



## Economic Policy Papers

**On the Cost-Effectiveness of National  
Economy-Wide  
Greenhouse Gas Emissions Abatement  
Measures**

**Chryso Sotiriou**  
*Cyprus University of Technology*

**Apostolos Michopoulos**  
*Cyprus University of Technology*

**Theodoros Zachariadis**  
*Cyprus University of Technology*

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# **On the Cost-Effectiveness of National Economy-Wide**

## **Greenhouse Gas Emissions Abatement Measures**

**Chryso Sotiriou, Apostolos Michopoulos and Theodoros Zachariadis<sup>‡</sup>**

### **ABSTRACT**

This paper explores cost-effective greenhouse gas abatement options for the European Union Member State of Cyprus, for those sectors of the national economy that are not subject to the region's Emissions Trading System. The analysis leads to the construction of a baseline and several alternative marginal emission abatement cost curves. It addresses all economic sectors and considers all different types of mitigation measures – improving energy efficiency, switching to low- or zero-carbon fuels, and inducing behavioural changes. We apply nationally appropriate data that are mainly derived from local market information and judgement of national experts. Finally, we present results of several sensitivity analyses, which address main shortcomings of marginal abatement cost curves that have been identified in the literature, and discuss the policy implications of each one of them. Apart from its relevance for EU Member States, this assessment is useful for all countries seeking guidance in their decarbonisation strategies.

Keywords: Abatement cost curves; Decarbonisation strategy; EU ETS; Sensitivity analysis

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<sup>‡</sup> Corresponding author, Address: Cyprus University of Technology, P.O. Box 50329, 3603 Limassol, Cyprus.  
Email: [t.zachariadis@cut.ac.cy](mailto:t.zachariadis@cut.ac.cy), Tel. +357 25002304.

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# **Ανάλυση Κόστους-Αποτελεσματικότητας Μέτρων Πολιτικής για τη Μείωση των Εκπομπών Αερίων του Θερμοκηπίου στην Κύπρο**

**Χρύσω Σωτηρίου, Απόστολος Μιχόπουλος και Θεόδωρος Ζαχαριάδης**

## **ΠΕΡΙΛΗΨΗ**

Η Κυπριακή Δημοκρατία, ως μέλος της Ευρωπαϊκής Ένωσης, έχει συγκεκριμένες δεσμεύσεις για μείωση των εκπομπών των αερίων του θερμοκηπίου, με στόχο τον μετριασμό της παγκόσμιας κλιματικής αλλαγής. Οι δεσμευτικοί στόχοι για το 2030 είναι φιλόδοξοι, όπως και για τα υπόλοιπα κράτη-μέλη της ΕΕ. Αυτό καθιστά επιτακτικό τον μακροχρόνιο σχεδιασμό κατάλληλης ενεργειακής και περιβαλλοντικής πολιτικής, με στόχο την επίτευξη των στόχων με το ελάχιστο δυνατό κόστος.

Σε αυτό το πλαίσιο, η μελέτη μας διερευνά τη δυνατότητα μείωσης των εκπομπών αερίων του θερμοκηπίου στην Κύπρο έως το 2030, με την εφαρμογή κατάλληλων τεχνολογικών και οικονομικών μέτρων σε όλους τους τομείς οικονομικής δραστηριότητας που δεν εμπίπτουν στο ευρωπαϊκό Σύστημα Εμπορίας Δικαιωμάτων Εκπομπών. Εξετάζονται όλα τα πιθανά μέτρα αποφυγής εκπομπών σε τομείς όπως η ελαφριά βιομηχανία, τα νοικοκυριά, ο τριτογενής τομέας, οι μεταφορές και η γεωργία. Παραδείγματα τέτοιων μέτρων είναι η ενεργειακή αναβάθμιση των υφιστάμενων κτιρίων, η αντικατάσταση βιομηχανικού εξοπλισμού με νέο υψηλότερης ενεργειακής απόδοσης, η ενεργή προώθηση της ηλεκτροκίνησης στα επιβατικά οχήματα, η αντικατάσταση λεωφορείων και φορτηγών με νέα που χρησιμοποιούν φυσικό αέριο ως καύσιμο, η συμπαραγωγή ηλεκτρισμού και θερμότητας στη βιομηχανία, η προώθηση της αναερόβιας χώνευσης με ταυτόχρονη παραγωγή ηλεκτρισμού στον τομέα των αποβλήτων, η επένδυση σε δημόσια μεταφορικά μέσα κ.ά.

Για κάθε μέτρο εξετάζουμε το προεξοφλημένο κόστος από την εφαρμογή του (που περιλαμβάνει το επιπλέον κόστος επένδυσης, το λειτουργικό κόστος και το κόστος καυσίμου) και την αποτελεσματικότητά του εκφρασμένη σε μείωση των εκπεμπόμενων τόνων αερίων του θερμοκηπίου μέχρι το 2050. Για τον σκοπό αυτό χρησιμοποιούμε οικονομικά δεδομένα από την εγχώρια αγορά και αξιοποιούμε εξειδικευμένη πληροφόρηση που προέρχεται από ειδικούς για κάθε τεχνολογία. Με βάση τα αποτελέσματα, κατασκευάζουμε καμπύλη οριακού κόστους μείωσης των εκπομπών αυτών, η οποία μας επιτρέπει, ανάλογα με το επίπεδο μείωσης των εκπομπών στο οποίο στοχεύουμε, να επιλέξουμε την υλοποίηση των πιο αποδοτικών από αυτά τα μέτρα, δηλαδή των μέτρων που έχουν το χαμηλότερο κόστος ανά τόνο μείωσης των εκπομπών.

Η ανάλυσή μας γίνεται από τη σκοπιά της χάραξης δημόσιας πολιτικής και όχι από ιδιωτική χρηματοοικονομική σκοπιά. Για τον λόγο αυτό, πέρα από το βασικό σενάριο ανάλυσης, εξετάζουμε και εναλλακτικούς υπολογισμούς που παίρνουν υπόψη και το όφελος εξαιτίας του περιβαλλοντικού κόστους που αποφεύγεται λόγω των μέτρων αυτών, εκφράζοντας έτσι σε οικονομικούς όρους το κόστος των εκπομπών αερίων του θερμοκηπίου καθώς και αερίων ρύπων. Τα αποτελέσματα μπορούν να αξιοποιηθούν άμεσα από τις κυπριακές περιβαλλοντικές αρχές. Επιπλέον, η μεθοδολογία που προτείνεται μπορεί να χρησιμοποιηθεί από οποιαδήποτε χώρα που έχει παρόμοιους περιβαλλοντικούς περιορισμούς.

## 1 Introduction

Governments around the world have made commitments to avoid serious climate change, by taking measures to reduce emissions of greenhouse gases (GHG) with the aim to stabilise the global average temperature rise to “well below” two degrees Celsius compared to temperature levels of the pre-industrial age (UNFCCC, 2016). Therefore, policy makers need to identify how to proceed with the required emission reductions at the least cost to society. Instead of applying standard cost-benefit analysis for this purpose, which would weigh the costs of emission abatement measures against the avoided damages from climate change, in practice most governments apply cost-effectiveness analyses. The two-degree temperature target is translated to an atmospheric GHG concentrations target, and then to objectives for gradually declining emissions by a given future year (e.g. 2050) which are regarded as consistent with the temperature target. Thus cost-effective emissions abatement comprises the mix of policies and measures which can meet the emissions target at least cost.

One way to determine this cost-effective policy mix is through top-down simulations with the aid of Integrated Assessment Models (IAM) (e.g. Kuik et al., 2009; Morris et al., 2013). These can assess the shadow cost of a given emissions target, and indicate that the preferred policies are those having a cost lower than this shadow cost. However, in many cases the technological detail of such models does not allow an identification of specific emission abatement measures that would be useful to policy makers of a country; moreover, IAMs are usually applied for large countries or world regions and can thus be of limited use for smaller countries.

The second approach is to construct bottom-up “measure-explicit” marginal abatement cost (MAC) curves (Vogt-Schilb and Hallegatte, 2014). A large number of emission abatement measures is identified, combining engineering and economic information about each policy, which leads to an assessment of each measure’s cost and the corresponding GHG emission abatement potential. This information is usually displayed in graphical form, whereby measures are illustrated in ascending order of costs.

This paper follows the latter approach and reports on the methodology and the outcome of building a bottom-up, measure-explicit MAC curve for the Republic of Cyprus. As a member state of the European Union (EU), Cyprus has committed to GHG emission reductions in line with EU decarbonisation objectives for year 2030. Compared to the emissions of year 2005, it has to reduce the emissions from heavy industries which are subject to the EU Emissions Trading system (ETS) by 40%, and the emissions from all other economic activities, i.e. those of non-ETS sectors, by 24%.

The ETS is an EU-wide cap-and-trade scheme, in which national governments have specific tasks. The caps have been set, and the operational details are determined at EU level. Therefore, emission reductions for ETS sectors can be taken for granted. Conversely, national policy makers have the exclusive responsibility for implementing abatement measures in non-ETS sectors. Therefore, work presented in this paper focuses on policies targeting non-ETS emissions, with the aim to assist the authorities of Cyprus in identifying cost-effective measures that can help attain the 24% emission reduction target.

In practice, however, the policy field is not *tabula rasa*. Emission abatement measures cannot be recommended from scratch because existing regulatory mandates have to be taken into account. There are several pieces of legislation at EU and national level that already constrain future emissions in various ways. For example, EU Regulations 443/2009 and 510/2011 define mandatory targets for carbon dioxide (CO<sub>2</sub>) emission levels of new passenger cars and vans in years 2020/2021 (OJEU, 2009; OJEU, 2011); or several EU Directives define energy performance requirements for new buildings<sup>1</sup>. Therefore, in order to provide meaningful policy support, this paper considers potential GHG emission abatement measures across the economy of Cyprus which are additional to the existing national and EU legislation.

Further from policies and measures that have already been identified by national authorities of Cyprus (MARDE, 2016), we consider any possible measure that could yield non-negligible GHG emission reductions. We assess the costs of each measure on the basis of a comprehensive data collection effort, after consultation with local experts in all economic sectors, and with the aid of data that were gathered from the national market. The emissions abatement potential of every measure is assessed taking into account real-world information about the availability, technical deployment potential and energy efficiency under local operating conditions. Such an approach is the most realistic – and hence the most useful to national policy makers.

Apart from being the first study to analyse cost-effectiveness of GHG abatement options for Cyprus, we contribute to the literature in several ways. First, we offer an analysis that is tailor-made to a specific policy context, which is similar for all EU countries but is also relevant for other countries around the world seeking guidance in their decarbonisation strategies. Second, we address all economic sectors, whereas other national studies usually covered a specific sector only, e.g. buildings in Toleikyte et al. (2018) and Timilsina et al. (2017); transport in Tomaschek (2015); or energy efficiency measures in Wächter (2013). Third, because we cover all economic sectors, we consider all different types of mitigation measures: improving energy efficiency, switching to low- or zero-carbon fuels, and inducing behavioural

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<sup>1</sup> See the European Commission's relevant webpage for a list of legislative requirements about new buildings: <https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings>

changes; and we provide a detailed description of the methodology to assess MAC curves for each one of them. Finally, we provide an extensive overview of the policy implications of our assessment by presenting a diverse set of sensitivity analyses. Usually sensitivity analyses consider different projections of future energy prices and different values of discount rates – with largely predictable results. Instead, this paper provides sensitivity runs which are meaningful for energy and climate policy discussions and shed light into different issues. One issue is the distinction between economic and financial cost-effectiveness analysis, i.e. whether different policy recommendations are derived depending on whether we examine measures based on a private or a social perspective. Another issue addressed in the sensitivity analysis is how the preferred policies may change if we consider the side-benefits of GHG abatement measures. Such side-benefits comprise the simultaneous reduction in ETS emissions from measures that target non-ETS sectors only, and the monetary benefits from the reduction of air pollutant emissions. Through these sensitivity analyses we address a main criticism of MAC curves (e.g. Kesicki and Ekins, 2012), i.e. that ancillary benefits or market barriers should also be considered in these assessments.

## **2. Methodology**

The analysis of this study is conducted from a public policy perspective, i.e. from the perspective of a social planner (e.g. a government) that attempts to maximise social welfare. Within the broader policy context of reducing emissions of greenhouse gases, the social planner is required to design a mitigation policy, which comprises a set of measures described by a) the emissions abatement cost and b) emissions abatement potential of each measure. The total abatement cost of a measure is the sum of the discounted investment, maintenance and fuel costs. The calculation is conducted for a period of 30 years, which is considered to be the maximum lifetime of any possible abatement measure. The emissions abatement potential is derived by calculating GHG emissions before and after the implementation of a mitigation measure. Then, for each measure, the cost per unit of emissions abated is calculated by dividing the cost difference by the difference in GHG emissions. If these measures are ranked in ascending cost order, then it is possible to illustrate them graphically in a bottom-up “measure-explicit” marginal abatement cost (MAC) curve as explained in the introductory section. The mathematical formulation for the cost-effectiveness assessment is provided in the Appendix.

All abatement options are assumed to be implemented around the year 2020, so that the cost-effectiveness index uses discounted costs and emission abatement over the 30-year period 2021-2050. One has to keep in mind that these abatement measures are meant to facilitate compliance of Cyprus with its 2030 non-ETS emission reduction targets. This means that, in

reality, these measures will be gradually implemented during the decade 2020-2030. As technology options, cost and abatement potential may change over the course of that decade, it might be appropriate to recalculate the marginal abatement cost curve for intermediate years during the decade in order to determine a more realistic mix of cost-effective mitigation policies. However, this recalculation was not conducted in the study because (despite foreseen reductions in the *absolute costs* of mitigation measures) there are no strong indications for a substantial differentiation in the *relative cost* of the various policies considered in our analysis. A year-by-year calculation would greatly increase the computational burden without leading to essentially different policy conclusions compared with our baseline approach. Sensitivity analyses, to be presented in Section 4.2, deal with other aspects that are more worth exploring.

To assess the expected fuel costs up to the year 2050 with and without mitigation measures, a projection of fuel prices for the period of study is necessary. The most recent officially adopted country-specific projections of fuel prices in Cyprus come from the study of Vougiouklakis et al. (2017), which are in line with the central scenario (“New Policies Scenario”) of the International Energy Agency’s World Energy Outlook 2016 (IEA, 2016).

Since we follow a social planner’s approach, costs and benefits are evaluated from a public policy perspective, hence fuel and electricity prices are net of taxes and duties. For this reason, we also use a real social discount rate of 4% to determine the present value of future cash flows, in line with recommendations from the literature (Kesicki and Strachan, 2011) and according to guidance provided to the government of Cyprus by the World Bank (2016).

### **3. Data and Measures Considered**

The following subsections describe the measures considered for each sector of the economy of Cyprus and the data used in the cost-effectiveness calculations.

#### **3.1. Residential Sector**

To explore GHG abatement options for residential buildings, we used data from a recent detailed national study (Vougiouklakis et al., 2017), which applied an engineering methodology to assess the maximum technical potential for energy savings in buildings, and then adapted these estimates to take into account realistic financial and technical constraints of the national market. Vougiouklakis et al. (2017) estimated the final heating and cooling energy consumption of the existing residential building stock using characteristic typologies of buildings in Cyprus, which were developed after a detailed analysis of official statistics. They distinguished into 84 building typologies based on building type, construction period and climatic area. We have extensively relied on data from that detailed modelling work, but have

aggregated them in order to arrive at a meaningful number of building variants which would be appropriate for the purpose of our study. We distinguish in two building types that turned out to be the most significant: single-family houses and multi-family buildings. We also classify buildings according to construction period based on the most important distinction: buildings completed before 2008 and from 2008 onwards. In this way, eight building typologies (i.e. four building types with and without refurbishment) were used instead of the initial 84. This classification of buildings is the most significant because energy performance regulations essentially started to be implemented in post-2008 buildings.

Carbon emission reductions in residential buildings are primarily due to the implementation of energy efficiency measures. Substitution towards lower-carbon fuels does not present a large abatement potential because most heating, cooling and hot water needs are satisfied through electric appliances, and the substitution of oil-fired boilers with biomass-fired ones is a realistic option for mountainous areas only, which account for less than 5% of the residential building stock of the country. We therefore considered the following measures:

- Deep renovation, i.e. renovation of the building envelope so that it becomes a near-Zero Energy Building (nZEB);
- Roof insulation;
- Wall insulation;
- Insulation of pilotis (for apartment blocks only);
- Replacement of heating and cooling systems with modern highly efficient heat pumps;
- Replacement of windows;
- Replacement of lightbulbs and electric appliances with modern highly efficient ones;
- Installation of solar thermal water heaters.

The implementation of these measures can incur different costs and cause different emission abatement levels according to building type and construction period. As a rule, the measures involve upfront investment costs, which however may be counterbalanced by fuel cost savings throughout the lifetime of the investment because of the energy savings that this investment yields. As shown in more detail in the Appendix, fuel cost savings may be the composite result of a reduction in energy demand, if the same fuel continues to be used, and/or a change in the fuel price, if fuel substitution occurs.

In line with the above, Table 1 presents the cost data and energy savings for each individual measure for the four different classes of buildings considered in our study. Note that the savings shown in Table 1 refer to the demand for *useful* energy, i.e. space heating, space

cooling, light and domestic hot water. To convert useful energy to the corresponding amount of *final* energy, which is required to calculate emissions abatement, the corresponding efficiency figures have to be used. Therefore, the bottom part of Table 1 shows the main technologies used for space heating and cooling in residential buildings in Cyprus by construction period, and their corresponding average thermal efficiency. To calculate final energy savings by abatement option, we compare with the predominant technology in each case, i.e. oil-fired boiler for older buildings and air-to-air split type heat pumps for more recent ones. Heat pumps are essentially the only technology used for space cooling, but with different seasonal energy efficiency ratios (SEER) depending on the age of the buildings. Note that the energy savings shown in Table 1 refer to operation of equipment that satisfies optimal thermal comfort requirements.

Table 2 shows the cumulative number of interventions foreseen for residential buildings up to 2030, as determined by Vougiouklakis et al. (2017). They have been based on an empirical assessment of the realistic potential in the household sector of Cyprus, taking into account financial, technical and behavioural aspects. Zachariadis et al. (2018b) provide a detailed justification of these figures.

By combining the information of Tables 1 and 2 it is possible to calculate the total discounted costs and energy savings from all measures to be implemented until 2030. To translate energy savings to GHG emission savings, Table 3 shows the GHG emission factors applied for the residential sector; these are primarily based on guidance provided by the United Nations Intergovernmental Panel on Climate Change (IPCC, 2006).

**Table 1: Technologies and fuels used in residential buildings of Cyprus by construction period, their corresponding efficiency figures and the shares of total use.**

<i>Heating systems for pre-2008 residential buildings</i>				<i>Heating systems for post-2008 residential buildings</i>			
<i>Technology</i>	<i>Fuel</i>	<i>Efficiency</i>	<i>Usage</i>	<i>Technology</i>	<i>Fuel</i>	<i>Efficiency</i>	<i>Usage</i>
Central heating	Gas oil	80%	23.6%	Central heating	Gas oil	80%	9.1%
Heat pump	Electricity	320%	15.2%	Heat pump	Electricity	320%	38.6%
Stove	Electricity	100%	17.1%	Stove	Electricity	100%	18.2%
Stove	LPG	70%	23.0%	Stove	LPG	70%	4.5%
Fireplace	Biomass	30%	7.3%	Fireplace	Biomass	30%	8.0%
Storage	Electricity	100%	4.5%	Storage	Electricity	100%	9.1%

<i>Cooling systems for pre-2008 residential buildings</i>				<i>Cooling systems for post-2008 residential buildings</i>			
<i>Technology</i>	<i>Fuel</i>	<i>Efficiency</i>	<i>Usage</i>	<i>Technology</i>	<i>Fuel</i>	<i>Efficiency</i>	<i>Usage</i>
Heat pump	Electricity	250%	100.0%	Heat pump	Electricity	320%	100.0%

Current (New) heat pump specifications

<i>Type</i>	<i>SEER</i>	<i>SCOP</i>	<i>Comment</i>	<i>Investment cost* [€]</i>	<i>Maintenance cost* [€]</i>	<i>Lifespan [y]</i>
Split, Air-to-Air (AA)	515%	475%	Actual data; applicable to residential single family buildings before 2008	3,200	128	15
Package, VRV	500%	460%	Actual data; Applicable to commercial buildings	92,500	3,700	15
Split, Air-to-Air (AA)	515%	475%	Actual data; applicable to residential single family buildings after 2008	4,000	160	15
Split, Air-to-Air (AA)	515%	475%	Actual data; applicable to residential multi family buildings before 2008	9,600	384	15
Split, Air-to-Air (AA)	515%	475%	Actual data; applicable to residential multi family buildings after 2008	14,400	576	15

Source: Vougiouklakis et al. (2017) and authors' estimates based on national statistical surveys.

**Table 2: Number of energy efficiency interventions in existing residential buildings of Cyprus up to 2030.**

<b>Intervention</b>	<b>Total number of interventions up to 2030</b>
<i>1. Single- and two-family houses</i>	
Deep renovation (nZEB)	1,000
Roof insulation	12,000
Wall insulation	2,500
Window frame system upgrade	3,500
Lighting and electronic appliances	21,000
Heat pumps	2,500
Solar thermal system for hot water production	3,500
<i>2. Multi-family buildings</i>	
Deep renovation (nZEB)	500
Roof insulation	3,500
Wall insulation	600
Ground floor/level insulation	300
Window frame system upgrade	2,000
Lighting and electronic appliances	5,500
Heat pumps	1,500
Solar thermal system for hot water production	500

Source: Vougiouklakis et al. (2017).

**Table 3: Emission factors of the three main greenhouse gases for the residential sector of Cyprus, for different fuels and electricity (based on the power generation mix of Cyprus for 2015); they are expressed in kilograms of CO<sub>2</sub>-equivalent per kWh.**

	<i>CO<sub>2</sub></i>	<i>CH<sub>4</sub></i>	<i>N<sub>2</sub>O</i>
Gas oil	0.267	9.00×10 <sup>-4</sup>	6.44×10 <sup>-4</sup>
LPG	0.227	4.50×10 <sup>-4</sup>	1.07×10 <sup>-4</sup>
Biomass	0.403	2.70×10 <sup>-2</sup>	4.29×10 <sup>-3</sup>
Electricity	0.743	7.21×10 <sup>-4</sup>	1.70×10 <sup>-3</sup>

Source: IPCC (2006); MECIT (2015).

Note: Emissions factors of non-CO<sub>2</sub> gases have been adjusted for their 100-year Global Warming Potential without climate-carbon feedback in line with the IPCC 4<sup>th</sup> Assessment Report.

### 3.2. Tertiary Sector

In the service sector, which is very diverse as it includes offices, shops, schools, hospitals, hotels etc., carbon emission abatement options are also primarily associated with energy efficiency measures. For this purpose, results from the study of Vougiouklakis et al. (2017) were used like in the residential sector. Additional energy simulations for a typical office building were performed in the frame of our study, for two different construction periods. Besides energy efficiency measures on the building envelope and in lighting equipment, installation of modern high-efficiency heat pumps and solar thermal heaters in buildings such as hotels, sports centres etc. were considered.

In addition to the above measures, the use of cogeneration (CHP – combined heat and power generation) was also considered for a number of installations of the tertiary sector. This mainly involves hotels and hospitals, which have considerable thermal energy needs, for end uses that require hot water. It was assumed that up to 80 CHP units can be realistically installed, with a nominal electricity capacity of 100 kW each. To achieve the maximum possible emission savings, it was assumed that the CHP units will be fuelled by LPG and replace gas oil fired boilers. In line with relevant industrial information, a total thermal efficiency of 89.7% was assumed for these units (34.2% for electricity and 55.5% for thermal energy), as opposed to 75% thermal efficiency of currently installed boilers.

Cost and energy savings data for this sector are presented in Table 4. As already mentioned for the residential sector, energy savings refer to the demand for *useful* energy, and efficiency figures of Table 1 are used to convert useful energy to *final* energy, which is required for emissions calculations. Final energy savings by abatement option are calculated through comparison with the predominant technology in each case, i.e. variant refrigerant flow heat pump systems for both space heating and space cooling, for buildings of all ages – but with different average seasonal energy efficiency ratios (SEERs) depending on their age.

Table 5 shows the cumulative number of interventions foreseen for service sector buildings up to 2030, which has been determined empirically by Vougiouklakis et al. (2017) taking into account financial, technical and behavioural aspects.

The GHG emission factors applied for the tertiary sector are the same as those for the residential sector that are presented in Table 3. It should be noted, however, that since heat pumps have been the predominant technology for both space heating and cooling and all ages, the measures considered for commercial buildings – with the exception of cogeneration – involve only indirect GHG emission reductions because they all involve changes in electricity consumption of these buildings. Hence, apart from cogeneration, no direct emission abatement is taken into account for these measures.

### 3.3. Industry

In the industrial sector, GHG emission abatement measures were explored with emphasis on the following subsectors that are relevant for Cyprus: (a) cement industry, (b) food and beverages, (c) mining, (d) water supply, (e) plastics (f) building material industry, (g) pharmaceutical and cosmetic industry. Due to the significant diversity of industries and the variety of processes and equipment applied, as well as the lack of existing data, the analysis was based on in-situ visits and interviews with the energy managers of the plants, and on data provided by local firms that are highly involved with the design, construction and maintenance of industrial equipment.

The following measures were considered in the industrial sector:

- Replacement of electricity transformers with modern highly efficient ones (i.e. achieving an efficiency of at least 95% under each loading percentage);
- Replacement of electric motors with modern highly efficient ones (efficiency class IE3 according to standard IEC 60034-30-1);
- Replacement of electric inverters with modern highly efficient ones (i.e. achieving an efficiency of at least 98% under each loading percentage);
- Installation of LED light bulbs;
- Installation of photovoltaics;
- Replacement of fuel oil fired burners with modern efficient ones, so that, in combination with the existing installed boilers, they achieve an efficiency of over 90%;
- Cogeneration.

Out of the possible measures, priority was given to those deemed as realistic by the industry, i.e. those which correspond to their economic capability and which involve technologies that are already available in the Cypriot market.

Cogeneration was considered for a number of industrial installations, for end uses (e.g. process hot water) that require thermal energy. It was assumed that up to 30 CHP units can be realistically installed in industrial plants across Cyprus, with a nominal electricity capacity of 100 kW each. To achieve the maximum possible emission savings, it was assumed that the CHP units will be fuelled by LPG and replace boilers burning fuel oil. In line with relevant industrial information, a total thermal efficiency of 89.7% was assumed for these units (34.2% for electricity and 55.5% for thermal energy), as opposed to 75% thermal efficiency of currently installed boilers. Table 6 illustrates the costs and assumed energy savings for the above mentioned measures, taking into account the diversity of uses and operation modes of equipment in industrial plants of Cyprus.

**Table 4: Costs and energy savings for each measure considered in commercial buildings and for LPG-fired cogeneration in the tertiary sector.**

Office building before 2008 (1990)						Office building after 2008					
Intervention	Change in useful energy demand [kWh <sub>th</sub> ]		Investment cost* [€]	Maintenance cost* [€]	Lifespan [y]	Intervention	Change in useful energy demand [kWh <sub>th</sub> ]		Investment cost* [€]	Maintenance cost* [€]	Lifespan [y]
	Heating	Cooling					Heating	Cooling			
Deep renovation (to nZEB)	-9,720	-21,300	141,000	6,520	20	Deep renovation (to nZEB)	-3,460	570	128,000	6,260	20
Roof insulation	-2,515	-7,270	12,000	240	20	Roof insulation	-415	-665	9,500	190	20
Wall insulation	-4,010	-490	55,000	1,100	20	Wall insulation	-1,890	-960	47,000	940	20
Pilotis insulation	-3,115	4,480	9,000	180	20	Pilotis insulation	-720	755	6,500	130	20
Windows replacement	1,470	-12,890	65,000	5,000	20	Windows replacement	-490	1,270	65,000	5,000	20
Lighting [kWh <sub>el</sub> ]	-12,200		7,600	228	18	Lighting [kWh <sub>el</sub> ]	-12,200		7,600	228	18
Solar thermal [kWh <sub>th</sub> ]	-6,000		3,600	300	20	Solar thermal [kWh <sub>th</sub> ]	-12,000		7,200	600	20
Energy Demand for: [kWh]	16,890	84,185				Energy Demand for: [kWh]	10,875	60,800			
	Electricity Production [kWh/y]	Heat Production [kWh/y]	Gas Oil Substitution [kWh/y]	Investment cost* [€]	Maintenance cost* [€/y]	Lifespan [y]	Capacity [units]				
CHP 100 kW <sub>el</sub> - LPG	815,760	1,322,640	1,765,000	165,000	4,950	15	30				

\* Without VAT

**Table 5: Number of energy efficiency interventions in existing commercial buildings of Cyprus up to 2030.**

<b>Intervention</b>	<b>Total number of interventions up to 2030</b>
Deep renovation (nZEB)	800
Roof insulation	3,000
Wall insulation	600
Pilotis insulation	150
Window frame system upgrade	800
Lighting and electronic appliances	7,000
Heat pumps	3,500
Solar thermal system for hot water production	2,500

**Table 6: Data and assumptions used in the cost-effectiveness calculations for the industrial sector**

<i>Intervention</i>	<i>Savings [kWh/kW/a]</i>	<i>Investment cost* [€/kW]</i>	<i>Maintenance cost* [€/kW]</i>	<i>Lifespan [y]</i>	<i>Overall Savings [kWh/a]</i>	<i>Overall Investment cost* [€]</i>	<i>Overall Maintenance cost* [€]</i>	<i>Capacity [kW]</i>
Electricity Transformer	234	15	0.15	20	14,865,000	1,740,000	17,400	
Electric Motor (up to 250 kW)	6	50	0.50	20	34,685,000	493,500,000	4,935,000	
Electric Motor (> 250 kW)	6	80	0.80	20				
Electric Inverter (up to 300 kW)	240	75	0.75	10	272,525,000	183,600,000	1,836,000	
Electric Inverter (> 300 kW)	240	100	1.00	10				
Lighting	1,898	780	31.20	13	173,425,000	72,860,000	2,914,400	
Photovoltaics	1,700	1,000	40.00	20	4,250,000	2,500,000	100,000	2,500
Burner replacement (LFO)	224	8.50	0.34	10	1,325,940	56,500	2,933	
		4.60	-					
	<i>Electricity Production [kWh/y]</i>	<i>Heat Production [kWh/y]</i>	<i>Fuel Substitution [kWh/y]</i>	<i>Oil</i>	<i>Investment cost* [€]</i>	<i>Maintenance cost* [€/y]</i>	<i>Lifespan [y]</i>	<i>Capacity [units]</i>
CHP 100 kWel - LPG	815,760	1,322,640	1,765,000	165,000	4,950	15	30	

\*Cost values without VAT

### 3.4. Road Transport

The transport sector is responsible for a considerable amount of non-ETS emissions of Cyprus. According to the latest National Greenhouse Gases Inventory Report (MARDE, 2017), transport contributed by 31.3% to energy related GHG emissions in 2015 and to 22.8% of total national GHG emissions for the same year, exhibiting an increase of 57% during the period 1990-2015.

Two measures are currently considered by national authorities for reducing carbon emissions of transport - promotion of public transport and promotion of low-CO<sub>2</sub> vehicles (MARDE, 2016). In order to stay in line with national policies that have been submitted up to now, mitigation measures that we initially considered for this sector are:

- Changes in CO<sub>2</sub>-based vehicle taxation in order to encourage the purchase of very low-CO<sub>2</sub> cars
- Infrastructure investments for walking and cycling
- Infrastructure investments for public transport
- Use of alternative fuels (e.g. CNG, electricity) for cars and/or trucks without changes in vehicle taxation.

The detailed methodology to assess the cost-effectiveness of all these measures is provided in the Appendix. For reasons explained in the following paragraphs, however, the first two of the above measures were not further considered in the frame of this study.

#### *3.4.1. Changes in CO<sub>2</sub>-based vehicle taxation*

Since 2013, CO<sub>2</sub> emissions are the basis for calculating both registration taxes (levied to new passenger cars when they are purchased) and annual circulation taxes in Cyprus. By making the CO<sub>2</sub>-based vehicle taxation more stringent, a shift to very low CO<sub>2</sub> cars can occur because a number of consumers will buy a lower emission car compare to the one that they would otherwise purchase; this will reduce the emission levels of new cars entering the market and hence the overall carbon emissions of road transport – assuming that the vehicle distance travelled remains the same in both mitigation and reference scenarios.

In the hypothetical case of implementing such a scheme, the tax system can be made more stringent either by increasing the tax rates applicable to each CO<sub>2</sub> emission segment, or by reducing the thresholds of each segment, so that e.g. the lowest registration fee and road tax does not apply to cars emitting between 120 and 150 g/km but between 90 and 120 g/km. Similarly, a zero registration fee (currently applying to cars emitting less than 120 g/km) would only be applicable to cars emitting less than 90 g/km.

Notwithstanding the above considerations, it should be noted that recent legislative developments at EU level effectively impose a more stringent CO<sub>2</sub>-based taxation for passenger cars, without the need for additional national measures. More specifically, as of 2019, the CO<sub>2</sub> emission levels of cars will be reported on the basis of emission tests made in the new WLTP (Worldwide Harmonised Light Vehicle Test Procedure) driving cycle, which is more representative of today's car capabilities and driving conditions than the "New European Driving Cycle" (NEDC) that was used up to now. As a result, the reported CO<sub>2</sub> emission levels are expected to be considerably higher for most cars in comparison to the levels that would be reported under NEDC measurements. Therefore, this measure is currently taken for granted by policy analysts and hence it is not further examined in this paper since our study considers mitigation measures that are additional to the existing ones.

#### *3.4.2. Infrastructure investments for walking and cycling*

Because of large uncertainties about the amount of investments that are realistic and the quantitative impact of such measures on passenger mobility, and in the absence of related information from national authorities of Cyprus, the effect of walking and cycling infrastructure was not further examined in this study.

#### *3.4.3. Infrastructure investments for public transport*

Cyprus has a very low share of public transport in passenger mobility (around 2%), hence increasing the modal share of buses seems to be a meaningful and necessary policy option. This mitigation measure is accompanied by the related investment cost, operation and maintenance cost and fuel cost of new buses, to be accompanied by large energy and emission savings due to the lower use of private cars.

With appropriate incentives for public transport, it is assumed that there will be a shift of a certain amount of passenger kilometres from private cars to buses. Based on the occupancy rates of each mode, there will be a reduction in the distance travelled with private cars and a rise in the distance travelled with buses. This will induce a change in fuel costs: extra fuel costs because of the additional operation of buses, minus the avoided fuel costs of cars due to the reduction in their use. The associated emission reduction will be due to the decreased use of fuel (and hence lower emissions) in passenger cars, minus the additional emissions to be generated by the more intensive use of buses.

#### *3.4.4. Use of alternative fuels for cars and/or trucks*

For this measure it is assumed that, as a result of subsidies or a regulatory obligation, a fraction of new cars sold each year use a low-carbon or zero-carbon powertrain. This entails

a change in all costs; alternative fuelled vehicles are generally more costly to purchase but have lower fuel costs. Emission reduction is achieved due to the use of a lower-carbon fuel.

Using alternative fuels is assumed not to affect total passenger mobility (i.e. passenger kilometres of private cars), but only the average emission factor of new cars, and hence also the average emission factor of all cars in use. In the case of passenger cars, fuel switch is assumed to take place from conventional (petrol and diesel powered) cars to fully electric cars. In the case of freight transport, fuel switch is assumed to occur from diesel powered to CNG-powered trucks.

Table 7 summarises the main data and assumptions used for the cost-effectiveness calculations in the road transport sector, limited to those of subsections 3.4.3 and 3.4.4. Assumptions on technical and cost data (such as vehicle prices and vehicle fuel consumption for different technologies) have been based on data recommended by the European Commission for the preparation of National Energy and Climate Plans, which were provided to energy and environmental authorities of EU Member States, but were adapted – where necessary – to national circumstances of Cyprus according to the judgement of the authors.

**Table 7: Data and assumptions used in the cost-effectiveness calculations for the road transport sector.**

Parameter	Parameter Name	Parameter Value	Unit	Source
$\alpha$	Fraction of new cars sold up to 2030 using low-carbon powertrain	50	%	Assumption
	Fraction of new trucks sold up to 2030 using Compressed Natural Gas as a fuel	50	%	Assumption
<i>AFC</i>	Average Fuel Consumption of passenger cars			
	<i>Gasoline</i>	7.7	l/100 km	European Commission recommended data for "ordinary" technologies
	<i>Diesel</i>	5.9	l/100 km	
	<i>Electricity</i>	0.2	kWh/km	IRENA (2015)
	Average Fuel Consumption of buses			
	<i>Diesel</i>	28	l/100 km	National estimates used in the Odyssee-Mure database
	Average Fuel Consumption of trucks			
	<i>Diesel</i>	32	l/100 km	National estimates used in the Odyssee-Mure database
	<i>Compressed natural gas</i>	14	MJ/km	Copert model (personal communication with Emisia S.A.)
<i>EF</i>	Emission Factor of a given GHG by type of fuel			
	<i>Gasoline</i>			
	CO2	69,300	kg/TJ	IPCC (2006)
	CH4	25	kg/TJ	IPCC (2006)
		0.625	tCO <sub>2-e</sub> /TJ	Calculated
	N2O	8	kg/TJ	IPCC (2006)
		2.384	tCO <sub>2-e</sub> /TJ	Calculated
	CO2-e	2.398	kgCO <sub>2-e</sub> /l	Calculated
<i>Diesel</i>				
CO2	74,100	kg/TJ	IPCC (2006)	

Parameter	Parameter Name	Parameter Value	Unit	Source
	CH4	3.9	kg/TJ	IPCC (2006)
		0.098	tCO <sub>2-e</sub> /TJ	Calculated
	N2O	3.9	kg/TJ	IPCC (2006)
		1.162	tCO <sub>2-e</sub> /TJ	Calculated
	CO2-e	2.759	kgCO <sub>2-e</sub> /l	Calculated
	<i>Electricity</i>			
	CO2	0.7407	kgCO <sub>2</sub> /kWh <sub>el</sub>	Cyprus GHG Inventory
	CH4	2.847 × 10 <sup>-5</sup>	kgCH <sub>4</sub> /kWh <sub>el</sub>	Report (MARDE 2017);
	N2O	5.694 × 10 <sup>-6</sup>	kgN <sub>2</sub> O/kWh <sub>el</sub>	applies to the current power
	CO2-e	0.743	kgCO <sub>2-e</sub> /kWh <sub>el</sub>	generation mix of Cyprus Calculated
	<i>Compressed natural gas</i>			
	CO2	56,100	kg/TJ	IPCC (2006)
<i>KMV</i>	Average kilometres travelled by passenger car	12,000	km/car	National estimates used in
	Average kilometres travelled by truck	25,000	km/truck	the Odyssee-Mure database
<i>NEW</i>	Newly registered passenger cars	25,000	cars/y	National estimates used in
	Newly registered trucks	500	trucks/y	the Odyssee-Mure database
<i>OR</i>	Occupancy Rate of passenger cars	1.5	passengers/car	Assumption
	Occupancy Rate of buses	15	passengers/bus	Assumption
<i>ΔPKT</i>	Amount of passenger kilometres shifted up to 2030 from cars to buses	434,000,000	pkm	Assumption (7% of total number of pkm in 2015 according to European Commission (2017))
<i>n</i>	Lifetime			
	<i>Public Transport</i>	12	y	
	<i>Conventional Cars</i>	12	y	
	<i>Electric Cars</i>	12	y	
	<i>CNG-powered trucks</i>	12	y	
<i>INV</i>	Investment Cost			
	<i>Public Transport (total)</i>	100,000,000	€	Assumed expenditures for public transport infrastructure

Parameter	Parameter Name	Parameter Value	Unit	Source
	<i>Conventional Car</i>	18,918	€	and purchase of additional buses for the entire period 2020-2030 European Commission recommended data for "ordinary" technology
	<i>Electric Car</i>	25,839	€	European Commission recommended data for "ordinary" technology, assuming an extra premium in retail price of battery electric cars
$\Delta INV$	Difference of Investment Cost <i>CNG-powered truck vs. Diesel-powered truck</i>	30,000	€	Based on European Commission recommended data, assuming extra cost for CNG trucks because currently no CNG infrastructure exists

Note: The first column of this table refers to symbols which are explained in the detailed methodological description included in the Appendix.

### 3.5. Agriculture

The only agricultural emission mitigation measure considered in this paper – apart from measures already taken in the recent past and in addition to formal obligations of the Republic of Cyprus – is the reduction of emissions from manure management from the promotion of anaerobic digestion for animal waste (MARDE, 2016). This may be implemented through a) either a full exploitation of the biogas production capacity of existing animal waste processing plants, b) or through an investment in new anaerobic digesters. This section describes the approach used to assess costs and emission reduction for this measure.

As regards the amount of GHG emissions to be reduced, MARDE (2016) estimated a decrease of 15.3 thousand tonnes of CO<sub>2</sub> equivalent by 2020, or 8.5% compared with the baseline situation without measures; this decrease is assumed to remain the same up to 2030.

Based on data from Kythreotou (2014), which had been obtained through dedicated surveys with Cypriot farmers, and after further communication with MARDE staff, we calculated the amount of additional animal waste that has to be fed to anaerobic digesters in order to achieve these emission reductions. The calculation, described in Zachariadis et al. (2018a), relied on a forecast of the evolution of the animal population in Cyprus by animal type and on specific waste-related information for the kinds of animals whose waste is most likely to be utilised in anaerobic digestion – i.e. cattle, pigs and poultry. It turned out that the 8.5% reduction in GHG emissions of this sector will require an extra amount of 90,000-99,000 cubic metres (c.m.) of waste per year to be directed to anaerobic digestion.

It was then possible to assess the investment and operation cost of installations that will have to use these additional amounts of animal waste. Based on recently collected information by the Cyprus Employers and Industrialists Federation (OEB), which is unpublished but became available to the authors, it turned out that there is a potential for further use of existing biogas plants, up to a maximum of around 90,000 c.m. of waste per year. For this potential to be exploited, one option would be that animal waste from small farms is collected and delivered to the biogas operators. A probably more realistic alternative is to collect organic waste (e.g. from municipal waste) and send it to biogas plants; in this case the plants should be equipped with a pasteuriser in order to feed the organic waste to the anaerobic digester.

Currently only two of the thirteen existing biogas plants are equipped with pasteurisers. We therefore assumed that, for the other plants to fully exploit their capacity, at least nine more plants will need a pasteuriser. According to national data, each pasteuriser has an installation cost of about 200,000 Euros – or 1.8 million Euros in total and a maintenance cost of 300 Euros, or 2700 Euros per year in total. Based on these calculations, it was then possible to

derive the costs associated with this measure, for a lifetime of 30 years. We also assumed, in line with existing industrial data, that the additional quantity of 90,000 c.m. of organic waste per year will lead to an additional electricity production of 716 MWh/year, which will have to be accounted for in the cost and emission reductions because they will correspond to an equal amount of electricity avoided by thermal power plants. The additional thermal energy to be generated by biogas CHP plants was ignored in our calculations because a large part of the thermal energy produced already now is wasted as there is limited thermal capacity which can exploit it.

This analysis ignores the impact of transporting additional amounts of waste to the biogas plants. In other words it assumes that the additional cost and emissions caused by vehicles transporting waste to anaerobic digesters are similar to the corresponding costs and emissions of transporting this waste to landfills or other sites.

### 3.6. Waste management

We initially considered the implementation of planned GHG emission mitigation measures for waste management in line with national policies described by MARDE (2016), according to which the possible policies comprise: biogas recovery from controlled waste management sites; promotion of anaerobic digestion in wastewater treatment plants; reduction of the amount of biodegradable waste being disposed in landfills; and separate collection of biodegradable waste. To collect information about the above measures and eventual additional policies, we conducted interviews with staff from several national authorities – the Waste Unit of the Environment Department, the Ministry of the Interior, the Water Development Department and the Municipality of Paphos. Based on these discussions and the relevant data gathered, and for the reasons explained by Zachariadis et al. (2018a), we did not consider any measures to reduce GHG emissions from waste management; all realistic measures in this sector are already implemented, so there was currently no scope for additional measures to be included in our study.

## **4. Results**

Based on the methodology, the data and the assumptions described in the previous sections, it is possible to assess the discounted costs and GHG emission savings for each one of the individual measures that have been considered. The first subsection below reports the results of our baseline calculations. Subsection 4.2 describes three sensitivity cases and shows the corresponding alternative results.

#### 4.1. Baseline MAC curve

Figure 1 highlights the results of the cost-effectiveness calculation, by showing the marginal GHG emissions abatement cost curve when only non-ETS emissions are considered. This means that a) measures reducing electricity-generated emissions are excluded; and b) abatement calculations include only the reduction of direct GHG emissions, thereby ignoring the indirect emission reductions due to decrease in electricity consumption, which would be subject to the ETS. In this framework, the most cost-effective measures turn out to be the following:

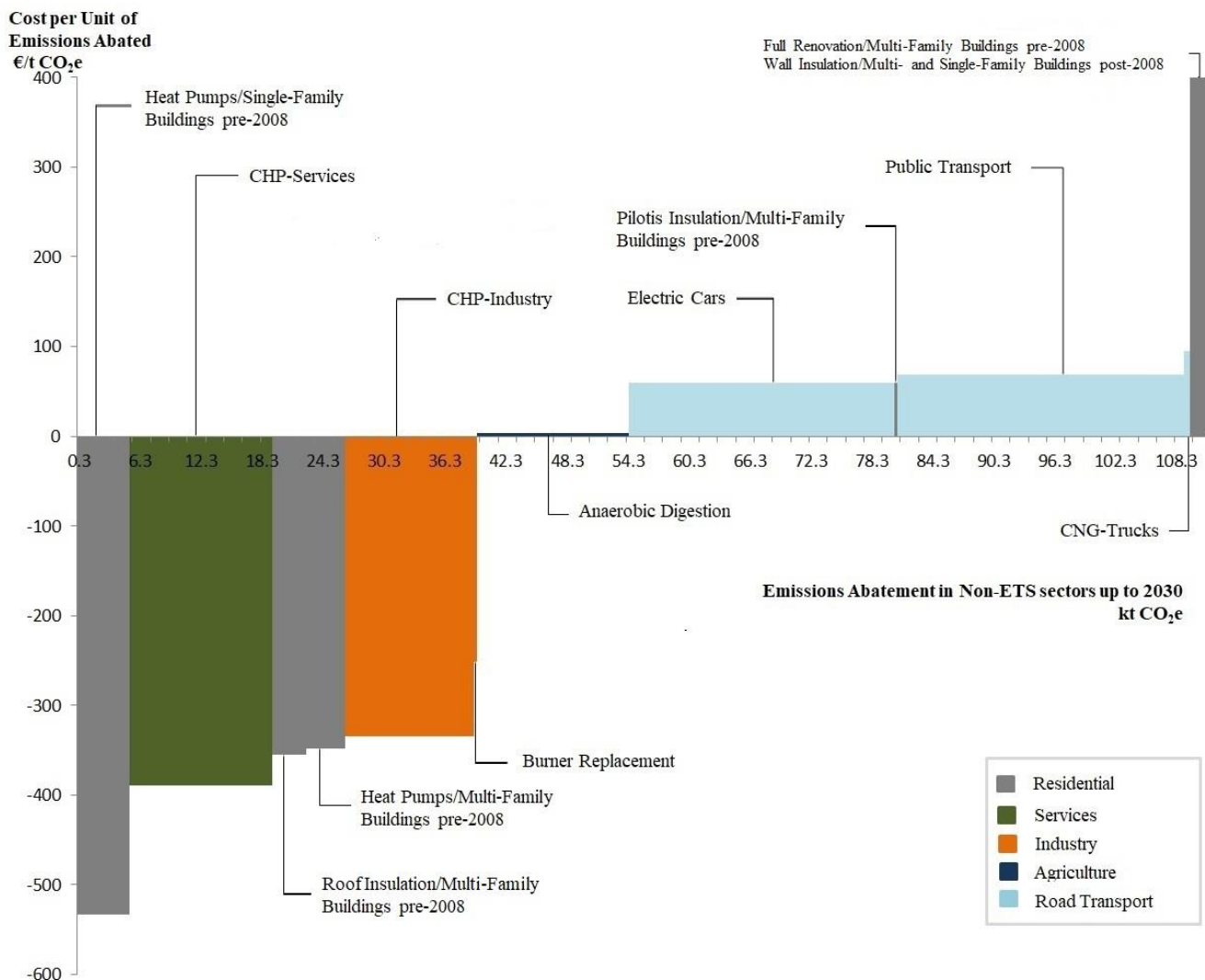
- the installation of heat pumps in pre-2008 residential buildings;
- cogeneration in the industrial and tertiary sector;
- roof insulation in pre-2008 residential multi-family buildings;
- the increased use of anaerobic digestion for animal waste;
- the replacement of burners in industry.

In terms of emission abatement potential, heat pumps, industrial and commercial cogeneration, animal waste exploitation, and promotion of electric cars and public transport seem to be the most promising measures.

It is also evident from Figure 1 that implementation of all these measures is expected to yield net social benefits because the measures with negative costs outweigh those with positive costs: the size of the shaded area beneath the horizontal axis is greater than the size of the area of measures above the axis. The issue of MACs with negative costs has been widely discussed in the literature. Obviously, MAC calculations may largely ignore adjustment costs, behavioural aspects, transaction costs or other market failures. Still, since our appraisal views the cost-effectiveness of measures from a societal (public policy) perspective, these results send two clear policy messages:

- First, a large number of the GHG emission mitigation measures considered here can yield net benefits to society and therefore have to be adopted; even if some costs of market failures are underestimated, the net benefits are so large that they almost certainly outweigh actual costs.
- Second, because of the large potential social benefits, authorities can accelerate progress towards decarbonization of the economy by removing financial and regulatory barriers that hinder the full implementation of these measures – and thus can help alleviate market failures and increase net societal gains.

**Figure 1: Marginal GHG emissions abatement cost curve for Cyprus, taking into account the emissions abatement potential in non-ETS sectors.**



Note: Each measure is coloured according to the economic sector to which it belongs, as shown in the legend of the graph.

It should be reminded that the measures examined here are meant to be *additional* to the measures already implemented by national authorities. In other words, it should not be expected that the measures of Figure 1 alone will meet the national commitments of EU energy and climate policy up to 2030. However, observing the horizontal axis of Figure 1, it turns out that even if all these additional measures are adopted up to 2030, they are projected to yield GHG emission savings of 108 Gg of CO<sub>2</sub>-equivalent, which amount to merely 2.1% of the 2005 GHG emissions of non-ETS sectors. As explained in more detail by Zachariadis et al. (2018a), if they are counted together with the already adopted policies and measures of the government of Cyprus, they are insufficient for meeting the 24% non-ETS emission

reduction commitments of Cyprus up to 2030. Although this is a country-specific result, it is relevant for non-ETS emission reduction pledges of several other EU Member states as well.

## 4.2. Sensitivity analyses

### *4.2.1. Composite effect of mitigation measures in both non-ETS and ETS sectors*

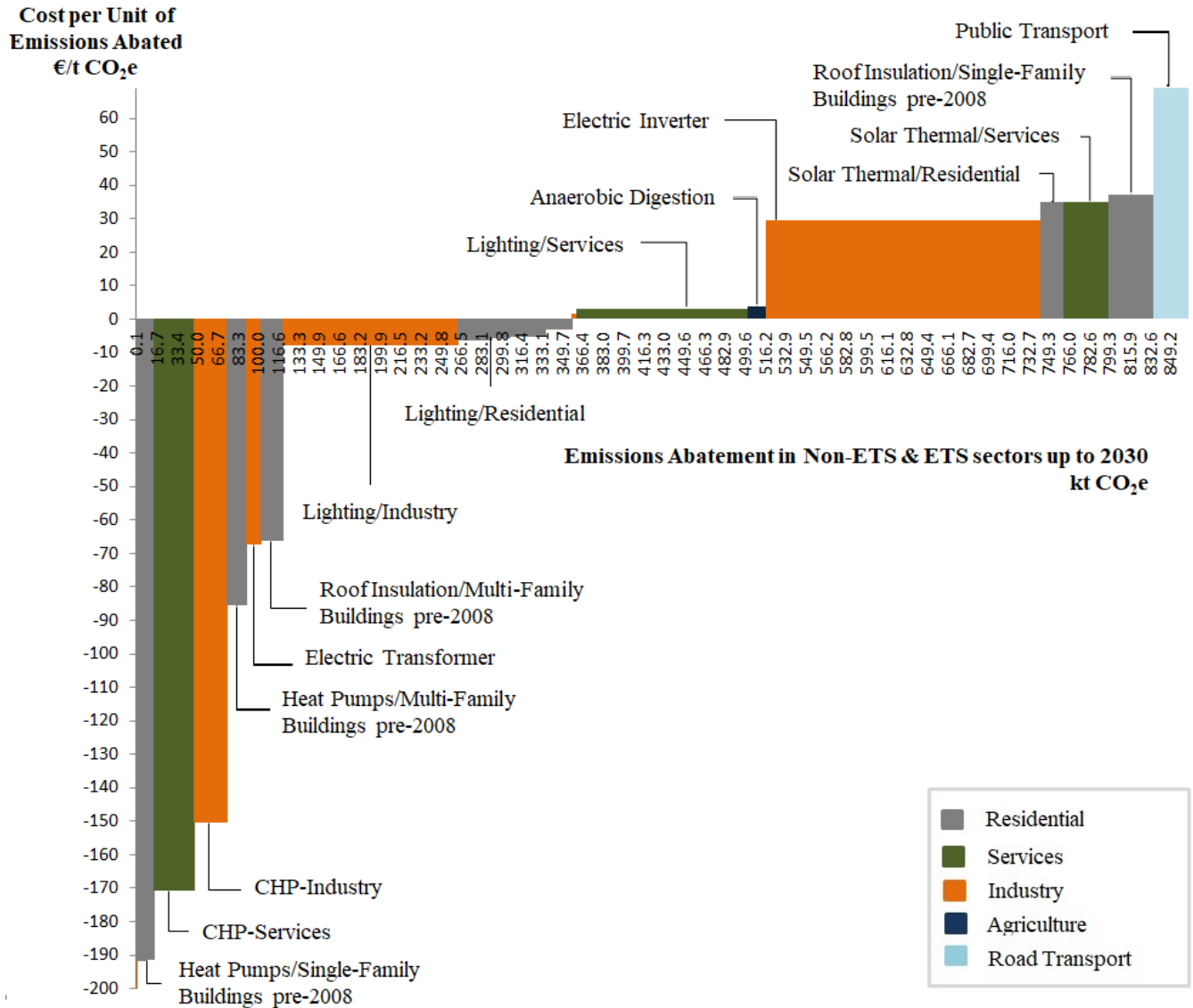
As mentioned above, Figure 1 presented all measures in non-ETS sectors of the Cypriot economy which reduce direct GHG emissions. However, some of these measures affect emissions of ETS sectors as well. For example, insulation of pre-2008 buildings reduces the amount of fuel used for heating (direct emissions) but also the electricity needed for cooling in summer time (indirect emissions of the power generation sector); and the promotion of electric cars reduces fuel consumption of conventional vehicles but increases electricity generation (and thus emissions of power plants). Moreover, there are important GHG abatement measures which involve reduction in electricity use and thus affect ETS emissions only. Therefore, an alternative cost-effectiveness calculation would include all changes in GHG emissions from all relevant measures, irrespective of whether emission reductions are direct or indirect; this offers a more holistic view of the GHG emission reduction potential and the resulting cost-effectiveness of individual abatement measures.

Figure 2 presents the results of these calculations. To facilitate presentation, the graph shows only measures that can achieve abatement up to a cost of 70 Euros per tonne CO<sub>2</sub>-equivalent. Because a larger number of measures is considered in this case, total emission abatement amounts to almost 850 Gg of CO<sub>2</sub>-equivalent – more than seven times higher than in the baseline case; and if measures of even higher cost – not shown in Figure 3 – are taken into account, total abatement exceeds 1000 Gg of CO<sub>2</sub>-equivalent. The ranking of measures according to their cost-effectiveness changes, depending on the kind of measure considered. Measures involving a new technology that consumes electricity, such as installation of heat pumps or promotion of electric cars, become less cost-effective because the emissions of the new technology are higher if indirect emissions from fossil-fuelled power generation is accounted for. Moreover, new measures occur, involving electric technologies, some of which have a favourable cost-effectiveness index, e.g. replacement of electric transformers in industry as well as replacement of lighting equipment both in industry and in the building sector.

One can derive two policy implications from this sensitivity analysis: that cost-effectiveness of specific non-ETS GHG emission abatement measures may be overestimated if the side-effects of these measures to ETS emissions are ignored; and that several ETS-related policies may be economically more favourable than non-ETS measures – which has to be taken

seriously by governments when designing cost-optimal GHG abatement if trading between non-ETS and ETS emissions is possible.

**Figure 2: Marginal GHG emissions abatement cost curve for Cyprus, taking into account mitigation measures for both non-ETS and ETS sectors**



#### 4.2.2. Inclusion of GHG and air pollution costs

As a rule, measures intended to reduce GHG emissions also affect the emissions of air pollutants and thereby have an impact on human health, agricultural production, ecosystems and the built environment. Although many of these measures lead to improved air quality, it is necessary to assess the effects case by case because the size and sign of these impacts is

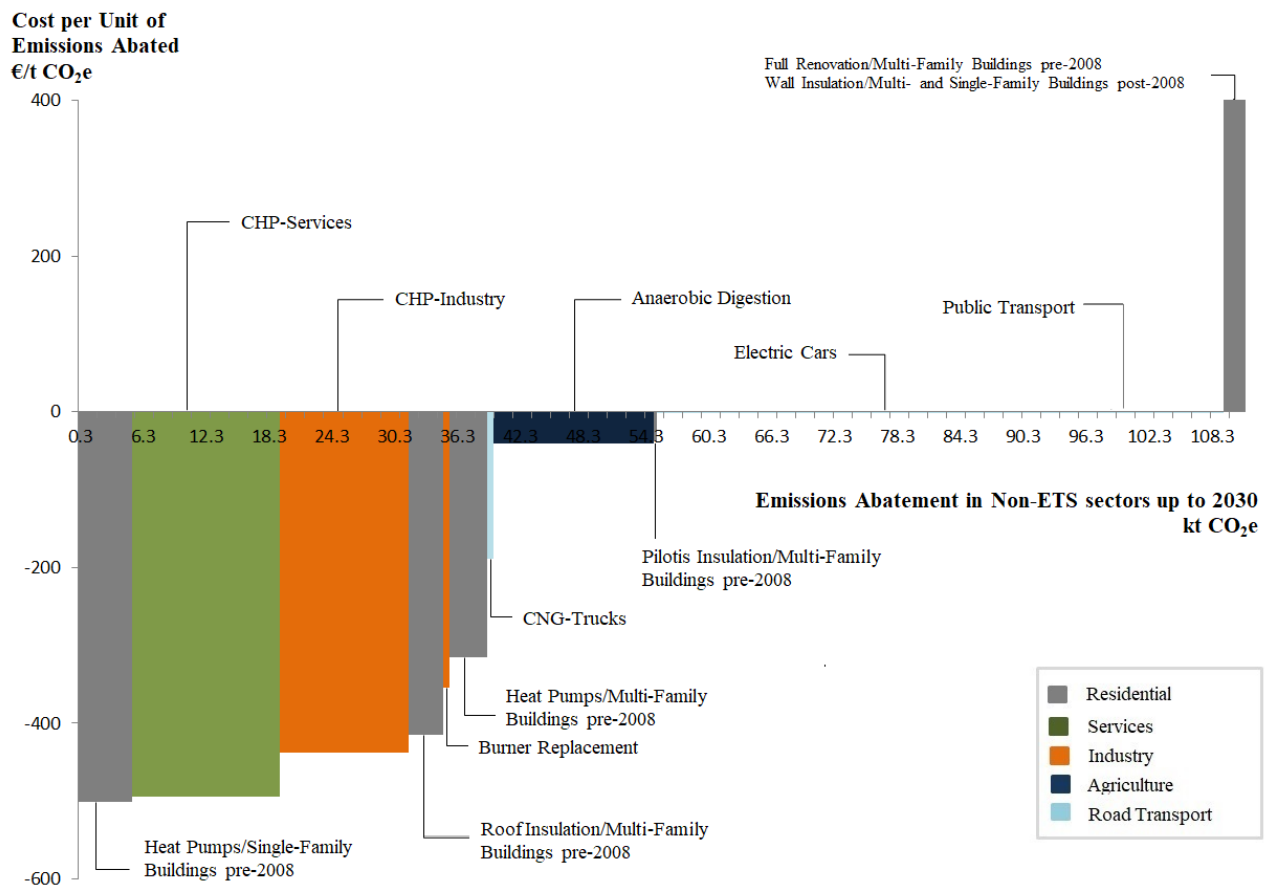
not known in advance, and there are measures (such as electrification of transport) which may improve or deteriorate air quality depending on specific conditions.

Therefore, a useful sensitivity analysis of the effect of GHG mitigation measures is to include external costs in such an assessment; these are the damage costs incurred by additional emissions of pollutants or greenhouse gases due to the introduction of a mitigation measure, minus the damage costs avoided because of reduced emissions thanks to these measures. Our alternative cost-effectiveness assessment includes the external costs of GHG, nitrogen oxide (NO<sub>x</sub>) and sulphur dioxide (SO<sub>2</sub>) emissions. For such a calculation it is necessary to estimate the emissions generated and avoided from a specific mitigation measure and multiply the amount of emissions by the marginal damage cost, which is expressed in Euros per tonne of each gas. Emission calculations for air pollutants were based on the internationally accepted methodology recommended in the EMEP/EEA Emissions Inventory Guidebook (EEA 2013) with the aid of national data on fuel quality and power generation emissions; details on this estimation are provided by Zachariadis et al. (2018a). Marginal damage costs for the case of Cyprus have been estimated by Zachariadis and Hadjikyriakou (2016).

Figure 3 displays the resulting MAC curve. In general, measures become economically more favourable if the additional side-benefits of reduction in air pollutant emissions are considered. It is particularly noteworthy that road transport related measures, i.e. the promotion of electric cars and public transport as well as the replacement of diesel fuelled trucks with CNG-powered ones, are assessed to have zero or negative net social costs, whereas they were more costly in the baseline calculations of Figure 1. Similarly, anaerobic digestion, which displayed slightly positive net costs in Figure 1, becomes socially beneficial if one accounts for the cost of avoided emissions because of the electricity production of power plants avoided thanks to the more intensive operation of biogas plants fuelled from anaerobic digesters.

It has to be noted that some mitigation measures have substantial additional side-benefits, which have not been quantified here – for example, promotion of public transport leads to reduced costs of congestion and accidents; electrification of cars reduces urban noise levels; and energy conservation measures reduce a nation's import dependency. Accounting for such avoided damages would make road transport related measures even more cost-effective.

**Figure 3: Marginal non-ETS GHG emissions abatement cost curve for Cyprus, taking into account the external damage costs from emissions of CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>2</sub>**



#### 4.2.3. Economic or financial assessment?

The approach presented so far has been based on a social planner's perspective, trying to derive results that are relevant for public policy makers. These are also called economic assessments, as opposed to financial assessments which provide insights into the decisions of a private firm or a household (IEA, 2008). To gain a better understanding of the difference between the two approaches in our case, we have repeated the cost-effectiveness calculations from a private perspective. This means essentially changing two important aspects of the calculations:

- Using retail energy prices in the calculations, i.e. prices which include all duties, excise taxes and Value Added Tax where applicable. The public policy approach applied in this paper so far included only the costs of fuel imports since these are actual costs for the

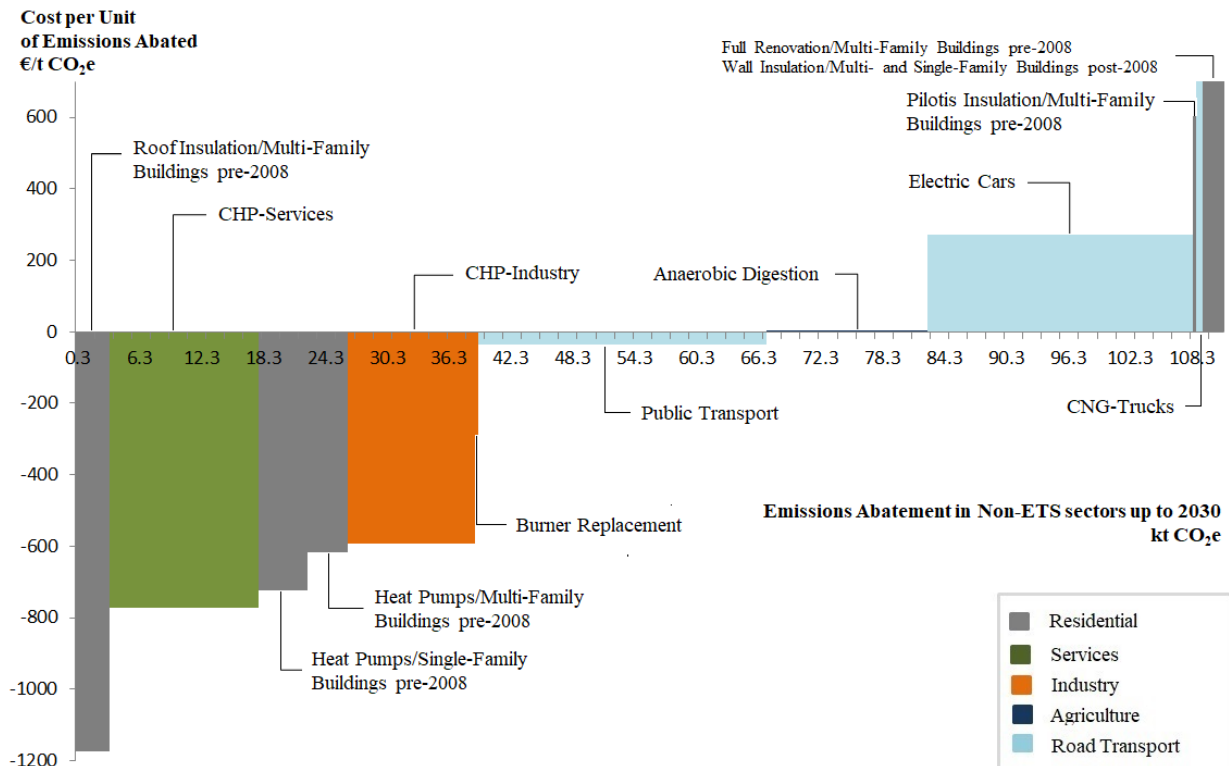
national economy, and duties and taxes are just monetary transfers within the economy and hence not of interest to the economic assessment. Using the financial approach considerably changes fuel costs since duties and taxes account for about half of the retail prices of fossil fuels, and fuel costs represent only about a quarter of the retail electricity price.

- Using discount rates which reflect the investment decisions of private economic actors (households or firms). Instead of the flat real social discount rate of 4% used up to now in this paper, in this sensitivity case we applied sector-specific discount rates which are similar to those used by the European Commission in its long-term energy and climate modelling assessments (European Commission, 2016; pp. 112-113). These discount rates are 9% for industry, 9.5% for freight transport, 14% for households and 11% for all other sectors (in real terms).

Results of the financial appraisal are illustrated in Figure 4. Although most of the measures involve upfront investment costs and gradual savings over the lifetime of the investment, and a higher discount rate increases the present value of costs in such cases, still the most decisive parameter is the use of retail energy prices in the assessment. As a result, measures that save large quantities of electricity over their lifetime have a lower net cost per tonne of GHG abated than with the economic calculations shown in Figure 1. Such measures are roof insulation and installation of heat pumps in buildings, and cogeneration in the industrial and tertiary sectors. Conversely, where future cost savings are relatively less important than the high upfront cost, or where the measure involves replacing a fossil fuel with electricity that has a high retail price, such measures become less attractive compared to Figure 1; this is the case e.g. with the full building renovation and the promotion of CNG powered trucks (in the former case) and the promotion of electric cars (in the latter case).

Comparing the results of this case with baseline results, a reasonable conclusion for policy makers could be that those measures exhibiting a negative net social cost and having an even more negative private cost (such as several types of energy renovations in buildings), are mitigation options which are socially beneficial and may need some relatively simple financial or behavioural incentives, or targeted regulation, in order to be adopted by private economic actors. On the other hand, measures which appear to be more costly from a private perspective than for society would need a clear economic incentive in order to be adopted by households or firms; examples of this type of measures are electric cars and replacement of conventional trucks with CNG fuelled ones. At the same time, keeping in mind the air pollution benefits that were included in Figure 3, such strong economic incentives may be welfare-improving and should therefore be pursued by governments.

**Figure 4: Marginal non-ETS GHG emissions abatement cost curve for Cyprus under a financial appraisal approach**



## 5. Conclusions and Policy Implications

This paper has presented an approach to construct bottom-up “measure-explicit” marginal abatement cost curves for economy-wide measures to reduce GHG emissions in the EU Member State of Cyprus, with a focus on those emissions that are not subject to the EU Emissions Trading System. We have provided a generic methodological approach and have used appropriate national data on the costs and effectiveness of all realistic measures. If similarly appropriate data are collected and used for interventions in any other specific country or region, our methodology can be used to assess the most cost-effective GHG emission abatement options in that region too.

Our analysis leads to some clear conclusions about the appropriate GHG emission mitigation policies and measures to be pursued by the government of Cyprus in the coming years. The major building blocks of an appropriate national climate strategy, with emphasis on emissions abatement for non-ETS sectors of the economy, are the following:

- In road transport, which contributes about half of all non-ETS emissions in the country, emphasis should be given to measures that will promote the penetration of low-carbon

vehicle technologies such as fully electric cars and CNG-powered trucks; and the reduction in the use of motor vehicles through the promotion of public transport.

- In the field of waste management, the main measure should be the more intensive use of anaerobic digestion in existing biogas plants.
- In the buildings sector, major interventions should include replacing old heating installations with modern highly efficient heat pump systems, and promoting cogeneration in buildings of the tertiary sector like hospitals and hotels.
- Measures in the Cypriot industry should focus on the installation of modern highly efficient LPG-fuelled burners and the promotion of industrial cogeneration.

As illustrated in Figures 1 to 4 of this paper, many of the above mentioned policies are expected to yield net benefits to society from an economic viewpoint; these benefits become even more pronounced if side-benefits of these measures (such as reduction in air pollutant emissions and improvements in traffic congestion and energy import dependency) are taken into account. In order to reap these environmental and economic benefits, the government of Cyprus has to remove financial and regulatory barriers that hinder progress towards decarbonization. At the same time, targeted and potentially strong economic incentives may be warranted when measures a) appear to more costly from a private than from a public perspective and b) have substantial side benefits such improved air quality this is the case in measures directed to road transport.

Obviously the methodological problems associated with MAC curves, as identified in the literature, are valid and require careful attention. Some of these issues can be addressed through proper sensitivity analyses such as the ones presented in this paper – addressing the interaction between non-ETS and ETS sectors; accounting for side-benefits of mitigation measures; and observing cost-effectiveness from both a public and a private perspective.

Other issues related to MAC curves are of a methodological nature. With the aid of the rich database that we have compiled including costs and abatement potential for a large number of economy-wide emission mitigation measures, it is possible to address some of these methodological problems. For example, it is important to keep in mind that the measures up to 2030 are just one step towards the EU long term objective of reducing GHG emissions by 80-95% in 2050. The choice of abatement measures may change if a policy-maker has the long-term target in mind. Our data enable the development of an intertemporal optimization model in order to find the optimal mix and optimal timing of measures that can meet a decarbonization for year 2050 at least cost. Moreover, the optimal timing also depends on the speed of implementation of measures – something that we can address with the aid of expert

knowledge from the local market of Cyprus. This can be a fruitful, practical and policy-relevant extension of the model developed by Vogt-Schilb and Hallegatte (2014) for two theoretical mitigation measures. Moreover, collection of real-world data on the costs and potential of measures to abate air pollutants such as NO<sub>x</sub>, SO<sub>2</sub> and particulate matter can lead to the creation of a multi-criteria optimization model that can advise policymakers for a policy mix to simultaneously mitigate GHG and air pollutant emissions; this can address concerns that MAC curves neglect the side-effects of climate policy to air pollution policy.

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## Appendix

### Detailed Methodology to Assess the Cost-Effectiveness of Emission Mitigation Measures

#### A1. Outline of the Methodology

Within the broader policy context of reducing emissions of greenhouse gases (GHG), there is a set of mitigation measures described by a) their emissions abatement cost and b) emissions abatement potential. This information can reveal the cost-effectiveness of each option and can be illustrated in a MAC curve. The following paragraphs describe the methodology to assess this cost-effectiveness and derive the MAC curve, in line with standard approaches applied in the literature – e.g. Timilsina et al. (2017).

GHG emissions are calculated before and after the implementation of a mitigation measure, and this emission abatement is associated to the costs of the measure in comparison with the reference technology or device or process. For each measure, the cost per unit of emissions abated can be calculated with the following formula:

$$CPA(i) = \frac{c_i^m - c_i^{ref}}{E_i^{ref} - E_i^m}$$

where  $c$  and  $E$  denote total discounted costs and emissions, respectively, and the superscripts  $m$  and  $ref$  refer to mitigation and reference scenario.  $CPA$  is expressed in constant Euros per tonne of CO<sub>2</sub> equivalent abated.

#### Abatement cost

There are  $N$  abatement options, indexed by  $i$ . Those measures are assumed to be implemented around the year 2020. As technology options, cost and abatement potential may change over the course of the decade 2020-2030, it may be advisable to recalculate the marginal abatement cost curve for the middle of next decade and determine the cost-effective mix of post-2025 policies with the aid of the 2025 calculations. However, this recalculation was not conducted in the study because there are no strong indications for a substantial differentiation in the relative cost of the various policies considered in our analysis.

The total cost for a measure  $i$ , discounted at rate  $r$  over its lifetime, can be expressed as follows:

$$C_i = \sum_{t=0}^T \frac{IC_{it}}{(1+r)^t} + \frac{O\&MC_{it}}{(1+r)^t} + \frac{FC_{it}}{(1+r)^t}$$

where  $IC$  refers to investment cost,  $O\&MC$  refers to operating and maintenance costs for each year and  $FC$  denotes the annual fuel costs;  $t$  refers to time in years and the summations run from  $t = 0$  to  $t = T$ .  $T$  denotes a period (in years) that could be considered as the maximum lifetime of any possible abatement measure in a given economic sector (e.g.  $T = 30$ ).

The discount rate, which expresses the rate at which society discounts future monetary values, is used to compare the costs and benefits that occur in different time periods, by determining the present value of future cash flows. Thus, it is an essential component of any present value or future value calculation. As the study is conducted from a public policy perspective, a social discount rate of 4% was used, in line with recommendations from the literature (Kesicki and Strachan, 2011; Steinbach and Staniaszek, 2015) and according to guidance provided to the government of Cyprus by the World Bank (2016).

The time horizon  $T$  that we consider is the 30-year period 2021-2050. Some mitigation options (e.g. change in lighting) may have a shorter economic lifetime and therefore may be installed more than once during period  $T$ . As a result, the annual investment cost  $IC$  is calculated with the aid of the following formula:

$$IC_{it} = INV_i \cdot r \cdot \frac{(1+r)^n}{(1+r)^n - 1}$$

where  $INV$  is the up-front investment cost of the mitigation option  $i$ , and  $n$  is its economic lifetime. Note that  $INV$  may decline over the years because of technological progress, so that a replacement of equipment after  $n$  years may be effected with new equipment having a lower  $INV$ . However, in the absence of reliable estimates, such a change in future investment cost over the years was not assumed in this study.

It is also possible to include external costs in such an assessment; these are the damage costs incurred by additional emissions of pollutants or greenhouse gases due to the introduction of a mitigation measure, minus the damage costs avoided because of reduced emissions thanks to these measures. In this study we have conducted an alternative cost-effectiveness assessment – presented in Section 10 – that includes the external costs of CO<sub>2</sub>, nitrogen oxide (NO<sub>x</sub>) and sulphur dioxide (SO<sub>2</sub>) emissions. For such a calculation it is necessary to estimate the emissions generated and avoided from a specific mitigation measure and multiply the amount of emissions by the marginal damage cost, which is expressed in Europe per tonne of each gas. More information about the data used is provided in Annex II of this report.

## GHG emissions

Commitments to reduce GHG emissions require emissions abatement achieved in each activity  $i$ . In general, emissions generated through the use of a specific technology/fuel can be calculated as follows:

$$E = A \cdot EF_{GHG} = A \cdot (EF_{CO_2} + 25 EF_{CH_4} + 298 EF_{N_2O})$$

where  $A$  refers to the relevant activity rate and  $EF$  denote the emission factors of the three main greenhouse gases carbon dioxide, methane and nitrous oxide; the two latter are multiplied by their Global Warming Potential<sup>2</sup> in order to be expressed in CO<sub>2</sub>-equivalent terms.

If  $a_i$  is the GHG emissions abatement achievable with each measure  $i$  over a year, then:

$$a_i = \Delta E_i = E_i^{ref} - E_i^m = A^{ref} \cdot EF_{GHG}^{ref} - A^m \cdot EF_{GHG}^m$$

This abatement can be attained through a reduction in activity ( $\Delta A$ ) and/or a reduction in the emission factor ( $\Delta EF$ ) due to the use of a lower-carbon technology or fuel:

$$\Delta E_i = \Delta A \cdot EF_{GHG} + A \cdot \Delta EF_{GHG}$$

where  $EF_{GHG}$  is the GHG emission factor of the process or fuel which is related to the measure  $i$ , and  $\Delta A$  is the change in the activity rate achieved through the implementation of measure  $i$ . Technological solutions (e.g. investment in renewable energy technologies or energy efficiency measures) will change the second part of the right hand of the above equation, leaving the first part (i.e. activity rates) unchanged. Some emission factors are sector- and process-specific, therefore they are separately presented by sector in each one of the sections below.

## **A2. Household and Tertiary Sector**

As shown in Section 4, there is a number of emission mitigation options that can be applied in buildings. The implementation of these measures can incur different costs and cause different emissions abatement levels according to building type and construction period.

The total cost for a measure  $i$ , discounted at rate  $r$  over the period can be expressed as follows:

$$C_i = \sum_{t=0}^T \frac{IC_{it}}{(1+r)^t} + \frac{O\&MC_{it}}{(1+r)^t} + \frac{FC_{it}}{(1+r)^t}$$

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<sup>2</sup> We use GWP<sub>100</sub> values for methane and nitrous oxide without climate carbon feedback, according to the IPCC 4<sup>th</sup> Assessment Report and in line with guidance provided to environmental authorities.

where

$IC$	Annualised Investment Cost [€/y]
$O\&MC$	Annual Operational and Maintenance Cost [€/y]
$FC$	Annual Fuel Cost [€/y]
$r$	Discount Rate

The symbol  $t$  refers to time in years and the summations run from  $t = 0$  to  $t = T$ .

The annual fuel cost  $FC$  can be calculated with the following formula:

$$FC = ED \cdot P_f$$

where

$ED$	Annual Energy Demand [toe/y]
$P_f$	Fuel Price [€/toe]

Therefore, the change in fuel cost between reference and mitigation scenario can be expressed as:

$$\begin{aligned}\Delta FC &= FC^{ref} - FC^m \\ \Delta FC &= ED^{ref} \cdot P_f^{ref} - ED^m \cdot P_f^m \\ \Delta FC &= \Delta ED \cdot P_f + ED \cdot \Delta P_f\end{aligned}$$

In other words, fuel cost savings may be the composite result of a) a reduction in energy demand, even if the same fuel continues to be used, and/or b) a change in the fuel price, if fuel substitution occurs.

To compute the emissions abatement for each measure  $i$ , emissions of GHG are calculated by multiplying energy demand by the corresponding emission factor. The energy demand corresponds to the appropriate activity data described in the previous section and is measured in kWh/y.

Emissions can be also estimated as the product of fuel consumption (on a mass or volume basis, i.e. in tn/y or m<sup>3</sup>/y) and an emission factor expressed in an appropriate unit (e.g. tn CO<sub>2</sub>-equivalent per tn of fuel).

The following equation is used to estimate the emissions abatement  $a_i$ , which is the change in emissions between the reference and mitigation scenarios.

$$a_i = \Delta E_i = E_i^{ref} - E_i^m$$

$$\Delta E_i = ED^{ref} \cdot EF_{GHG}^{ref} - ED^m \cdot EF_{GHG}^m$$

$$\Delta E_i = \Delta ED \cdot EF_{GHG} + ED \cdot \Delta EF_{GHG}$$

where

$ED$  Energy Demand [kWh]

$EF_{GHG}$  GHG Emission Factor by fuel or technology type [kg CO<sub>2</sub>-eq. / kWh]

As already explained in the previous section, the above relationship shows that emissions abatement can be attained through a reduction in final energy demand ( $\Delta ED$ ), keeping the fuel used the same as before, through a reduction in the emission factor ( $\Delta EF$ ) due to the use of a lower-carbon technology or fuel, or through a combination of both effects, i.e. final energy savings plus fuel substitution. In light of the findings of the energy efficiency study of Vougiouklakis et al. (2017), emissions abatement in buildings will be primarily due to energy savings that can be attained by the different measures listed earlier in this Section, and only to a limited extent by fuel substitution.

### A3. Road Transport

#### GHG emissions

Emissions from road transport can be estimated based on two independent sets of data: vehicle kilometres (distance travelled by the vehicle) and fuel sold (amount and type of fuel consumed). In general, the GHG emissions from this sector can be calculated as follows:

$$E = A \cdot EF_{GHG}$$

where the total emissions from road transport  $E$  are estimated as a function of the emission factor  $EF$  as mass per unit of activity rate  $A$  (e.g. fuel consumed or distance travelled).

The equation of estimating the emission from road transport on the basis of the type and amount of fuel consumed can be expressed as:

$$E = FS \cdot EF_{GHG}$$

where  $FS$  denotes fuel sold (fuel consumed) in a given time period, and  $EF$  is the composite emission factor of the three main greenhouse gases carbon dioxide, methane and nitrous oxide for the specific fuel.

If the activity parameter is distance travelled, then emissions are calculated as follows:

$$E = D \cdot EF_{GHG}$$

where  $D$  refers to the kilometres travelled in a given time period.

The above expressions have to be calculated separately for each fuel (primarily petrol and diesel) and each type of vehicle considered (e.g. passenger cars, buses, light and heavy duty trucks). Table 7 provides details on the underlying figures used for this analysis.

### 1. More stringent CO<sub>2</sub>-based vehicle taxation

Emission reduction  $a$ , can be calculated as follows:

$$a = \Delta E = \sum_f \left( NEWVKT_f \cdot \left( EF_{GHG,f}^{ref} - EF_{GHG,f}^m \right) \right)$$

where

$NEWVKT$  Vehicle Distance Travelled by newly registered cars in a given year using fuel  $f$  [km]

$EF_{GHG}$  Composite GHG Emission Factor [g CO<sub>2</sub>-eq/km]

To estimate  $NEWVKT$ , it is assumed that a) annual new registrations of cars will be similar to those of recent years, and b) the share of petrol and diesel powered cars in new registrations will also remain at the same level with that of the last years (about 50% for petrol and 50% for diesel cars).

As regards the change in emission levels induced by the new tax system, it would be reasonable to assume that making the system more stringent can reduce new car CO<sub>2</sub> emission levels by 10 g/km compared to what they will be without a tax change. This assumption is based on evidence provided by the Transport Ministry of Cyprus in an interim evaluation of the current tax system, which was introduced by the end of year 2013. This report is available in Greek and has been provided to the study team, but has not been openly published.

### 2. Infrastructure Investments for a) public transport and b) walking and cycling

#### *a) Public Transport*

Cyprus has a very low share of public transport in passenger mobility (around 2%), hence increasing the modal share of buses seems to be a meaningful and necessary policy option. This mitigation measure is accompanied by the related investment cost, operation and maintenance cost and fuel cost of new buses, to be accompanied by large energy and emission savings due to the lower use of private cars. The total discounted cost  $C$  of the measure is calculated with the aim of the following formula:

$$C = \sum_{t=0}^T \frac{IC_t}{(1+r)^t} + \frac{O\&MC_t}{(1+r)^t} + \frac{FC_t}{(1+r)^t}$$

where

*IC* Annualised Investment Cost [€/y]

*O&MC* Annual Operational and Maintenance Cost [€/y]

*FC* Annual Fuel Cost [€/y]

*r* Discount Rate

Index *t* refers to time in years.

With appropriate incentives for public transport, it is assumed that there will be a shift of a certain amount of passenger kilometres ( $\Delta PKT$ ) from private cars to buses. Based on the occupancy rates of each mode ( $OR_{car}$  and  $OR_{bus}$  respectively), there will be a reduction in the distance travelled with private cars ( $\Delta VKT_{car}$ ) and a rise in the distance travelled with buses ( $\Delta VKT_{bus}$ ):

$$\Delta VKT_{car} = \Delta PKT / OR_{car}$$

$$\Delta VKT_{bus} = \Delta PKT / OR_{bus}$$

where it is assumed, based on international and local experience, that  $OR_{car} = 1.5$  passengers/vehicle and  $OR_{bus} = 15$  passengers/vehicle.

The fuel cost *FC* has two components: extra fuel costs because of the additional operation of buses, minus the avoided fuel costs of cars due to the reduction in their use. The former is a function of the distance (vehicle kilometres) that public transport modes will travel ( $VKT_{bus}$ ) and the price of the given fuel  $P_f$ , in this case automotive diesel. Public modes' fuel costs can be calculated with the aid of the following formula:

$$\Delta FC^{bus} = \Delta FS^{bus} \cdot P_{diesel}$$

where

$\Delta FS$  Change in the amount of fuel sold / consumed by buses

$P_{diesel}$  Fuel Price

The fuel consumed is related to the additional bus kilometres travelled based on the following formula:

$$\Delta FS^{bus} = \Delta VKT_{bus} \cdot AFC_{diesel}$$

where

$AFC$  Average Fuel Consumption of buses [l/km]

Correspondingly, the fuel cost that will be avoided due to lower use of private cars is:

$$\Delta FC^{avoided} = \sum_f (\Delta FS_f^{avoided} \cdot P_f)$$

where

$\Delta FS$  Change in the amount of fuel sold / consumed

$P$  Fuel Price

The avoided fuel consumption is linked to the reduction of vehicle kilometres of cars as follows:

$$\Delta FS_f^{avoided} = \sum_f (\Delta VKT_{car,f} \cdot AFC_f)$$

where

$\Delta VKT$  Vehicle Kilometres avoided by cars using fuel  $f$  [km]

$AFC$  Average Fuel Consumption of cars using fuel  $f$  [l/km]

As a result, the difference in fuel costs due to the additional penetration of public transport modes can be calculated with the following formula:

$$\Delta FC = \Delta FC^{bus} - \Delta FC^{avoided} = \Delta FS^{bus} \cdot P_{diesel} - \sum_f (\Delta FS_f^{avoided} \cdot P_f)$$

The associated emission reduction  $a$ , due to the enhanced public transport system, can be calculated as follows:

$$a = \Delta E = \sum_f (\Delta FS_f^{avoided} \cdot EF_{GHG,f}^{avoided}) - \Delta FS^{bus} \cdot EF_{GHG,diesel}^{bus}$$

where  $EF_{GHG}$  is the relevant composite GHG emission factor.

#### b) Walking and Cycling Infrastructure

Improving the infrastructure for walking and cycling is associated with an investment cost  $IC$  and operational and maintenance cost  $O\&MC$ . The total discounted cost  $C$  is:

$$C = \sum_{t=T_0}^T \frac{IC_t}{(1+r)^t} + \frac{O\&MC_t}{(1+r)^t}$$

The avoided fuel cost, because of the increased share of walking and cycling that will reduce the use of private cars, is calculated with the aid of the following formulas:

$$\Delta FC^{avoided} = \sum_f \Delta FS_f^{avoided} \cdot P_f$$

and

$$\Delta FS_f^{avoided} = \sum_f \Delta VKT_{car,f} \cdot AFC_f$$

where

$\Delta FS$	Change in the amount of fuel sold / consumed
$P_f$	Fuel Price
$\Delta VKT$	Vehicle Kilometres avoided by cars using fuel $f$ [km]
$AFC$	Average Fuel Consumption of cars using fuel $f$ [l/km]

This reduction in fuel consumption can result in emission mitigation equal to:

$$a = \Delta E = \sum_f (\Delta FS_f^{avoided} \cdot EF_{GHG,f}^{avoided})$$

where  $EF_{GHG}$  is the associated composite GHG emission factor.

Because of large uncertainties about the amount of investments that are realistic and the quantitative impact of such measures on passenger mobility, the effect of walking and cycling infrastructure was not further examined in this study.

### 3. Use of alternative fuels for cars and/or trucks

For this measure it is assumed that, as a result of subsidies or a regulatory obligation, a fraction of new cars sold each year use a low-carbon or zero-carbon powertrain. This entails a change in all costs; alternative fuelled vehicles are generally more costly to purchase but may have lower maintenance and fuel costs. Using alternative fuels is assumed not to affect total passenger mobility (i.e. passenger kilometres of private cars), but only the average emission factor of new cars, and hence also the average emission factor of all cars in use.

In order to calculate the total discounted cost  $C$  of such a measure, one needs to calculate the change in each cost item. The change in investment and O&M costs will be

$$\Delta IC = NEW \cdot (IC_{alt} - IC_{conv})$$

$$\Delta O\&MC = NEW \cdot (O\&MC_{alt} - O\&MC_{conv})$$

where

*NEW* the number of newly registered vehicles per year that run on an alternative instead of a conventional fuel

*alt, conv* indices denoting alternative fuelled and conventional vehicles respectively.

The difference in fuel cost will be:

$$\Delta FC = FC^m - FC^{ref} = FS^m \cdot P_f^m - \sum_f FS_f^{ref} \cdot P_f^{ref}$$

where

*FS* Fuel Sold/Consumed

*P<sub>f</sub>* Fuel Price

Superscripts *ref* and *m* denote the reference and mitigation scenario, respectively. The fuel consumed can be calculated with the following general equation, with the distanced-based activity remaining the same for both scenarios.

$$FS_f = VKT \cdot AFC_f = NEW \cdot KMV \cdot AFC_f$$

where

*VKT* Vehicle Distance Travelled [km]

*KMV* Distance Travelled per Vehicle (km/vehicle)

*AFC* Average Fuel Consumption of vehicles running on fuel *f* [l/km]

The equation to evaluate the emissions abatement *a* is:

$$a = \Delta E = E^{ref} - E^m$$

Based on the general equation for calculating emissions from road transport based on distance travelled, the equation is formed as follows:

$$a = \Delta E = VKT \cdot (EF_{GHG}^{ref} - EF_{GHG}^m) = NEW \cdot KMV \cdot (EF_{GHG}^{ref} - EF_{GHG}^m)$$

where  $EF_{GHG}$  is the related composite GHG emission factor.

The reduction here is achieved through the difference in the emission factor  $\Delta EF_{GHG}$  due to the use of a lower-carbon fuel.

In the case of passenger cars, fuel switch is assumed to take place from conventional (petrol and diesel powered) cars to electric cars. In the case of trucks, fuel switch is assumed to occur from diesel powered to CNG-powered trucks.

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