 2015) implies that these countries will take actions to implement their INDCs. In the past, both countries provided an indicative list of options to reduce GHG emissions in their National Communications (NCs) to UNFCCC, and also in preparation of nationally appropriate mitigation actions (also referred to NAMAs⁵) in accordance with an agreement made in the 16th Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) in Cancun, Mexico in 2011 (UNFCCC, 2011).

The low carbon strategies, NAMAs, NC and INDC all present list of potential options that could be implemented to reduce GHG emissions. While various approaches could be adopted to prioritize GHG mitigation options, the tool often used in low carbon strategies⁶, NAMA and NC, is the marginal abatement cost (MAC) curves. Energy efficiency options are the most common GHG mitigation options identified in a MAC curve analysis. These options are often found as the cheapest ones with negative costs of GHG abatement in most existing literature on green growth and low carbon strategies (see e.g., World Bank, 2014; World Bank, 2013; Cervigni et al. 2013; de Gouvello et al. 2010; Johnson et al. 2009; Mckinsey and Company, 2009, 2010, 2011). However, the economies of energy efficiency vary across countries depending on the rate at which future energy consumption is

³ The low emission development (LED) strategy is being developed under the financial support of USAID through Winrock International; it is known as “Enhancing Capacity for Low Emissions Strategies (EC-LEDS)/ Clean Energy Program” in Georgia.

⁴ INDC refers to UNFCCC parties’ post 2020 action plan outline in response to the decision made at COP19.

⁵ NAMAs are GHG mitigation actions voluntarily offered by Non-Annex I countries. They include policies, programs and actions across the economic sectors with potential to reduce GHG emissions from the baseline in 2020 (UNFCCC, 2011).

⁶ Please see the series of low carbon studies produced by the World Bank over the last few years (World Bank, 2014; World Bank, 2013; Cervigni et al. 2013; de Gouvello et al. 2010; Johnson et al. 2009).

expected to increase, the current level of inefficiency and awareness of the availability of the best practice technologies to improve energy efficiency.

The concept of MAC curves has been used in the literature for a long time in determining potential for GHG mitigation from various options in different economic sectors (production sectors, buildings, transportation sectors). Examples of early studies using MAC curves include UNEP (1992), Jackson (1991, 1995), Timilsina and Lefevre (1998), Timilsina et al. (2000). Apart from academia, private companies, such as McKinsey & Company (McKinsey and Company, 2009, 2010, 2011), Bloomberg (Bloomberg, 2010); and international institutions, such as World Bank (World Bank, 2009; 2010; 2012) have been widely using the concept the MAC curve to prioritize climate change mitigation options/technologies in various countries.

Although the literature on MAC curve is rich, there are still some methodological issues that need to be resolved. For example, should an MAC curve analysis compare potential GHG mitigation options in a static fashion as if all mitigation potential of an option can be exploited now, or should the MAC curve be based on analysis over a time period in which the GHG mitigation option, such as improvement of energy efficiency, is implemented gradually? The latter approach can be interpreted as a dynamic MAC curve analysis and it would be more realistic because it is impractical to assume that the full GHG mitigation potential of a measure is ready for exploitation in a short interval of time. Another issue is if the investment costs of GHG mitigation be the same when: (i) an energy inefficient device or process already installed in an existing facility be replaced with new energy efficient device or process and (ii) when consumers face a choice between energy efficient and inefficient device/process to install in a new facility (e.g., choice of roof and window insulations in a building to be built). Further, what assumptions are to be made regarding the penetration of a GHG mitigation measure in the baseline where no policy measures are introduced to incentivize the implementation of the measure?

Existing studies have used different approaches to address these issues. Most existing studies do not differentiate between the existing and new facilities while developing MAC curves and thus use the same opportunity costs in both cases. Therefore, MAC curves produced by various studies are not comparable and the use of the same opportunity costs is misleading. Moreover, existing studies use different assumptions on penetration rate of GHG mitigation measures in baseline as well as climate change mitigation scenarios. This also leads to different calculations of GHG mitigation potential of the same measure.

This paper aims to present a methodology to contribute in resolving these issues. The methodology is then implemented to calculate the MAC curve for selected energy efficiency measures in the building sector in Armenia and Georgia. One of the key contributions of the methodology developed here is that it distinguishes between the existing buildings and new buildings. This is critically important because the likelihood of adoption of energy efficient appliances is higher in the new buildings due to several reasons, such as awareness of consumers and already introduced energy efficiency standards. Moreover, the probability of adopting energy efficient measures that require major reconstruction/remodeling of existing buildings would be low. For example, households might not be willing to dismantle walls of their houses to replace them with energy efficient walls. Existing studies are not found to take into account these important issues, they assume all energy inefficient devices and processes are replaced and thus likely to overestimate GHG mitigation potential of a GHG mitigation option.

The study also differentiates between existing stock of appliances and new stock of appliances especially when they make assumptions on the cost of an appliance.⁷ The use of an incremental costs (i.e., the difference between the capital costs of an efficient appliance and its inefficient counterpart that would have been considered in the baseline) approach when the existing stock of inefficient appliances is replaced with their efficient counterparts and thus underestimates the MAC of that energy efficiency measure. Our study suggests to use the full cost of the new efficient appliances instead of the incremental costs in such a situation. This is because normally there does not exist markets for already used energy inefficient technologies. Building owners might need to pay disposal costs when they want to discard their old appliance. Our study has accounted all these issues, which are often neglected in the existing literature.

The paper is organized as follows: Section 2 presents the methodology we developed followed by data and assumptions in Section 3. Results and sensitivity analysis are presented in Section 4 and 5, respectively. Finally, key conclusions are drawn in Section 6.

⁷ The differentiation between existing and new buildings and also between existing stock of appliances and new stock of appliances has different implications. This is because some existing buildings might have already adopted new stock of appliances, if that is the case those new stock of appliances would be part of baseline. On the other hand, some new buildings could still use inefficient appliances. Thus, a baseline could include not only existing buildings but also new buildings depending upon whether or not the buildings use inefficient or efficient appliances. The same logic is applicable for the mitigation scenario as well.

2. Methodology

Normally two types of approaches are used to calculate MAC curves: static and dynamic. The static approach considers all GHG mitigation technologies/options are compared assuming as if they are implemented now, and all emissions reductions can be realized immediately. However, in reality, realization of GHG mitigation potential of a technology/option occurs over time. For example, not all buildings with inefficient lightbulbs could adopt efficient lightbulbs immediately; it might take years. Hence, it is important to take into account the gradual process of energy efficiency improvement. A dynamic approach to calculate MAC can account for more realistic adoption trajectories of efficient appliances where adoption of energy efficient appliances occurs over time. Note also that the rates at which efficient appliances are adopted vary across the appliances. While existing buildings could adopt energy efficient appliances over time, all new buildings yet to be built could be mandated to use efficient appliances. Therefore, it is important to distinguish new and old buildings while estimating MAC curves.

The (dynamic) marginal abatement cost of an efficient appliance/technology/measure (MAC) is calculated as follows:

$$MAC = \frac{C^M - C^B}{E^B - E^M} \quad (1)$$

where C and E refers to discounted total costs and total emissions, superscripts M and B refers to GHG mitigation and baseline scenarios. We can express C and E as follows:

$$C = \sum_0^t \frac{IC_t}{(1+r)^t} + \frac{FC_t}{(1+r)^t} \quad \text{and} \quad E = \sum_0^t \frac{AE_t}{(1+r)^t} \quad (2)$$

where IC refers to annualized investment cost, FC refers to annual fuel and other O&M costs and AE refers to annual GHG emissions; t refers to time, expressed in terms of year and r is discount rate.⁸ The annual cost of investment or annuity of a measure/option, no matter whether it is installed in the baseline or mitigation scenario, is calculated as follows:

⁸ Note in Equation (2) that physical quantity of GHG mitigation is also discounted using the same rate used for discounting the costs. This is a standard approach used in any project feasibility analysis or levelized cost calculation. For example, please see Ouyang and Ling (2014). The discounting rate is real discount rate; it reflects the time preference of having monetary value or physical quantity of goods now than later.

$$IC = INV.r.\frac{(1+r)^n}{(1+r)^n - 1} \quad (3)$$

where INV is the initial, up-front investment cost of a measure (e.g., device or process) and n is economic life of that measure. Note that ‘n’ is different from ‘t’ in Equation 2. Because, during the 20 years of study horizon we have considered here, a measure, such as electric lightbulbs, might be installed at multiple times if their economic life ‘n’ is smaller than the span of the study horizon (i.e., 20 years).

Energy efficient appliances will penetrate gradually in the buildings. The rate of penetration would be different in the existing buildings and the new buildings. If an existing building already have an energy consuming device (e.g., refrigerator), the lifetime of which is not spent yet, it has to pay the full costs of the new or efficient appliances to replace the existing inefficient appliances because it has already paid for existing device. In this case (i.e. if such replacement is done), the total investment cost also includes the residual value of the existing appliance that is being replaced with the efficient appliance. On the other hand, if a household is buying a new appliance because it does not have an appliance already or its previous appliance needs to be retired, it has two choices: (i) buying a new but still inefficient appliance and (ii) buying a new efficient appliance. In this case, the net investment of the household buying a new and efficient appliance would be the cost difference between efficient and inefficient appliances; it does not need to pay the full cost of the efficient appliances (it pays only the incremental cost). Equations (4) and (5) capture all these costs.

$$FC_t = FC_{t \text{ ext}}^{EE} + FC_{t \text{ ext}}^{Non-EE} + FC_{t \text{ new}}^{EE} + FC_{t \text{ new}}^{Non-EE} \quad (4)$$

$$IC_t = IC_{t \text{ ext}}^{EE} + IC_{t \text{ ext}}^{Non-EE} + IC_{t \text{ new}}^{EE} + IC_{t \text{ new}}^{Non-EE} \quad (5)$$

where, superscript ‘EE’ and ‘Non-EE’ refers to energy efficient and non-energy efficient technologies; subscripts ‘ext’ and ‘new’ refer to, respectively, pre-existing and new stock of appliances - whether in new building or in old buildings, but where old appliance has retired. Each of these cost components are calculated as follows:

$$FC_{t \text{ ext}}^{EE} = N_{t \text{ p-ext}}^{EE} * FP_t * FU_t^{EE} \quad (6)$$

$$FC_{i \text{ ext}}^{Non-EE} = N_{i \text{ p-ext}}^{Non-EE} * FP_i * FU_i^{Non-EE} \quad (7)$$

$$FC_{i \text{ new}}^{EE} = N_{i \text{ new}}^{EE} * FP_i * FU_i^{EE} \quad (8)$$

$$FC_{i \text{ new}}^{Non-EE} = N_{i \text{ new}}^{Non-EE} * FP_i * FU_i^{Non-EE} \quad (9)$$

where, FP_t and FU_t are price and quantity of fuel used by a device or process in year t and N refers to number of devices or process installed.

In the same manner, different annual investment costs (IC_t) and annual emission released from them (AE_t) are calculated, except the annual investment cost of replacing existing device or process, which, in case of mitigation scenario also includes the residual value of the appliance to be replaced.

The annualized investment cost $IC_{t \text{ ext}}^{EE}$ is calculated in the same manner as for the new inefficient device, thus by Eq. (3). But this annualized costs are accounted only for years from the remaining lifetime of the existing appliance, thus covering the residual value of the existing appliance.

The main uncertain variables in Eqs. 6-9 are the numbers of efficient and non-efficient technologies or share of efficient and inefficient technologies in both existing and new stocks of appliances under the baseline and mitigation scenarios, i.e., $N_{i \text{ p-ext}}^{EE}$, $N_{i \text{ p-ext}}^{Non-EE}$, $N_{i \text{ new}}^{EE}$, $N_{i \text{ new}}^{Non-EE}$.

We assumed various penetration rates based on historical data and current stocks of appliances (see Appendix A for details). In addition, each year, when technologies from pre-existing stock retire, they need to be substituted by new ones. This has been modeled by gradually reducing the number of pre-existing technologies and substituting them with new technologies. New technologies will be also installed in new buildings that are created in the future. Baseline and mitigation scenario differentiate the penetration of efficient technologies that can occur in this new stock. In addition, the mitigation scenario considers possibility of earlier switching from non-efficient technology to the efficient technology in pre-existing stock. Early switching, in this sense, means that household purchases efficient technology before its current inefficient one is retired. In this cases it pays full cost of the new efficient appliances instead of the incremental costs.⁹

Since the variable N is the most critical one as it determines the penetration of energy efficient device or processes in the total stock of the devices and processes in a country, special attention is needed dealing with this variable in both the baseline and the mitigation scenario. Please see Appendix

⁹ An appliance installed before 2014, which we used as base year, will continue to operate until the expiry of its economic life. The owner of the appliance has two choices: wait until the appliance operates end of its economic life to replace it with a new efficient appliance or replace it before the end its economic life. In the former case, the actual capital costs to be borne by the appliance owner/user are the incremental costs (i.e., the difference of the costs between efficient appliance and the inefficient appliance). In the latter case, the owner/user of the appliance has to bear the full costs of the efficient appliance as there would be no market for his used appliance.

A for more details on the estimation of $N_{i\ p-ext}^{EE}$, $N_{i\ p-ext}^{Non-EE}$, $N_{i\ new}^{EE}$ and $N_{i\ new}^{Non-EE}$ under the baseline and the energy efficiency scenarios.

3. Data and Assumptions

A wide range of data is required to calculate MACs for buildings sector. In this section we discuss the data and their sources. The data that is needed to calculate MACC are following:

- Demographic and economic characteristics and drivers (i.e. population and household numbers, area of commercial space, etc.)
- End-use penetration and technology characteristics in base year and their future projections
- Fuel net calorific values and emission factors
- Fuel and technology costs

3.1 Data Sources for Armenia

Major statistics such as historical growth of population, households, household size were taken from National Statistical Service Yearbook 2014 (NSSRA, 2014). Prices for electricity for different users are based on information available in various notifications of the Public Services Regulatory Commission of Republic of Armenia (PSRCRA, 2014). Data related to technological and pricing of inefficient and efficient energy utilizing technologies are obtained from various sources including GEF (2014a), GEF (2014b), EBRD (2014). The database of MARKAL-Armenia model used for Armenia's low carbon study (USAID, 2014) was also used for data and assumptions related to penetration rates in the baseline and climate change mitigation scenarios.

3.2 Data Sources for Georgia

A large number of secondary sources have been used to collect the required data for energy efficiency MAC analysis for Georgia. Some of the key sources include recent household energy survey carried out by the Winrock International EC-LEDs project (Winrock International, 2014), which provided data on average household area, average household size (number of persons per household), average percentage of heated area in dwellings, share of households using gas for heating, penetration of end-use technologies, both efficient and inefficient (refrigeration, washing machine, lighting bulbs) in households. Energy Audits carried out by EC-LEDs project (Sustainable Development Centre Remissia, 2014) was used to collect information on costs of different insulation

measures in residential and commercial buildings and also for natural gas consumption for heating. The demographic and economic projections (e.g., projections of population, household size and GDP) and projections of natural gas prices and average electricity grid emission factor are obtained from the MARKAL- Georgia model. All data sources used by the MARKAL-Georgia model are identified in Appendix B. National energy balance and statistical year book were used for fuel consumption values (National Statistics Office of Georgia, 2014)). Electricity prices were obtained from the local electricity distributor Telasi Ltd. (<http://www.telasi.ge/en/customers/tariffs>). The detailed data for Georgia Energy efficiency MAC analysis and their sources are presented in Appendix B.

3.3. Selection of Energy Efficiency Measures and Associated Assumptions

The estimation of MAC curve for the residential sector depends on several factors including number of households, demolition rate of existing households, rate of new household construction, percentage of existing households with efficient appliances, percentage of newly built households with efficient appliances, energy consumption rates of both efficient and inefficient appliances, costs of those appliances and other variables. There are variety of energy utilizing devices and process which could be considered for GHG mitigation in the buildings, such as space heating devices (kerosene stoves, electric heaters), water heaters, refrigerators, washers and dryers, cooking appliances, electronic devices (TV, computers). Two options are normally available to reduce GHG emissions from these device or processes: improving their thermal efficiency and replacing more carbon intensive fuels used by these devices with less or none carbon intensive fuels. For space heating we considered the insulation improvement measures, such as increasing wall insulation, reducing heat leakage from windows and improving roof insulations. We did not consider energy efficiency improvements of space heating devices (e.g., kerosene stoves, electric heaters) because the efficiency of these devices is already relatively higher ($> 87\%$) thereby leaving a small margin to further improve their thermal efficiencies. Central space heating units (a unit that can supply heat through out a building) could be an option, however a central heating system may not be feasible physically in the existing buildings as it require major remodeling of houses and it would be also too expensive. Moreover, the central heating systems are for heating the entire house or buildings, which would increase energy consumption and GHG emissions. The insulation improving measures we have considered here are also recommended by the energy audits (Sustainable Development Centre Remissia, 2014). The energy audit also show that ranges (cooking devices) and water heaters, which mostly use natural gas do not offer much room for efficiency improvements; fuel substitution, for

example replacement of gas water heaters with solar water heaters would provide higher potential for GHG reduction than through increased efficiency of gas water heaters. Therefore, the study does not include efficiency improvements in ranges and water heaters.

Other measures we considered in reducing GHG mitigation from the residential sector include lightbulbs, TV, refrigerator and washing machines. The average number of bulbs per household is 8, and they operate around 5.26 hours daily. Almost 70% of households use incandescent bulbs, 8% efficient bulbs, and 22% have both. Almost all households have TV, from which around 11% is new LED type TVs. 84% of household own refrigerator and among them 48% state that their refrigerator is energy efficient. Around 68% have the washing machine, 43% of which is purchased after 2010. As for the cooling systems the typical cooling system in Georgia is local split system, used to cool one or two rooms. The central cooling systems are very rare in country, and would result in increase of consumption.

The GHG mitigation potential is sensitive to the assumptions made on their future penetration. Historical rate of penetration could be a guidance. Government policies and incentive mechanism available also affect the rates of penetration. Based on these factors we have made assumptions on the penetration rates of measures and options with potential to reduce GHG emissions.

Like in the residential buildings, space heating is the main energy end-user in the commercial and public buildings. Therefore, improved building insulation provides the highest potential to save building energy consumption and GHG mitigation. The selection of these options in Georgia are based on energy audits (Sustainable Development Centre Remissia, 2015) and Sustainable Energy Action Plans (SEAP) of cities (Zugdidi SEAP 2014, Batumi SEAP 2014, Kutaisi SEAP 2014). Other technologies, such as refrigerators, cooling systems, etc. could also be considered but required data were not available.

The discount rate used in the analysis is a social discount rate, which is assumed to be 7.5%, which is commonly used for infrastructure project evaluation in Armenia and Georgia. Since the results are sensitive to discount rates, we have carried out sensitivity analysis.

4. Results

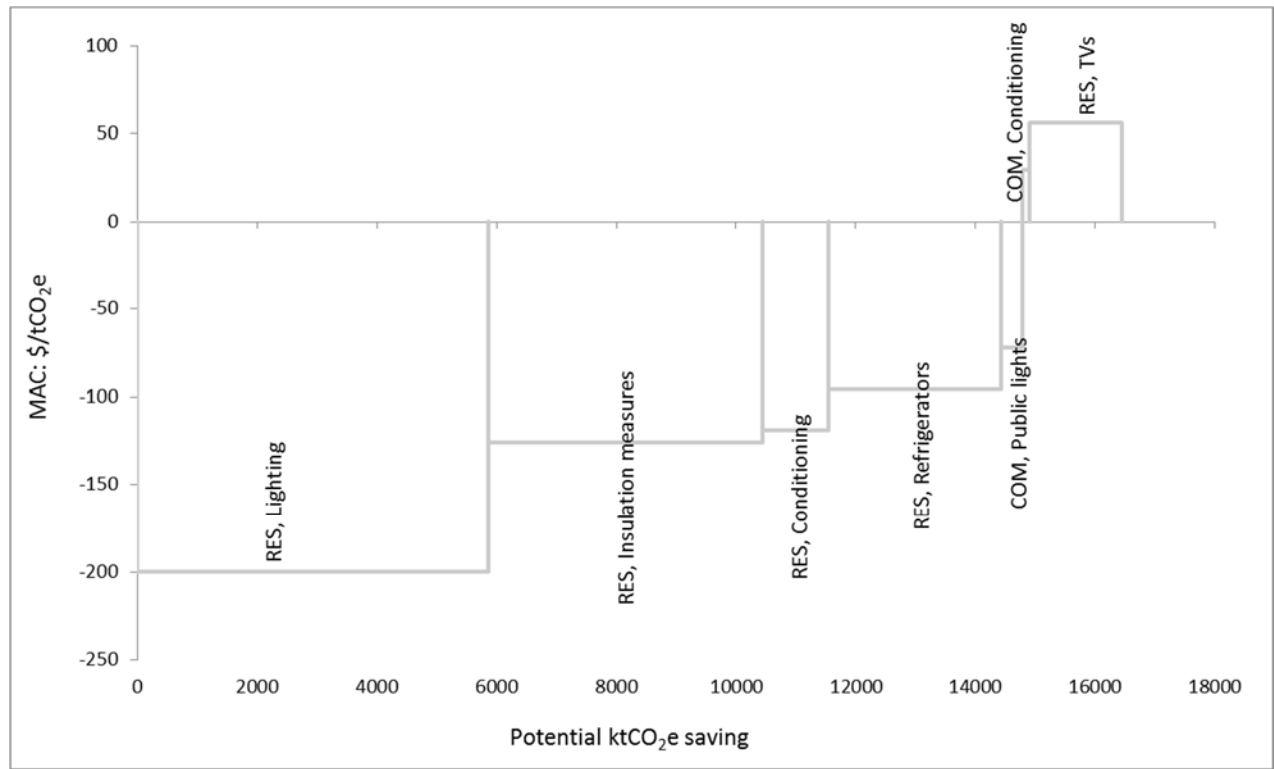
The marginal abatement cost curve consisting of various GHG mitigation options related to energy efficiency improvement is presented in Figure 1. The residential and commercial sector energy efficiency measures considered in this study are estimated to reduce 16.4 million tons of CO₂ in

Armenia over the 2015-2035 period and 6.2 million tons of CO₂ in Georgia over the same time horizon.

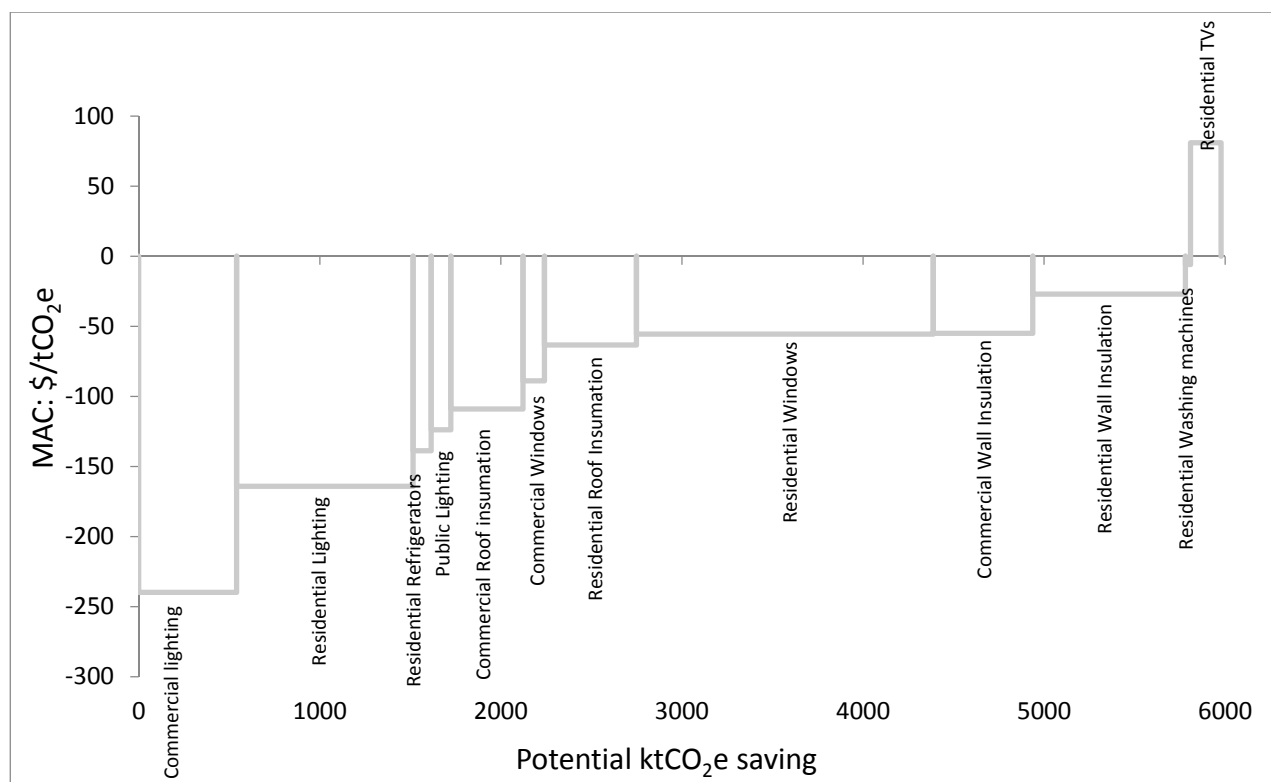
As illustrated in Figure 1, replacement of energy inefficient lightbulbs (i.e., incandescent lamps) with efficient lightbulbs (i.e., Light Emitting Diode or LED) is the most cost effective measure in saving energy and reducing GHG emissions from the building sector in both countries. These measure could save 5.9 million tons of CO₂ emissions over the next 20 years (i.e., during the 2015-2035 period) in Armenia and 1.6 million tons of CO₂ emissions in the same period in Georgia. At the same time, these measures would save between US\$74 (street lighting in Armenia) and US\$240 (efficient lighting in public buildings in Georgia) values of energy while reducing a ton of CO₂ emissions. While efficient lighting in buildings exhibits the highest potential for GHG reduction in Armenia (38% of the total GHG mitigation potential from the energy efficiency measures considered in this study), improved thermal efficiency (improved insulation in walls, windows and roofs) does the same in Georgia (69% of the total mitigation potential).

Figure 1: Marginal GHG abatement cost curve of energy efficiency measures in the building sectors in Armenia and Georgia

(a) Armenia



(b) Georgia



Improvement of insulations in walls, roofs and windows are found to have potentials of reducing 4.6 and 4.3 million tons of CO₂ emissions in Armenia and Georgia respectively over the 20 years (2015-2035). All insulation measures in both countries demonstrate negative mitigation costs (or net benefits from energy savings). The value of energy savings from these measures varies between US\$27 (wall insulation in commercial building in Georgia) and US\$129 (public building insulation in Armenia) while reducing a ton of CO₂. Replacement of energy inefficient television sets with their energy efficient counterparts are found relatively expensive options to save energy and reduce CO₂ emissions in both countries. Moreover, this option has a relatively small GHG mitigation potential in both countries.

Table 1 presents the combined potential of GHG mitigation from the different options considered in the analysis. We have considered the most important energy-end uses in the residential sector including space heating, lighting, refrigeration, cooling, washing machine and most widely used electronic devices (television sets). In Armenia, the adoption of efficient appliances in both existing and new residential buildings has a potential of reducing 19% GHG emissions in 2020 to 41% reductions in 2035. The corresponding potentials are relatively smaller in Georgia (6% in 2020 and

15% in 2035) because most of energy efficiency in the residential buildings in Georgia is expected to occur in the baseline due to existing policies and programs. The potential reductions of GHG emissions in the commercial sector are relatively smaller as compared to that in the residential sector in absolute amount (i.e., million tons). However, in terms of percentage reduction, the commercial sector potential is much higher than that of residential buildings in Georgia thereby implying more space to improve energy efficiency in the commercial and public buildings. Note however that the aggregate emission reduction are, however sensitive to several parameters assumed, such as rate of penetration or adoption of efficient devices and process in the buildings. We have carried out later sensitivity analysis on these parameters.

Table 1: Aggregated GHG mitigation potential of energy efficiency measures considered in this study

	2020	2025	2030	2035
(a) Armenia				
Residential Sector				
Total GHG emissions from heating, lighting, refrigeration, cooling and TV use (million tons)	2.96	3.05	3.15	3.23
GHG mitigation from the options considered in this study (million tons)	0.56	0.84	1.12	1.31
% reduction of GHG emissions due to the options considered in this study	18.9%	27.6%	35.7%	40.5%
Commercial/public Sector				
Total GHG emissions from cooling and street lighting (million tons)	0.083	0.087	0.091	0.094
GHG mitigation from the options considered in this study (million tons)	0.019	0.024	0.031	0.036
% reduction of GHG emissions due to the options considered in this study	22.5%	28.1%	33.7%	37.9%
(b) Georgia				
Residential Sector				
Total GHG emissions from heating, lighting, refrigeration, TV and washing machine use (million tons)	1.56	2.19	2.9	3.58
GHG mitigation from the options considered in this study (million tons)	0.09	0.19	0.35	0.52
% reduction of GHG emissions due to the options considered in this study	5.7%	8.9%	11.9%	14.6%
Commercial/public Sector				
Total GHG emissions from heating, lighting and street lighting (million tons)	0.24	0.31	0.39	0.45
GHG mitigation from the options considered in this study (million tons)	0.04	0.08	0.14	0.20
% reduction of GHG emissions due to the options considered in this study	16.3%	26.4%	35.9%	43.3%

We have also distinguished the GHG mitigation potential between the replacement of pre-existing stock of appliances (i.e., appliances already in use as of base year, 2014) and the new stock of appliances. The latter includes appliances in (a) existing buildings which have not used any of the electrical appliance and are expected to use appliances in the future and (ii) new buildings. While existing buildings may not replace their windows, walls and roofs to improve energy efficiency unless they are aged enough to replace, new buildings have a complete freedom of selecting either efficient or inefficient appliances/measures (see Table 2). This differentiation reveals an interesting insight. For electrical appliances (i.e., lightbulbs, refrigerators, washing machine and TVs), almost entire GHG mitigation potential accrue through new stock of appliances. The reason is that households normally do not replace their existing appliance only for the purpose of energy savings as long as the appliance is operating. For example, a household may not discard an existing refrigerator and buy a new one because the latter is more energy efficient; it replace the existing refrigerator only when it stops to work, in such a situation it has two choices, buying energy inefficient refrigerator or buying efficient one. The probability of a households to choose energy efficient brand when it purchases electrical appliances is discussed in data and assumption section above. The same logic is applicable to other appliances and measures, particularly washing machine, television sets, walls and roofs of buildings. In such appliances and measures majority of GHG mitigation comes through new stock of appliances/measures.

On the other hand, some measures, for example, windows have long life span. Both Georgia and Armenia have introduced norms for new buildings to use windows with high insulation starting from 2014. Therefore, energy efficient windows in the new buildings is part of baseline in our study. However, most windows in existing building stocks (i.e., existing as of 2014) are energy inefficient (or have low insulation). Thus, most potential in improving energy efficiency through improved window insulation, particularly in the residential buildings, exist in the pre-existing stock of windows.

Table 2: GHG mitigation potential between pre-existing vs. new stock

GHG Mitigation option	Total mitigation potential during the 2015-2035 period (Thousand tons)	% of total mitigation from the pre-existing stock	% of total mitigation from the new stock
(a) Armenia			
Residential buildings			
Lightbulbs	5,862	0.2%	99.8%
Refrigerators	2,894	20.6%	79.4%
Air conditioners	1,089	6.6%	93.4%
TV sets	1,538	16.5%	83.5%
Insulation	4,588	100%	0%
Commercial buildings			
Air conditioners	116	74.3%	25.7%
Public lighting	354	0.5%	99.5%
(b) Georgia			
Residential buildings			
Lightbulbs	975.0	1.3%	98.7%
Refrigerators	99.5	0.0%	100.0%
Washing machine	27.9	0.0%	100.0%
TV sets	168.6	0.0%	100.0%
Window insulation	1639.3	88.1%	11.9%
Wall insulation	843.5	16.9%	83.1%
Roof insulation	507.8	43.7%	56.3%
Commercial buildings			
Indoor Lightbulbs	540.3	0.1%	99.9%
Public Lighting	108.7	1.2%	98.8%
Window insulation	118.3	55.4%	44.6%
Wall insulation	549.6	9.4%	90.6%
Roof insulation	399.3	16.3%	83.7%

5. Sensitivity Analysis

The calculations of marginal costs, GHG mitigation potential and the MAC curves are sensitive to several parameters, such as assumptions on the penetration rates of energy efficient devices and processes in future years, evolutions of costs of energy efficient technologies overtime, etc. Among these variables, penetration rate would be very sensitive because it influences both the baseline and mitigation or energy efficient scenario. To measure the level of sensitivity of penetration rates, we carried out analyses with varying rates of penetration in both baseline and mitigation scenarios.

5.1 Penetration of energy efficient technologies in the baseline scenario

It is very important to distinguish between the penetration of efficient technologies that occur by itself and as a result mitigation policies or programs or incentives. The penetration that occurs

itself, without designed policies should be reflected in baseline scenario. For example, if existing standards require all new buildings to use better insulated windows, the penetration of energy efficient windows will be high in the baseline. If such a standard does not exist and buildings either unaware of energy efficient appliances or do not have an incentive to adopt the energy efficient appliances, penetration of efficient appliances in the baseline would be low. As the mitigation potential is measured by comparing the situation in the baseline, the potential is sensitive to what is assumed in the baseline for the penetration of efficient appliances. Thus, we conducted a sensitivity analysis by changing the penetration rates energy efficient measures in the baseline. First, we assumed to decrease the penetration rates by 5 percentage point, followed by increasing the penetration rates by 5 percentage point. The results of this sensitivity analysis are displayed in Table 3. Let us take an example of refrigerator in Georgia to explain the sensitivity results presented in Table 3. Earlier in the main analysis, we assumed that 20% of newly bought refrigerators will be energy efficient. The sensitivity analysis shows that if the baseline penetration rate of refrigerators in the residential buildings is decreased to 15% from 20%, the marginal abatement cost would increase (here it becomes less negative) by about 1% to US\$ -138/tCO₂ from US\$139/tCO₂, on the other hand, if the baseline penetration rate is increased to 25% from 20%, the marginal abatement cost would decrease (here it becomes more negative) by about 1% to US\$ -140/tCO₂ from US\$139/tCO₂. The potential GHG mitigation from energy efficient refrigerators would increase by 21%, if we assume 5 percentage point less penetration of efficient devices in baseline situation and the potential GHG mitigation from the energy efficient refrigerators would decrease by 22% if we assume 5 percentage point more penetration of efficient devices in baseline situation. Note that lower penetration of energy efficient appliances in the baseline implies would mean more potential of GHG mitigation remains under the mitigation scenario and vice versa.

Table 3: Sensitivity of baseline penetration level of energy efficiency measures**(a) Armenia**

Energy efficiency measures	Marginal abatement cost		Reduction of CO ₂ emissions	
	(US\$/tCO ₂)		('000 tons of CO ₂)	
	Main analysis	5% increase	Main analysis	5% increase
Residential buildings				
Lightbulbs	-199.8	-199.8	5861.5	5482.3
Refrigerators	-96.1	-95.9	2894.4	2695.8
Air conditioners	-119.0	-117.5	1089.3	1023.2
TV sets	56.2	58.5	1538.3	1453.8
Insulation	-125.6	-125.6	4587.9	4568.3
Commercial buildings				
Air conditioners	29.4	32.1	115.5	113.6
Public lighting	-72.2	-72.1	353.9	329.6

(b) Georgia

Energy efficiency measures	Marginal abatement cost (US\$/tCO ₂)			Reduction of CO ₂ emissions ('000 tons of CO ₂)		
	Main analysis	Sensitivity analysis		Main analysis	Sensitivity analysis	
		5% decrease	5% increase		5% decrease	5% increase
Residential buildings						
Refrigerator	-138.9	-137.9	-140.4	100	121	78
Television sets	80.9	84.6	76.0	169	191	147
Washing machine	-5.9	-3.6	-9.2	28	33	23
Lightbulbs	-164.2	-161.7	-167.4	975	1,073	877
Double-glazed windows	-55.7	-57.0	-54.2	1,639	1,688	1,590
Roof insulation	-63.3	-	-63.7	508	-	469
Wall Insulation	-27.0	-	-28.2	843	-	748
Commercial buildings						
Public Lights	-123.9	-	-123.3	109	-	97
Lightbulbs	-239.9	-	-241.6	540	-	500
Double-glazed windows	-88.9	-91.3	-85.9	118	132	105
Roof insulation	-109	-	-109.1	399	-	377
Wall Insulation	-55	-	-55.1	550	-	517

The sensitivity analysis results presented in Table 3 reveal that marginal GHG abatement costs of energy efficiency measures are not much sensitive to their level of penetration in the baseline. But their GHG mitigation potential is highly sensitive to the baseline penetration rates.

5.2 Rate of adoption of energy efficient technologies under the mitigation scenario

Higher the rate of adoption of energy efficient technologies, higher would be the GHG mitigation potential of an energy efficient measure. To test this, we decreased the annual rates of adoption or change in penetration rates of energy efficient appliances by one percentage points followed by increasing the rates by one percentage point. The results are presented in Table 4. Let us take the example of refrigerator in Georgia again to explain the sensitivity analysis results presented in Table 4. In the main analysis earlier, we assumed that the penetration rate of efficient refrigerator would increase by 3% annually under the mitigation scenario. If the annual growth of the penetration rate of efficient refrigerators in the residential buildings is increased to 4% from 3% before, the marginal abatement cost would increase (becomes more negative here) by 7.5% to US\$ -149/tCO₂ from US\$ -139/tCO₂. The GHG mitigation potential of efficient refrigerators would increase more significantly, by 57%, because more efficient technologies penetrate in mitigation scenario, more emissions are saved. If the penetration rate of efficient refrigerators is increased more slowly in mitigation scenario, by 2%, instead of 3% in the main analysis, the marginal abatement costs would decrease by 24%. The mitigation potential also decreases by 59% because if less efficient technologies penetrate in mitigation case less emissions are saved. Thus, the marginal abatement costs as well as the GHG mitigation potential are sensitive to the assumption on the change in penetration rates of energy efficient technologies.

Table 4: Sensitivity of penetration level of energy efficiency measures in the mitigation scenario

(a) Armenia

Energy efficiency measures	Marginal abatement cost (US\$/tCO ₂)			Reduction of CO ₂ emissions (‘000 tons of CO ₂)		
	Main analysis	Sensitivity analysis		Main analysis	Sensitivity analysis	
		1% decrease	1% increase		1% decrease	1% increase
Residential buildings						
Lightbulbs	-199.8	-199.8	-199.8	5861.5	5036.1	6633.6
Refrigerators	-96.1	-95.6	-96.4	2894.4	2388.5	3353.4
Air conditioners	-119.0	-115.5	-121.5	1089.3	923.2	1240.8
TV sets	56.2	61.5	52.3	1538.3	1331.6	1727.8
Insulation	-125.6	-125.6	-125.6	4587.9	4587.9	4587.9
Commercial buildings						
Air conditioners	29.4	36.0	23.7	115.5	110.3	120.2
Public lighting	-72.2	-72.0	-72.4	353.9	307.7	397.1

(b) Georgia

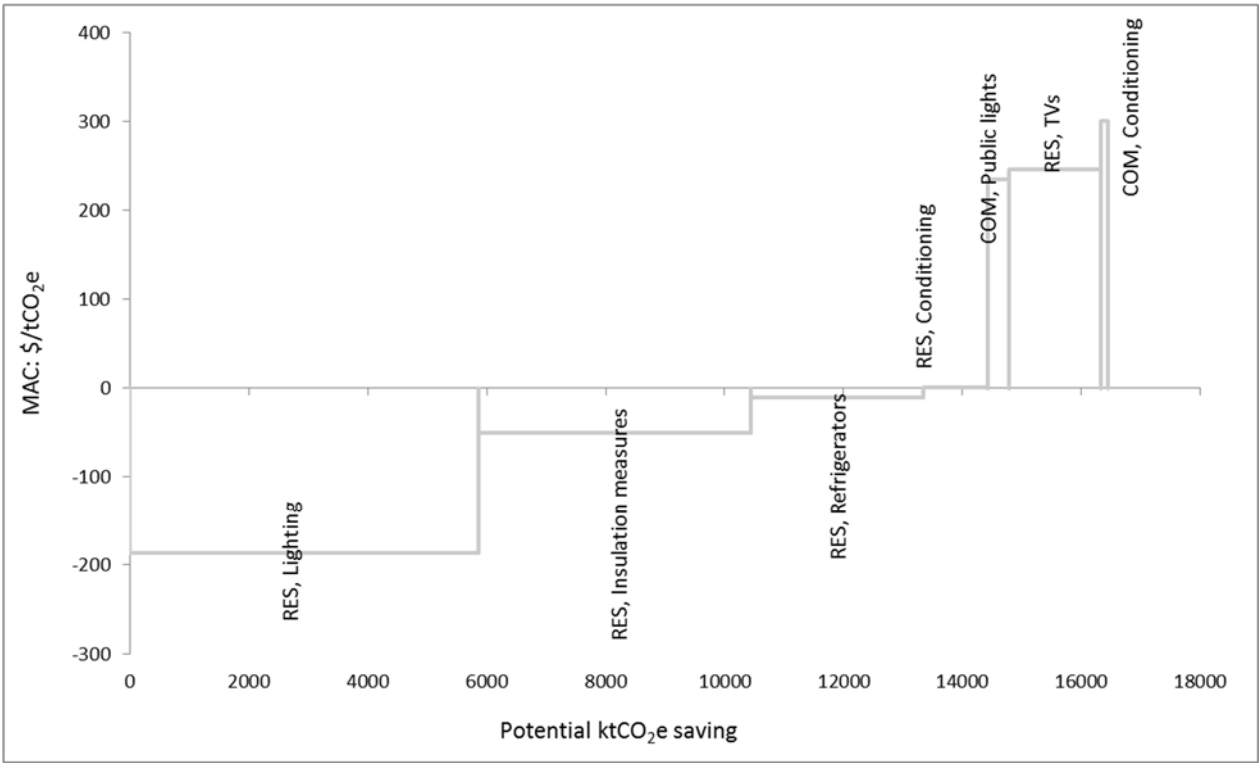
Energy efficiency measures	Marginal abatement cost (US\$/tCO ₂)			Reduction of CO ₂ emissions ('000 tons of CO ₂)		
	Main analysis	Sensitivity analysis		Main analysis	Sensitivity analysis	
		1% decrease	1% increase		1% decrease	1% increase
Residential buildings						
Refrigerator	-138.9	-105.3	-149.3	100	41	157
Television sets	80.9	85.4	78.7	169	113	224
Washing machine	-5.9	11.9	-12.7	28	15	41
Lightbulbs	-164.2	-159.7	-167.1	975	785	1,160
Double-glazed windows	-55.7	-51.3	-	1,639	1,495	-
Roof insulation	-63.3	-62.3	-64	508	393	622
Wall Insulation	-27	-26.1	-27.5	843	563	1,124
Commercial buildings						
Public Lights	-123.9	-112.5	-131.7	109	84	133
Lightbulbs	-239.9	-236.1	-242.2	540	438	637
Double-glazed windows	-88.9	-79.4	-	118	82	-
Roof insulation	-109	-108.7	-109.2	399	342	451
Wall Insulation	-55	-54.7	-55.2	550	465	627

5.3 Sensitivity on discount rate

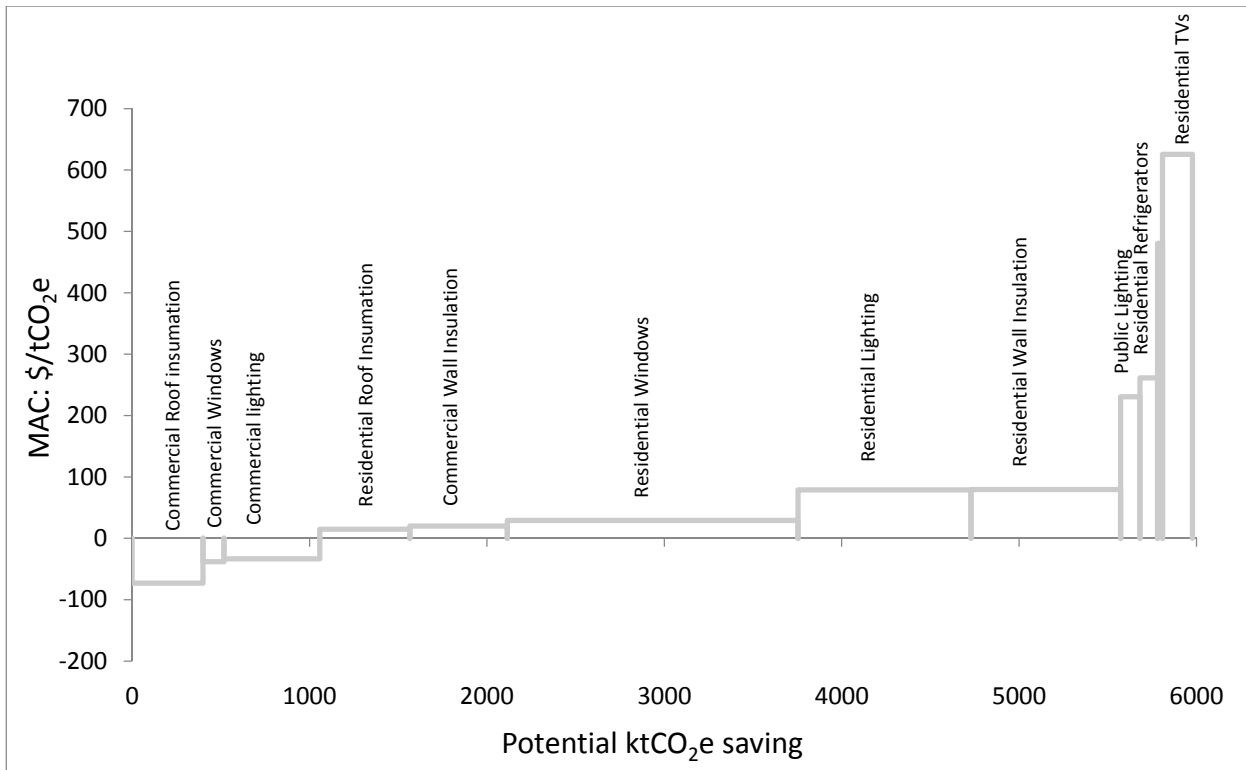
The magnitude of marginal abatement costs are sensitive to discount rate. Many GHG mitigation measures with negative marginal abatement cost derived using social discount rates may not be implemented with higher discount rates. Private investors (either banks or individuals) normally uses higher discount rates because they see higher risks in new and emerging technologies. To reflect this situation, we doubled discount rate from 7.5% in the main analysis to 15% in the sensitivity analysis. All energy efficiency measures except energy efficient walls, windows and lighting systems in the commercial building, have now positive marginal abatement costs. Note that all energy efficiency options except television sets had negative marginal costs in the main analysis where 7.5% discount rate was used.

Figure 2. Sensitivity analysis on discount rate: MAC curve when discount rate is doubled to 15%

(a) Armenia



(b)Georgia



6. Conclusions

This study develops a methodology to estimate a marginal abatement cost curve for energy efficiency measures and applies the methodology in the building sector in Georgia. The key contribution of the methodology is that it distinguishes between the existing and new buildings and also between the existing stock of appliances and new stock of appliances.

The study shows that all energy efficiency improvement measures considered with exception of television sets are negative cost options meaning that these options saves more money by reducing energy consumption than that invested for their implementation, at the same time they reduce GHG emissions. However, this attractiveness of the energy efficiency options are highly sensitive to several parameters, particularly the discount rate. When discount rate is doubled to 15% in the sensitivity analysis from the original value of 7.5% in the main analysis, almost all GHG mitigation options turned to be positive cost options. The study also shows that the potential for GHG mitigation of a measure will depend on the assumption on their penetration rates under the baseline as well as under climate change mitigation or energy efficient scenarios. If a higher penetration rate of an energy efficient appliance is assumed in the baseline due to already existing standards and regulations, the

potential emissions reduction from that appliance under the mitigation scenario would be smaller as a large potential would already be realized in the baseline. The study also argue that the costs of existing stock of appliances should be treated differently for those already in operation from those available in the market but not yet used.

The literature of marginal abatement cost curve analysis is rich because of the hundreds of analyses carried out by academia, research institutions and industries. The purpose of the analysis is to indicate the level of GHG mitigation potentials and corresponding marginal abatement costs of various measures and options. However, it is important to note that the potential may not be realized automatically even if the associated marginal cost is negative. This is because there exist a large number of technical, financial and institutional barriers inhibiting their implementation. Therefore, the indicative potential might be unrealistic from the perspective of their realization. To estimate more realistic GHG mitigation potentials, some experimentation would be needed to understand the likely penetration rate of adoption of energy efficient and clean technologies. For example, households could be surveyed to understand whether or not they replace their existing energy utilizing appliances if they know that they save more money over the years (in present value terms) than their investment for the replacement. If they are not interested, what incentive would they require to do so? Those experiments could tell what level of incentives would be needed to realize the GHG mitigation options. The costs of these incentives should be accounted for to calculate the true marginal cost of a GHG mitigation potential. Expanding marginal cost analysis incorporating the costs of incentives for their realization would be an area of future expansion of this study.

References

- Asian Development Bank (ADB). 1998. Asia Least Cost GHG Abatement Strategies: Summary Report, ADB, Manila.
- Bloomberg (2010). A Fresh Look at the Costs of Reducing US Carbon Emissions, Bloomberg New Energy Finance, New York.
- Cervigni, R., J. A. Rogers, and I. Dvorak (eds.) 2013. Assessing Low-Carbon Development in Nigeria: An Analysis of Four Sectors. World Bank, Washington, DC.

de Gouvello, C., Soares Filho, B., Nassar, A., Schaeffer, R., Alves, F., and Alves, J. (2010). Brazil Low-carbon Country Case Study. Energy Sector Management Assistance Program, The World Bank, Washington, DC.

Energy audits of buildings for Sustainable energy Action Plans of Covenant of Mayors cities, USAID's "Enhancing Capacity for Low Emission Development Strategies (EC-LEDS) /Clean Energy Program", internal reports of Sustainable Development Centre Remissia, 2014.

European Bank for Reconstruction and Development (EBRD) (2014). Regulatory Support for Renewable Heating and Cooling Policy, EBRD, Armenia.

Global Environmental Facility (GEF) (2014a). The potential of improving EE in panel multi-apartment buildings in the Republic of Armenia, GEF, Armenia.

Global Environmental Facility (GEF) (2014b). Green Urban Lighting, GEF, Armenia.

Government of Armenia (GOA) (2015). On approving the Intended Nationally Determined Contributions of the Republic of Armenia under the UN Framework Convention on Climate Change.

<http://www4.unfccc.int/submissions/INDC/Published%20Documents/Armenia/1/INDC-Armenia.pdf>

Government of Georgia (GOG) (2015). Georgia's Intended Nationally Determined Contribution Submission to the UNFCCC. http://www4.unfccc.int/submissions/INDC/Published%20Documents/Georgia/1/INDC_of_Georgia.pdf

Jackson, T. (1991). Least-cost greenhouse planning supply curves for global warming abatement. Energy policy, Vol. 19, No. 1, pp. 35-46.

Jackson, T. (1995). Joint Implementation and Cost Effectiveness under the Framework Convention on Climate Change, Energy Policy, Vo. 23, pp 117- .

Johnson, T.M., C. Alatorre, Z. Romo and F. Liu (2009). Low-Carbon Development for Mexico, World Bank, Washington, DC.

Knowledge, Attitude and behavior Baseline Survey, USAID's "Enhancing Capacity for Low Emission Development Strategies (EC-LEDS) /Clean Energy Program", Winrock International Georgia, 2014.

- McKinsey & Company (2009). Pathways to a Low Carbon Economy: Version 2 of the Global Greenhouse Abatement Cost Curve.
http://www.mckinsey.com/client_service/sustainability/latest_thinking/greenhouse_gas_abatement_cost_curves
- National Inventory Report, Third national Communication of Georgia to the UNFCCC, Government of Georgia, United Nations Development Program (UNDP), Global Environment facility (GEF) (2015).
- National Statistical Service of the Republic of Armenia (NSSRA), (2014). Statistical Yearbook 2014.
<http://armstat.am/en/?nid=586&year=2014>
- [National Statistics office of Georgia \(2014\), Energy Balance of Georgia 2013, Statistical publication, Tbilisi, Georgia.](#)
- [National Statistics office of Georgia \(2014\), Statistical Yearbook of Georgia 2014, Tbilisi, Georgia.](#)
- Public Services Regulatory Commission of the Republic of Armenia (2014). Various Notifications related to electricity tariff. <http://psrc.am/am/sectors/electric/tariffs>
- Ouyang X, Lin B. Levelized cost of electricity (LCOE) of renewable energies and required subsidies in China. *Energ Pol* 2014, Vol.70, pp. 64-73.
- Timilsina, G. R. and T. Lefevre (1999), Reducing GHG emissions from the Power Sector in Developing Asian Countries: An AIJ Prospective, *World Resource Review*, Vol. 11, No.1, PP. 115-131.
- Timilsina, G. R., T. Lefevre and S. Sherstha (2000), Techno-Economic Databases for Environmental Policy Analysis in Asia: Requirements and Barriers, *Pollution Atmospherique*, pp. 79-88.
- United Nations Environmental Program (UNEP) (1992) Atmospheric Brown Clouds. Regional Assessment Report with Focus on Asia, UNEP Nairobi.
- United Nations Framework Convention on Climate Change (UNFCCC) (2011). Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010, Addendum Part Two: Action taken by the Conference of the Parties at its sixteenth session, UNFCCC, Bonn, Germany.
- United Nations Framework Convention on Climate Change (UNFCCC) (2013). Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November

2013, Addendum Part Two: Action taken by the Conference of the Parties at its nineteenth session, UNFCCC, Bonn, Germany.

United Nations Framework Convention on Climate Change (UNFCCC) (2015). Report of the Conference of the Parties on its nineteenth session, held in Paris from 30 November to 11 December 2015, Addendum Part Two: Action taken by the Conference of the Parties at its twenty one session, UNFCCC, Bonn, Germany.

United States Agency for International Development (USAID) (2014). Armenia's Least-Cost Electricity Generation Plan, USAID, Armenia.

Vogt-Schilb, A., Hallegatte, S., 2014. Marginal abatement cost curves and the optimal timing of mitigation measures. *Energy Policy* 66, 645–653.

Winrock International Georgia (2014). Zugdidi Sustainable Energy Action Plan (SEAP), USAID, Georgia.

World Bank (2011), Transition to a Low-Emissions Economy in Poland, World Bank, Washington, DC.

World Bank (2014), FYR Macedonia Green Growth Country Assessment. World Bank, Washington, DC.

Appendix A: Estimation of Penetration Rates of Devices and Processes in an Economy under the Baseline and Energy Efficiency Scenarios

Baseline Scenario

For the baseline scenario let us denote $N_{i \text{ } p\text{-ext}}^{EE}$ by $BN_{i \text{ } p\text{-ext}}^{EE}$ and $N_{i \text{ } p\text{-ext}}^{Non-EE}$ by $BN_{i \text{ } p\text{-ext}}^{Non-EE}$.

Note that $BN_{i \text{ } p\text{-ext}}^{EE}$ and $BN_{i \text{ } p\text{-ext}}^{Non-EE}$ are the number of pre-existing efficient and non-efficient devices/processes correspondingly. We assume that they gradually decrease over time because existing devices/processes retire. These numbers depend on their values in the base year ($NY_{p\text{-ext}}^{EE}$, $NY_{p\text{-ext}}^{Non-EE}$), the economic lives of devices and processes (L_{EE} and L_{Non-EE}) and their remaining lifetime as of the base year. As a result $BN_{i \text{ } p\text{-ext}}^{EE}$ and $BN_{i \text{ } p\text{-ext}}^{Non-EE}$ are calculated as follows:

$$BN_{i \text{ } p\text{-ext}}^{EE} = \begin{cases} BN_{i \text{ } p\text{-ext}}^{EE} & ; BN_{i \text{ } p\text{-ext}}^{EE} > 0 \\ 0 & ; BN_{i \text{ } p\text{-ext}}^{EE} \leq 0 \end{cases}, \quad (A1)$$

where

$$BN_{i \text{ } p\text{-ext}}^{EE} = \begin{cases} BN_{i-1 \text{ } p\text{-ext}}^{EE} - \frac{N_{B \text{ } p\text{-ext}}^{EE}}{L_{EE} - NY_{p\text{-ext}}^{EE}} & ; Y_i > Y_B + NY_{p\text{-ext}}^{EE} \\ BN_{i-1 \text{ } p\text{-ext}}^{EE} & ; Y_i \leq Y_B + NY_{p\text{-ext}}^{EE} \end{cases} \quad (A2)$$

And

$$BN_{i \text{ } p\text{-ext}}^{Non-EE} = \begin{cases} BN_{i \text{ } p\text{-ext}}^{Non-EE} & ; BN_{i \text{ } p\text{-ext}}^{Non-EE} > 0 \\ 0 & ; BN_{i \text{ } p\text{-ext}}^{Non-EE} \leq 0 \end{cases} \quad (A3)$$

where

$$BN_{i \ p-ext}^{Non-EE} = \begin{cases} BN_{i-1 \ p-ext}^{Non-EE} - \frac{N_B^{Non-EE}}{L_{Non-EE} - NY_{p-ext}^{Non-EE}} & ; Y_i > Y_B + NY_{p-ext}^{Non-EE} \\ BN_{i-1 \ p-ext}^{Non-EE} & ; Y_i \leq Y_B + NY_{p-ext}^{Non-EE} \end{cases} \quad (A4)$$

where, Y_i and Y_B are, respectively i th and the base years. $N_{B \ p-ext}^{EE}$, $N_{B \ p-ext}^{Non-EE}$ are numbers of efficient and Non-efficient technologies in pre-existing stock in the base year; L_{EE} , L_{Non-EE} represent lifetime of efficient and Non-efficient technologies; NY_{p-ext}^{EE} , NY_{p-ext}^{Non-EE} are the- remaining lifetime for pre-existing efficient and non-efficient technologies in base year. To calculate $N_{i \ new}^{EE}$ and $N_{i \ new}^{Non-EE}$ (denoted for baseline scenario by $BN_{i \ new}^{EE}$ and $BN_{i \ new}^{Non-EE}$) we need the stock of new technologies (denoted as $N_{i \ new}^{Baseline}$), which, as stated above, is equal to the sum of new technologies in new buildings and new technologies in old buildings purchased due to the retirement of old technologies.

$$N_{i \ new}^{Baseline} = N_{i \ p-ext}^{New-Tech} + N_{i \ new}^{Tech} \quad (A5)$$

Where $N_{i \ new}^{Baseline}$ is the total number of newly bought technologies in Baseline scenario (in year i);

$N_{i \ p-ext}^{New-Tech}$ is the total number of new technologies for substituting pre-existing stock (in year i);

$N_{i \ new}^{Tech}$ is the total number of technologies in New buildings (in year i); Note that the total number of new technologies should also include those which get retired and needs to be substituted.

The number of new technologies in new buildings, $N_{i \ new}^{Tech}$ is projected separately. To calculate the number of efficient and non-efficient technologies in this new stock, we need the penetration of

efficient technologies in new stock of technologies, $P_{i EE}^{Baseline}$. We also assume that if the pre-existing efficient technology retires it will be substituted by efficient one again. So this ratio affects only the remaining part. Using this penetration rate we can calculate the number of efficient and non-efficient technologies in the new stock:

$$BN_{i new}^{EE} = N_{i new}^{Baseline} * P_{i EE}^{Baseline} + N_{B p-ext}^{EE} - N_{i p-ext}^{EE} \quad (A6)$$

$$BN_{i new}^{Non-EE} = N_{i new}^{Baseline} - N_{i new}^{EE} \quad (A7)$$

Energy Efficiency Scenario

For the energy efficiency scenario we denote $N_{i p-ext}^{EE}$ by $MN_{i p-ext}^{EE}$ and $N_{i p-ext}^{Non-EE}$ by $MN_{i p-ext}^{Non-EE}$.

The number of pre-existing efficient technologies in each year will be the same as in baseline scenario:

$$MN_{i p-ext}^{EE} = BN_{i p-ext}^{EE} \quad (A8)$$

But for non-efficient technology we assume that some of the pre-existing recently purchased technologies can be switched to EE technologies earlier than they are retired. Thus we introduce the early switching parameter ASw , defined as the percentage of pre-existing non-efficient technologies that get switched to efficient annually, because of this earlier switching the number of pre-existing non-efficient technologies reduces faster. It is calculated the following way:

$$MN_{i p-ext}^{Non-EE} = \begin{cases} BN_{i p-ext}^{Non-EE} - N_{i p-ext}^{Non-EE_Sw} & ; BN_{i p-ext}^{Non-EE} - N_{i p-ext}^{Non-EE_Sw} \geq 0 \\ 0 & ; BN_{i p-ext}^{Non-EE} - N_{i p-ext}^{Non-EE_Sw} < 0 \end{cases} \quad (A9)$$

Where $N_{i p-ext}^{Non-EE_Sw}$ is the number of non-efficient technologies switched to efficient earlier than the end of lifetime in existing stock in mitigation scenario (from the base year and up to year i), which depends on the ASw and is calculated as:

$$N_{i \text{ } p\text{-ext}}^{Non-EE_Sw} = N_{i-1 \text{ } p\text{-ext}}^{Non-EE_Sw} + N_{i-1 \text{ } p\text{-ext}}^{Non-EE} * ASw \quad (A10)$$

In the mitigation scenario we need to consider two sets of new stock of technologies. One, similarly of baseline scenario is accumulated due to the new buildings and the retirement of pre-existing technologies in old buildings, and the other one accumulated due to the early switching of non-efficient technologies to efficient ones. The first one we denote by $N_{i \text{ } new_Add}^{Tech}$, which is number of all technologies in new stock (in year i) equal to the new technologies that substitute retired technologies and new technologies for new buildings. It is calculated similarly to $N_{i \text{ } new}^{Baseline}$ in baseline scenario (eq.14). Since the penetration of efficient technologies, $P_{i \text{ } new_Add}^{EE}$ is higher in this new stock, the number of efficient technologies in new stock (in year i), $N_{i \text{ } new_Add}^{EE}$, will be calculated as

$$N_{i \text{ } new_Add}^{EE} = N_{i \text{ } new_Add}^{Tech} * P_{i \text{ } new_Add}^{EE} \quad (A11)$$

The early retirement of non-efficient technologies in pre-existing stock will require additional new stock, which means that in mitigation scenario we will need more new stock of efficient technologies. The new stock of technologies in mitigation scenario, will be calculated as:

$$MN_{i \text{ } new}^{EE} = N_{i \text{ } p\text{-ext}}^{Non-EE_Sw} + N_{i \text{ } new_Add}^{EE} \quad (A12)$$

Where number of non-efficient technologies switched to efficient earlier than the end of lifetime in existing stock in mitigation scenario (from the base year and up to year i) and is calculated by Eq.22.

$$MN_{i \text{ } new}^{Non-EE} = N_{i \text{ } new_Add}^{New-Tech} - N_{i \text{ } new_Add}^{EE} \quad (A13)$$

Appendix B: Data Sources and Assumptions

Residential Sector

There were approximately 1,192 thousand households in Georgia in 2014. Based on survey conducted by the Winrock International (Winrock International, 2014) the average size of dwelling is 100 sq.m. and 89% of households use modular heating options, such as electric heater, kerosene stoves that heat only a portion of the households¹⁰ and on average 43% of dwelling living space is heated. Although about 60% of the total households have access to natural gas, only 38% use it for heating. Majority (57%) of the households still use firewood for space heating. Electricity is usually used as supplementary heating fuel for other types of fuels – only 6% use it as a main source. The general tendency is that households switch over to natural gas as their income rise in places where gas distribution infrastructure exists. We assumed that households not only switches to natural gas for space heating but also will increase the heated area as income rises. Since the Winrock survey is the first of its kind carried out in Georgia and there exist no earlier survey which would help to determine trends, expert assessment was used to make projections for future. It was assumed that annual rate at which heated area increases is 2% and the number of households switching to natural gas increases by 1% per year. The Ministry of Energy assumes that by 2035 75% of population will have access to gas.

Major appliances owned by households are TV, refrigerator and washing machines. Almost all households have TV, from which around 11% is new LED type TVs. 84% of household own refrigerator and among them 48% state that their refrigerator is energy efficient. 68% of households use washing machines, 43% of which is purchased after 2010. The average number of bulbs per household is 8, and they operate around 5.26 hours daily. 70% of households use incandescent bulbs, 8% efficient bulbs, and 22% uses both. As for the cooling systems the typical cooling system in Georgia is local split system, used to cool one or two rooms. The central cooling systems are very rare in country, and would result in increase of consumption. The key technical and economic characteristics of appliances used in the household buildings are summarized in Table A1.

¹⁰

Table A1. Costs and technical performance of technologies for the residential sector

	Capital cost			Fuel consumption		
	Unit	Inefficient technology	Efficient technology	Unit	Inefficient technology	Efficient technology
Electrical Appliances						
Refrigerator	USD/unit	514.3	742.9	kWh/unit/year	800.0	500.0
TV	USD/unit	195.9	457.1	kWh/unit/year	363.2	116.8
Washing machine	USD/unit	329.5	398.5	kWh/unit/year	227.1	153.6
Lightbulbs	USD/unit	0.6	46.9	kWh/unit/year	115.2	23.0
Building Insulation						
Plastic double-glazed windows	USD/building	272.0	544.0	cu.m/ building /year		-18.5%
Roof insulation	USD/building		400.9	cu.m/ building /year		-14.7%
Wall Insulation	USD/building		1395.8	cu.m/ building /year		-36.0%

Sources: analysis of technologies sold on Georgian market for electric appliances, for building insulation measures – energy audits (Sustainable Development Centre Remissia 2014)

Table A.2 presents penetration rates of different technologies in households and Table A.3 presents penetration rates of efficient appliances.

Table A.2. Penetration rates of technology in households (%)

Appliance	2014	2035
Refrigerator	84%	93%
TV	100%	100%
Washing machine	68%	83%

Table A.3 shows the assumption on share of efficient technologies in new stock of technologies for baseline and mitigation scenarios, and value of early switching parameter. For example for refrigerators, in baseline case it is assumed that every year 20% of newly bought refrigerators are efficient, in mitigation scenario share starts from 25% in 2015 and goes up to 82% by 2034. The baseline values are based on 2014 data from residential survey (Winrock international, 2014), and shares for mitigation scenarios are based on expert assessment for moderate mitigation measures.

Table A.3. Share of energy efficient appliances in the new stock of appliances (%)

Technology	Baseline scenario	Mitigation scenario	Annual rate at which existing appliances are replaced with efficient appliance
Refrigerator	20%	25-82%	0.0%
TV	20%	25-82%	0.0%
Washing machine	20%	25-82%	0.0%
Bulbs	5%	10-86%	2.8%
Plastic double-glazed windows	80%	100%	5.0%
Roof insulation	0%	0-50%	1.0%
Wall Insulation	0%	0-50%	0.3%

Commercial Sector

Commercial sector includes commercial buildings as well as street lighting. The assessment of MACs for commercial sector was performed based on space area of commercial sector that uses gas for heating and number of bulbs used for street lighting. There are no statistics about the space amount of commercial sector of Georgia, so it was calculated based on energy audits of several commercial buildings performed in different cities of Georgia (Sustainable Development Centre Remissia, 2015). As a result, the average commercial area that is heated by gas was assessed as around 5 mln sq.ms. The growth rates than were based on GDP growth projections from commercial sector and elasticity from MARKAL-Georgia (MARKAL-Georgia, April 2015).

The key technical and economic characteristics of appliances used in the commercial buildings are summarized in Table A4.

Table A4. Costs and technical performance of technologies for the commercial sector

	Capital Cost			Fuel Consumption		
	Unit	Inefficient technology	efficient technology	unit	Inefficient technology	efficient technology
Electrical Appliances						
Public lights	USD/bulb	142.9	485.7	kWh/bulb/year	912.5	474.5

Lightbulbs	USD/bulb	0.6	43.2	kWh/bulb/year	124.8	25.0
Building Insulation						
Plastic double-glazed windows	USD/sq.m	2.0	4.0	kWh/sq.m/year		-15% from heating consumption
Roof insulation	USD/sq.m	0	3.7	kWh/sq.m/year		-24% from heating consumption
Wall Insulation	USD/sq.m	0.0	12.0	kWh/sq.m/year		-36% from heating consumption

Sources: analysis of technologies sold on Georgian market for electric appliances, for building insulation measures – energy audits (Sustainable Development Centre Remissia 2014)

Other technologies, such as refrigerators, cooling systems, etc. can be also considered for commercial sector, but they were not assessed here because there are no data available for the moment about types of the technologies that are used in commercial sector and their penetration.

The future penetration rates of efficient technologies and insulation measures in commercial sector are based on expert assessment. Theble A5 shows the assumptions on shares of efficient technologies in new stock in baseline and mitigation scenarios.

Table A5. Share of energy efficient appliances in the new stock of appliances (%)

Technology year and scenario	2035 baseline	2035 mitigation	Annual rate at which existing appliances are replaced with efficient appliance
Public lights	5%	60%	2.50%
Lightbulbs	1%	87%	3.00%
Plastic double-glazed windows	80%	100%	5.00%
Roof insulation	0%	89%	2.00%
Wall Insulation	0%	89%	1.00%

The emission factor for natural gas is 1.875 kg CO₂/cub.m (National Inventory Report, 2015). For electricity, we used average grid emission factors. Grid emission factors will change overtime as electricity generation mix changes. Based on MARKAL-Georgia (MARKAL-Georgia, April 2015), the grid emission factors are as presented in table A.4.

Table A6. Electricity average grid emission factor

	2015	2018	2021	2024	2027	2030	2033	2036
Electricity grid emission factor (kt/GWh)	0.142	0.126	0.121	0.127	0.125	0.124	0.125	0.125

Information on MARKAL-Georgia

Table A7. Key Data Sources for MARKAL-Georgia¹¹

Sector	Services
Energy Balance	National Statistics Office of Georgia
Natural gas prices	- Georgian Oil and Gas Corporation (GOGC) - Ministry of Energy - Georgian National Energy and Water regulatory Commission - Georgian Natural Gas Transportation Company
Oil Products prices	- Georgia Oil and Gas Company - Ministry of Finance - International Energy Agency
Coal Prices	- Saknakhshiri Ltd - National Statistics Office of Georgia
Biowood prices	- National Environmental Agency - USAID Publication “Potential of Biowood in Georgia and its effective use”
Geothermal energy prices	National Environmental Agency
Electricity prices	- Distribution Companies - Electricity Market Operator

¹¹ MARKAL -Georgia is the MARKAL model developed under the USAID funded Regional Energy Security and Market Development (RESMD) project.

Activity data for different sectors	• National Statistics Office of Georgia • Ministry of Economy and Sustainable Development study • Ministry of Internal Affairs • Electricity and gas distribution companies • EC-LEDS survey
Power Sector	• Ministry of Energy
Demand Drivers (e.g., GDP, population)	• Country Basic Data and Directions for 2013-2016 , Ministry of Finance • IMF GDP projections • World Bank GDP projections • National Statistics Office of Georgia