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Doctoral Dissertation

Techno-Economic Analysis of Energy and Environmental Policies: Supporting the Formulation of a Cost-Effective Decarbonisation Strategy in Cyprus

Chryso Sotiriou

Limassol, April 2021

CYPRUS UNIVERSITY OF TECHNOLOGY

FACULTY OF GEOTECHNICAL SCIENCES AND ENVIRONMENTAL MANAGEMENT

DEPARTMENT OF CHEMICAL ENGINEERING

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Approval Form

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Abstract

In order to align its ambition with the global Paris Agreement on Climate Change, the European Union (EU) declared that it aims to achieve ‘climate neutrality’ by 2050, i.e., achieve zero net emissions of greenhouse gases into the atmosphere. Decarbonisation by the mid-21st century requires a strong commitment to emission abatement measures, but national emission reduction pledges are usually made for the medium term. At the same time, climate policy is changing fast in the EU and becoming increasingly ambitious. In this context, this doctoral thesis aims to expand existing and develop new methodologies for assessing policies to identify cost-effective climate change mitigation strategies that are beneficial to society and in line with the goal to achieve ‘climate neutrality’ by 2050, and thereby to provide meaningful and realistic support to policymakers. The research is mainly applied at a national level for the EU Member State of Cyprus, across those sectors of the economy that are not subject to the EU Emissions Trading System. Impacts on public finances and air pollution related side-benefits of decarbonisation are also examined. Beyond country-specific methods and data, working within the EU policy context allows the methods and policy recommendations of this work to be applied in any EU member state and in other countries of the world that are faced with similar decarbonisation challenges.

Keywords: *climate change mitigation; emissions abatement; policy insights; abatement cost curves; cost optimisation; multi-objective optimisation; climate neutrality*

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Equations

Abbreviations

AUGMECON	Augmented ε-constraint method
AUGMECON2	Improved version of AUGMECON
BEV	Battery Electric Vehicle
c.m.	Cubic Metres
CASES	Cost Assessment for Sustainable Energy Systems
CH_4	Methane
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
EAC	Electricity Authority of Cyprus
EDGAR	Emissions Database for Global Atmospheric Research
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
ESD	Effort Sharing Decision
ESR	Effort Sharing Regulation
ETS	Emission Trading System
EU	European Union
GAMS	General Algebraic Modelling System
GDP	Gross Domestic Product
GHG	Greenhouse Gases
IAM	Integrated Assessment Models
IEA	International Energy Agency
incl.	including: used to say that something includes an amount or item
IPCC	United Nations Intergovernmental Panel on Climate Change
LED	Light Emitting Diode
LP	Linear Programming
LPG	Liquefied Petroleum Gas
LUC	Land-Use Change
LULUCF	Land Use, Land-Use Change and Forestry
MAC	Marginal Abatement Cost

MARDE	Ministry of Agriculture, Rural Development and Environment
MECIT	Ministry of Energy, Commerce, Industry and Tourism
MF	Multi-Family
MOMP	Multi-Objective Mathematical Programming
N_2O	Nitrous Oxide
NEDC	New European Driving Cycle
NOx	Nitrogen Oxides
nZEB	Near-Zero Energy Building
OEB	Cyprus Employers and Industrialists Federation
PF	Pareto Front
PM	Particulate Matter
PS	Pareto Solution
RES	Renewable Energy Sources
SCOP	Seasonal Coefficient Performance (applies to heat pumps)
SEER	Seasonal Energy Efficiency Ratio (applies to heat pumps)
SF	Single-Family
SO_2	Sulphur Dioxide
SOO	Single-Objective Optimisation
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
VAT	Value Added Tax
w/	with: used to replace the word “with” in any context
w/o	without: used to replace the word “without” in any context
WEM	“With Existing Measures” Scenario
WLTP	Worldwide Harmonised Light Vehicle Test Procedure

Units/Prefixes

€	euros	**tn**	tonne	**l**	litre
°C	degree Celsius	**W**	watt	**m^3**	cubic metres
g	grams	**Wh**	watt-hour	**k**	kilo
km	kilometres	**y**	year	**M**	mega
pkm	passenger-kilometres	**J**	joule	**G**	giga

Glossary of Keywords and Phrases

Baseline/reference	The state against which change is measured. Typically, reference scenarios are compared to mitigation scenarios that are developed to reach climate change mitigation targets (Allwood et al., 2014).
Carbon Dioxide, CO_2	The principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1 (IPCC, 2013).
Carbon Dioxide equivalent, CO_2 equivalent	The amount of carbon dioxide emission that would cause the same integrated radiative forcing, over a given time horizon, as an emitted amount of a greenhouse gas or a mixture of greenhouse gases. The equivalent carbon dioxide emission is obtained by multiplying the emission of greenhouse gas by its Global Warming Potential for the given time horizon (IPCC, 2013). For this thesis's purpose, total emissions are the sum of carbon dioxide, nitrous dioxide and methane, expressed in CO_2 equivalent, assuming a 100-year global warming potential.
Carbon Tax	A levy on the carbon content of fossil fuels. Because virtually all of the carbon in fossil fuels is ultimately emitted as carbon dioxide (CO_2), a carbon tax is equivalent to an emission tax on CO_2 emissions (Allwood et al., 2014).
Climate Change	Change in the state of climate that can be identified by changes in the mean and/or the variability of its properties, which persists for an extended period, typically decades or longer (IPCC, 2013).
Co-Benefits	The positive effects that a policy or measure aimed at one objective might have on other objectives (IPCC, 2014). Co-benefits are also referred to as ancillary benefits.
Cost-Effectiveness	A policy is more cost-effective if it achieves a given policy goal at a lower cost (IPCC, 2014).

Decarbonisation	The process by which countries or other entities aim to achieve a low-carbon economy or by which individuals aim to reduce their carbon consumption (Allwood et al., 2014).
Direct Emissions	Emissions that physically arise from activities within well-defined boundaries (e.g., a region, an economic sector, a company, or a process) (Allwood et al., 2014).
Emission Factor	The emissions released per unit of activity (Allwood et al., 2014).
Emissions Trading	A market-based instrument used to limit emissions. The environmental objective or sum of total allowed emissions is expressed as an emissions cap. The cap is divided into tradable emission permits that are allocated — either by auctioning or handing out for free (grandfathering) — to entities within the jurisdiction of the trading scheme (Allwood et al., 2014).
Externality	Externalities arise from a human activity when agents responsible for the activity do not take full account of the activity's impacts on others' production and consumption possibilities, and no compensation exists for such impacts. When the impacts are negative, they are external costs. When the impacts are positive, they are external benefits (Allwood et al., 2014).
Global Warming Potential	An index, based on radiative properties of greenhouse gases, measuring the radiative forcing following a pulse emission of a unit mass of a given greenhouse gas in the present-day atmosphere integrated over a chosen time horizon relative to that of carbon dioxide (IPCC, 2013).
Greenhouse Gases	Gaseous constituents of the atmosphere, both natural and anthropogenic, absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, atmosphere itself, and clouds. This causes global warming and climatic change (IPCC, 2013).

Indirect Emissions	Emissions that are a consequence of the activities within well-defined boundaries (e.g. a region, an economic sector, a company, or a process) but occur outside the specified boundaries (Allwood et al., 2014).
Long-Term	Relating to a long period of time. In this thesis's context, the terms long-term objective refer to the climate targets set for the year 2050.
Marginal Abatement Cost	The cost of one unit of additional mitigation (Allwood et al., 2014)
Measures	In climate policy, measures are technologies, processes or practices that contribute to mitigation (Allwood et al., 2014).
Medium-Term	Relating to a short period of time. In this thesis's context, the terms medium-term objective refer to the climate targets set for the year 2030.
Methane, CH_4	Methane is one of the greenhouse gases to be mitigated under the Kyoto Protocol and is the major component of natural gas and associated with all hydrocarbon fuels, animal husbandry and agriculture (IPCC, 2013).
Mitigation Scenario	A plausible description of the future that describes the implementation of mitigation policies and measures and how that will affect the emissions level.
Mitigation	In the context of climate change, it is the reduction of the flow of heat-trapping greenhouse gases into the atmosphere, either by reducing sources of these gases or enhancing the “sinks” that accumulate and store these gases (Allwood et al., 2014).
Multi-Objective Mathematical Programming	Part of mathematical programming dealing with decision problems characterized by multiple and conflicting objective functions that are to be optimized (Collette and Siarry, 2003).

Nitrogen Oxides, NOx	Any of several oxides of nitrogen (Allwood et al., 2014).
Nitrous Oxide, N_2O	One of the greenhouse gases to be mitigated under the Kyoto Protocol. The main anthropogenic source is agriculture, but it also comes from sewage treatment, combustion of fossil fuel, and chemical industrial processes (IPCC, 2013).
Pareto Front	Set of solutions selected based on Pareto optimality (Collette and Siarry, 2003).
Particulate Matter, PM	Very small solid particles emitted during the combustion of biomass and fossil fuels (Allwood et al., 2014).
Rebound Effect	Increases in consumption due to environmental efficiency interventions that can occur through a price reduction or other behavioural responses.
Single-Objective Optimisation	The search for a minimum or a maximum (the optimum) of a function (Collette and Siarry, 2003).

Sources:

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Nomenclature

Marginal Abatement Cost Curve Method | Chapter 2

$CPA\ (j)$	Cost-effectiveness index, cost per unit of emissions abated of measure *j*
c_j^{mit}	Total discounted costs of mitigation scenario of measure *j*
c_j^{ref}	Total discounted costs of reference scenario of measure *j*
E_j^{mit}	Total discounted emissions of mitigation scenario of measure *j*
E_j^{ref}	Total discounted emissions of reference scenario of measure *j*
$IC_{j,t}$	Investment cost of measure *j* for the time period *t*
$MC_{j,t}$	Maintenance cost of measure *j* for the time period *t*
$FC_{j,t}$	Fuel cost of measure *j* for the time period *t*
r	Discount rate
t	Time in years
INV_j	Up-front investment cost of measure *j*
n	Economic lifetime of measure *j*
A	Activity rate
EF_{GHG}	Emission factor of GHG
EF_{GHG}^{ref}	Emission factor of GHG for the reference scenario
EF_{GHG}^{mit}	Emission factor of GHG for mitigation scenario
EF_{CO_2}	Emission factor of CO_2
EF_{CH_4}	Emission factor of CH_4
EF_{N_2O}	Emission factor of N_2O
a_j	Abatement achieved by measure *j*
ΔE_j	Difference of emissions between reference and mitigation scenario
A^{ref}	Activity of reference scenario
A^{mit}	Activity of mitigation scenario
ΔA	Reduction in activity between reference and mitigation scenario
ΔEF_{GHG}	Difference in emission factor between reference and mitigation scenario
ED	Energy demand
P_f	Fuel price
ED^{ref}	Energy demand in reference scenario
ED^{mit}	Energy demand in mitigation scenario
ΔED	Difference in energy demand between reference and mitigation scenario
P_f^{mit}	Fuel price in mitigation scenario
P_f^{ref}	Fuel price in reference scenario
ΔP_f	Difference in fuel price between reference and mitigation scenario

FS	Fuel consumption
D	Distance travelled
OR_{car}	Occupancy rate of private cars
OR_{bus}	Occupancy rate of buses
ΔPKT	Amount of passenger kilometres shifted
$\Delta VKT^{ref,car}$	Change in the distance travelled in reference scenario
$\Delta VKT^{mit,bus}$	Change in the distance travelled in mitigation scenario
$AFC_{bus,f}$	Average fuel consumption of the buses by type of fuel
$AFC_{cars,f}$	Average fuel consumption of the private cars by type of fuel
NEW	Number of newly registered vehicles introduced by the mitigation scenario
VKT	Vehicle-kilometres travelled
KMV	Average distance travelled per vehicle for specific year

Single-Objective Optimisation Method | Chapter 3

$TC_{j,t}$	Total cost of abatement of measure *j* for time period *t*
$AC_{j,t}$	Abatement cost of measure *j*
$a_{j,t}$	Amount of abatement of measure *j* for time period *t*
i	Lifetime of measure *j*
fa_j	Full achievable abatement for measure *j*
$s_{j,t}$	Speed of implementation of measure *j*
$a_m^{objective}$	Required abatement for specific years set in the future
$E_{baseline,t}$	Emissions level of baseline scenario at time period *t*
E_t	Final emissions level for mitigation scenario at time period *t*

Multi-Objective Optimisation Method – Model | Chapter 5

Sets

j	Mitigation measures available for consideration,
t	Periods of time, step of a year
i	Lifetime of mitigations measures

Subsets

$lbj(j)$	Mitigation measures with loose economic and behavioural barriers
$sbj(j)$	Mitigation measures with strict economic and behavioural barriers
$sbj25(j)$	Mitigation measures with strict economic and behavioural barriers introduced after 2025

Variables

$a_{j,t}$	Abatement achieved through the implementation of measure *j* for the time period *t*

Parameters

r	Discount rate

$\boldsymbol{n}(\boldsymbol{t})$	Number of periods
$\boldsymbol{df}(\boldsymbol{t})$	Discount factor
$\boldsymbol{ldf}(\boldsymbol{i})$	Lifetime discount factor
$\boldsymbol{fa_j}$	Full abatement of mitigation measure *j*
$\boldsymbol{AC_{j,t}}$	Abatement cost of mitigation measure *j* for the time period *t*
$\boldsymbol{ACdisc_{j,t}}$	Discounted abatement cost of mitigation measure *j* for the time period *t*
$\boldsymbol{s_{lbj,t}}$	Speed of implementation of mitigation measure *j* with loose economic and behavioural barriers for the time period *t,* subset $lbj(j)$
$\boldsymbol{ssl_{sbj}}$	Starting level of speed of implementation of mitigation measure *j* with strict economic and behavioural barriers, subset $sbj(j)$
$\boldsymbol{sincr_{sbj,t}}$	Speed increase of mitigation measure *j* with strict economic and behavioural barriers, subset $sbj(j)$, for the time period *t*
$\boldsymbol{ss_{sbj,t}}$	Annual speed of implementation of mitigation measure *j* with strict economic and behavioural barriers, subset $sbj(j)$, for the time period *t*
$\boldsymbol{ssl_{sbj25}}$	Starting level of speed of implementation of mitigation measure *j* with strict economic and behavioural barriers introduced after 2025, subset $sbj25(j)$
$\boldsymbol{sincr25_{sbj25,t}}$	Speed increase of mitigation measure *j* with strict economic and behavioural barriers introduced after 2025, subset $sbj25(j)$, for the time period *t*
$\boldsymbol{ss25_{sbj25,t}}$	Annual speed of implementation of mitigation measure *j* with strict economic and behavioural barriers, subset $sbj25(j)$, for the time period *t*

1 Introduction

1.1 Background and Context

Climate change is undoubtedly one of the greatest challenges that the world faces. The changes in the climate system are evidenced, while human influence is clear (IPCC, 2014). The anthropogenic greenhouse gas (GHG) emissions continue to increase since the pre-industrial era, despite a growing number of climate change mitigation policies (IPCC, 2014), making the reduction of GHG emissions one of the most pressing problems of our day.

Attempts have been made in the context of strengthening the global response to the threat of climate change. During the 21st conference of parties of the United Nations Framework Convention on Climate Change (UNFCCC), global leaders have set a common cause to undertake efforts to combat climate change through the Paris Agreement (UNFCCC, 2015). The climate goal of the Paris Agreement, as mentioned in Article 4.1, is "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (UNFCCC, 2015). The agreement sets an ambitious goal: parties pledged "to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century". This will require a reduction in GHG emissions to zero levels by the end of the century (Collins et al., 2013; IPCC, 2014; Steinacher et al., 2013).

The global annual emissions for the period 1990-2019 of fossil carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and fluorinated gases are illustrated in Figure 1.1 retrieved from United Nations Environment Programme (UNEP) Emissions Gap Report for 2020 (United Nations Environment Programme, 2020). The trend suggests that the increase of GHG emissions observed in 2017 and 2018 continued in 2019 but at a lower growth rate. GHG emissions reached in the year 2019 a level of 52.4 billion tonnes of

CO_2 equivalent without Land-Use Change (LUC) emissions and 59.1 billion tonnes of CO_2 equivalent when including LUC emissions with the fossil CO_2 emissions being the dominant (around 65% of total GHG emissions).

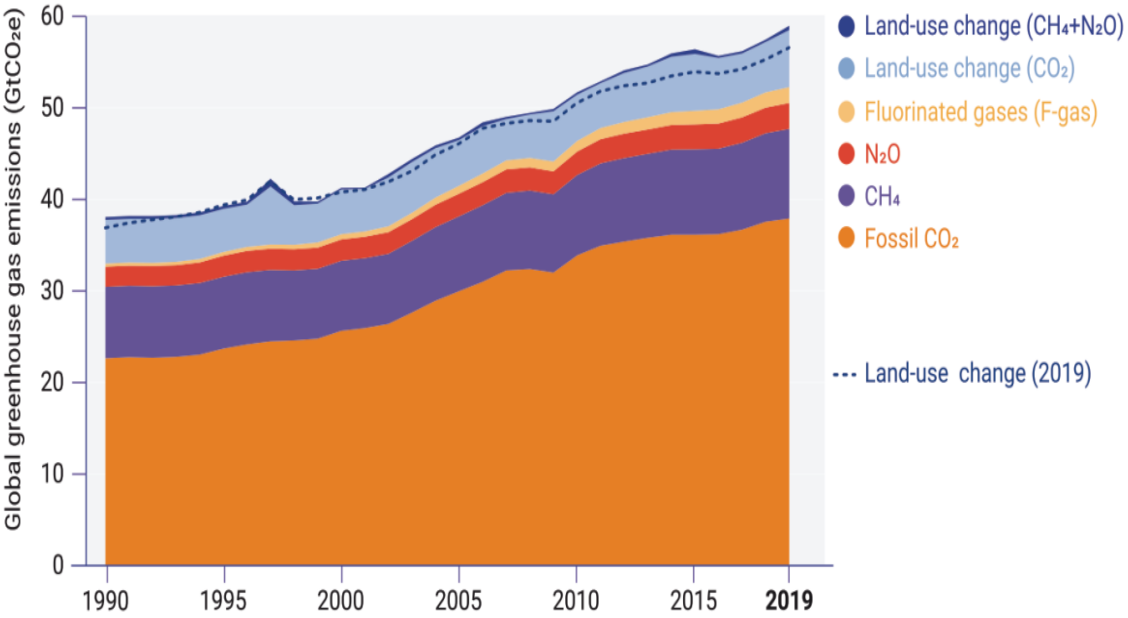

Figure 1.1 | Global GHG emissions by source. Source: UNEP Emissions Gap Report (United Nations Environment Programme, 2020).

The sectoral contribution of GHG emissions across sectors is demonstrated in Figure 1.2, where emissions appear to grow across all categories, but with indications that the growth is slowing for electricity and heat generation. A similar trend has been noted at the European Union (EU) level due to the power sector's rapid decarbonisation (European Environment Agency, 2020). Transport, on the other hand, which constitutes an important contributor (around 14% of global GHG emissions on average over the last decade), and especially road transport, continues to have strong growth.

The COVID-19 pandemic in the following year, 2020, led to a reduction in emissions, with the main changes occurring from transport as COVID-19 restrictions were targeted to limit mobility. However, it has been suggested that this crisis provides only a short-term reduction and will not play an essential role in decreasing emissions for

2030 if the economic recovery does not incorporate strong climate change policies (United Nations Environment Programme, 2020). Projections of emissions under the International Energy Agency (IEA) sustainable recovery scenario suggest that 2030 emissions will only be significantly reduced if COVID-19 economic recovery is used as a chance to pursue strong decarbonisation (IEA, 2020).

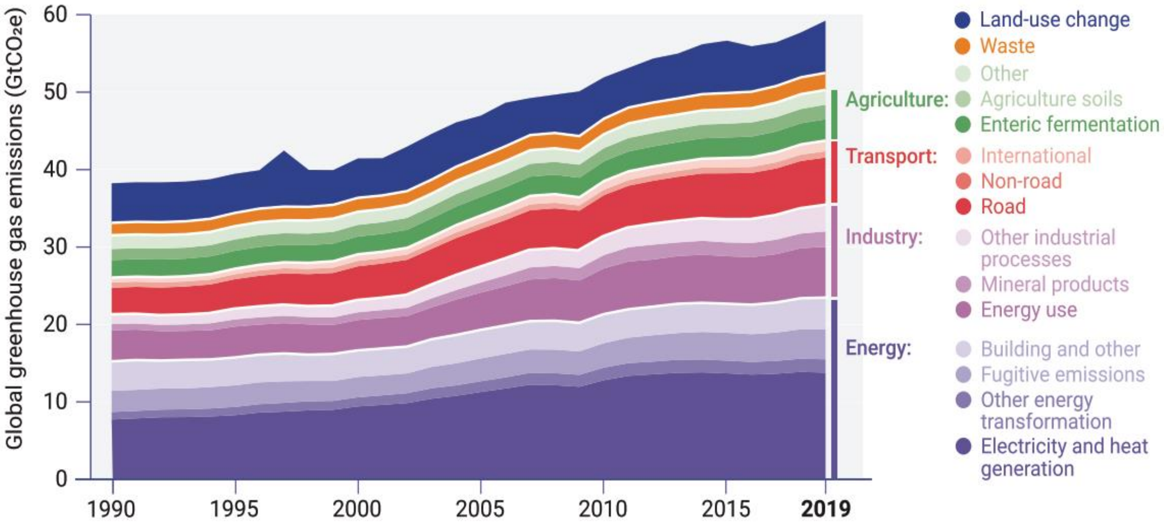

Figure 1.2|Global GHG emissions by sector. Sources: Emissions Database for Global Atmospheric Research (EDGAR) (Crippa et al., 2020) and UNEP Emissions Gap Report (United Nations Environment Programme, 2020).

Many governments around the world are increasingly committing themselves to strict energy- and climate-related targets for the medium and the long term. Thus, policymakers need to identify how to deal with the required emission reductions, ideally prioritising interventions that will have the least cost to society. This involves deciding an appropriate, cost-effective mix of GHG abatement policies and measures that can be implemented so as to meet the emission reduction objective in the target year. In this context, this doctoral thesis's objective is to explore methodologies for assessing energy and environmental policies and measures to identify appropriate climate change mitigation strategies. To narrow down this broad subject and in order to provide some useful insights regarding the decarbonisation pathway of Cyprus, an island country in the Eastern Mediterranean with a population of around 900,000, the research is mainly applied at a national level. Cyprus became an EU member in 2004 and thus has implemented climate change policies in compliance with the relevant EU legislation. This research identifies and assesses additional country-specific measures in order to provide meaningful and realistic support to national policymakers. Working within the EU policy context allows the methods and policy recommendations of this work to be applied in other EU member states, which are faced with the same decarbonisation challenges, albeit in somewhat different policy contexts.

The EU is combating climate change through ambitious policies aiming to be a climate-neutral economy by 2050. The 2030 Climate and Energy Framework includes EU-wide targets and policy objectives from 2021 to 2030. The key targets comprise reducing GHG emissions from 1990 levels, increasing the share in renewable energy and improving energy efficiency. The GHG target is implemented by the EU Emissions Trading System (ETS), the Effort Sharing Regulation with national emissions reduction targets and the Land Use, Land-Use Change and Forestry (LULUCF) Regulation. As part of the European Green Deal – an ambitious package of measures presented in December 2019 – the European Commission proposed in September 2020 to raise the 2030 GHG emission reduction target (European Commission, 2020). To set Europe on a responsible path to the 2050 'climate neutrality' target, the proposal aims to move the target from 40% (existing ambition) to at least 55% compared to 1990 levels. All three pieces of climate legislation under the 2030 Climate and Energy Framework will be updated in line with the new ambition level – proposals will be formulated by June 2021.

The Green Deal[1] consists of the following climate action initiatives: a) the European Climate Law to write into law the goal of net-zero GHG emissions by 2050, b) the European Climate Pact to engage citizens, communities and organisations in climate

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[1] More information for EU climate action and the European Green Deal available on the website of the European Commission, the EU's executive body: https://ec.europa.eu/clima/policies/eu-climate-action_en

action, c) the 2030 Climate Target Plan to further reduce net GHG emissions as mentioned above and d) the new EU Strategy on Climate Adaptation to make Europe adapted to the inevitable impacts of climate change and a climate-resilient society by 2050.

Key EU legislations and policies for fighting climate change include, as mentioned above, the EU ETS, a cornerstone of EU climate action and a tool for reducing GHG. It works on the 'cap and trade' principle – a cap is set on the total amount of GHG that can be emitted by each installation covered by the system, and firms purchase or sell emission allowances depending on whether their emissions are above or below the cap respectively. It includes more than 11,000 heavy energy-using installations (power and heat generation, oil refineries, steel works, and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids, and bulk organic chemicals) and commercial aviation.

Under the EU ETS, national governments have specific but limited tasks. Conversely, national policymakers have the exclusive responsibility for implementing abatement measures in non-ETS sectors or Effort Sharing sectors – sectors outside emissions trading, such as transport, buildings, agriculture, and waste. The Effort Sharing legislation sets annual emission trajectories for each EU Member State for the period 2013-2020 in the Effort Sharing Decision, or ESD (EU, 2017, 2013, 2009) and for the period 2021-2030 in the Effort Sharing Regulation, or ESR (European Environment Agency, 2018) adopted in May 2018. These emission trajectories are translated into binding national annual emission targets.

Measures taken at the EU level are putting constraints on these Effort Sharing emissions. For example, carbon dioxide emission standards for new cars and vans (EU Regulation 2019/631) and heavy-duty vehicles (EU Regulation 2019/1242) can facilitate road transport emissions reduction[2]. The legislative framework that includes

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[2] See the European Commission's relevant webpage for European strategy for low-emission mobility: https://ec.europa.eu/clima/policies/transport_en

the Energy Performance of Buildings Directive (2010/31/EU) and the Energy Efficiency Directive (2012/27/EU) targets the building sector's decarbonisation[3]. Eco-design requirements for energy-related products and energy labelling systems can serve additional emission reductions from buildings. Two legislative acts have also been adopted to restrict emissions from fluorinated greenhouse gases – the Fluorinated Greenhouse Gases Regulation (EU Regulation No 517/2014) and the Mobile Air-Conditioning Directive (2006/40/EC)[4].

Achieving these non-ETS decarbonisation targets is considered very challenging for most EU countries, probably more so than the targets for the heavy industry subject to the ETS (European Environment Agency, 2018). For 11 countries (Cyprus included) in 2018, the Effort Sharing emissions were greater than the annual Effort Sharing emission allocations of the corresponding countries. In 2019, another country joined this group bringing the total to 12 (European Environment Agency, 2020). Therefore, the work presented in this thesis focuses on policies targeting non-ETS emissions, with the aim to assist the authorities of Cyprus in identifying abatement measures that can help attain the challenging non-ETS emissions reduction target and to provide general policy implications regarding the decarbonisation of these sectors.

An earlier decision, adopted by EU leaders in October 2014, was to reduce economy-wide domestic GHG emissions by 40% in the year 2030 compared to those of 1990. The contribution to the overall target for the sectors of the economy not covered by the EU ETS was set to be 30% of emissions reduction by 2030 compared to 2005 emissions. In view of the European Green Deal, however, this target is considered inadequate to lead to the declared ambition of the EU to reach net-zero emissions by 2050. Therefore, the 2030 objective is under revision by the time of this writing (April 2021), with the declared aim to increase the target to at least 55% emissions reduction

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[3] See the European Commission's relevant webpage for a list of legislative requirements about new buildings: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings_en

[4] See the European Commission's relevant webpage for EU legislation to control Fluorinated Greenhouse Gases: https://ec.europa.eu/clima/policies/f-gas/legislation_en

below 1990 levels in 2030; a relevant proposal was tabled in September 2020 (European Commission, 2020) and is negotiated among EU bodies with the aim to be adopted as part of the European Climate Law by the summer of 2021.

As a member state of the EU, Cyprus has committed to GHG emission reductions in line with EU decarbonisation objectives for the year 2030, as mentioned above. Compared to the emissions of the year 2005, it has to reduce the emissions from heavy industries which are subject to the EU ETS by 40%, and the emissions from all other economic activities, i.e. those of non-ETS sectors, by 24%. This was the national target before the introduction of the European Green Deal and the consideration of strengthening the 2030 objective (European Commission, 2020). By the time of this writing, the new EU climate target for 2030 has not been formulated in specific emission reduction requirements for non-ETS sectors of individual member states.

According to the latest national GHG inventory report submitted to the UNFCCC secretariat in May 2020 (MARDE, 2020), for the year 2018, the total GHG emissions reached the level of 8.420 million tonnes of CO_2 equivalent, including LULUCF and 8.81 million tonnes of CO_2 excluding LULUCF. The latest compared to 1990 emissions level have increased by 55%. However, a reduction of 1.8% is noted between the years 2017 and 2018. Energy constitutes the most significant contributor to the national GHG emissions when compared to emission produced by the rest of the economic sectors. More specific 3.360 million tonnes of CO_2 equivalent are related to electricity production, while another 2.067 million tonnes of CO_2 equivalent are generated from transport for the year 2018. The dependence of the energy sector on fossil fuels and of transportation on private cars justifies this trend. The increased penetration of renewable energy sources (RES) in the final consumption results in a reduction in energy industries' related emissions in recent years. Figure 1.3 illustrates the above-discussed trends focusing on CO_2 emissions, which are by far the main contributor amongst the main GHG – CO_2, N_2O and CH_4.

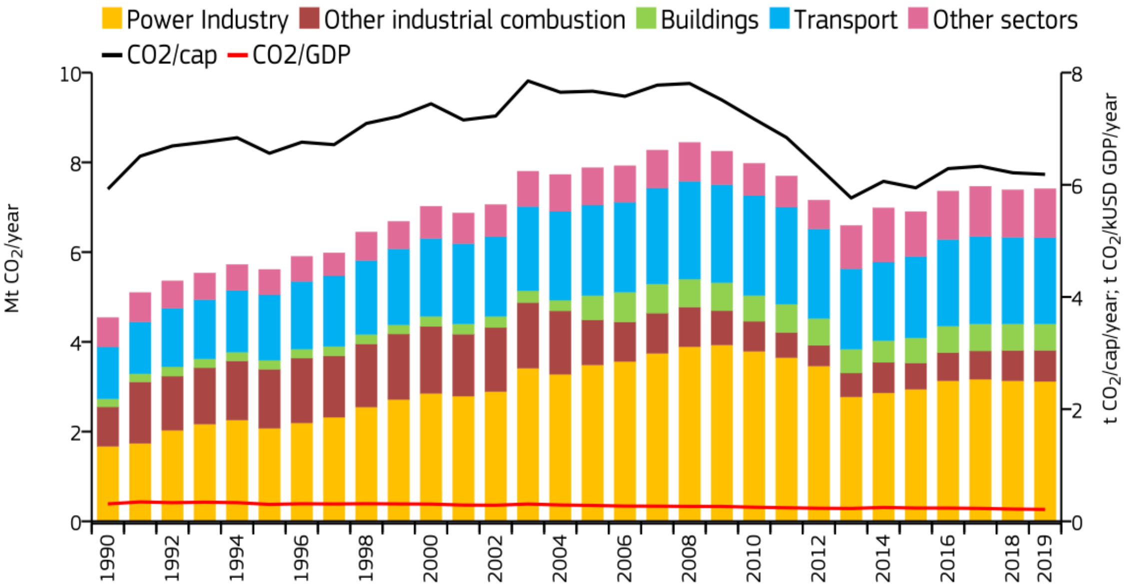

Figure 1.3|Cyprus CO₂ emissions by sector. Source: Emissions Database for Global Atmospheric Research (EDGAR) (Crippa et al., 2020).

Based on the EU's approach to deal separately with the heavy installations and the rest of the economy, the ETS in Cyprus includes the following; three electricity production installations, one cement producing installation and six installations producing ceramics. For the year 2017, the contribution of ETS emissions on the total national emissions was 52%. Regarding the economic sectors outside EU ETS, which is the focus of the research, the majority of the emissions come from road transport with a share of the total national non-ETS emissions (excluding LULUCF emissions) for the year 2017 up to 49%. Non-ETS energy, waste management and agriculture follow with a share of 18, 14 and 12%, respectively.

1.2 Objectives of the Thesis

In this international and EU policy context, the objective of this doctoral thesis is to expand existing and develop new methodologies for assessing policies and measures in order to identify cost-effective and realistic climate change mitigation strategies that are beneficial to society and in line with the goal to achieve climate neutrality by 2050.

To narrow down this broad subject and in order to provide some valuable insights regarding the decarbonisation pathway of Cyprus, an island country in the Eastern Mediterranean, the research is mainly applied at the national level. Cyprus became an EU member in 2004 and thus has implemented climate change policies in compliance with the relevant EU legislation. This research identifies and assesses country-specific measures across non-ETS sectors in order to provide meaningful and realistic support to national policymakers.

Beyond country-specific methods and data, working within the EU policy context allows the methods and policy recommendations of this work to be applied in other EU member states, which are faced with the same decarbonisation challenges albeit in somewhat different policy contexts.

1.3 Related Work

Considerable research effort has been devoted to the design of effective climate policies for stabilising global climate and tackling other environmental threats. One way to determine a cost-effective policy mix is through top-down simulations with the aid of Integrated Assessment Models (IAM) (e.g. Klepper and Peterson, 2006; Kuik et al., 2009; Morris et al., 2011). 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. They do not depict specific mitigation measures, and the usual outcome of those models is a ‘continuous’ Marginal Abatement Cost (MAC) curve (Ellerman and Decaux, 1998; Viguier et al., 2003). Therefore, in many cases, such models' technological detail does not allow 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’ 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 (e.g. Enkvist et al., 2007; McKinsey, 2009a).

MAC curves have also been used, except from the EU (Blok et al., 2001), by many countries and regions, like the Netherlands (Blok et al., 1993) and California (Sweeney et al., 2008), with a focus on climate change mitigation. However, the earliest MAC curves were not built in the context of carbon emissions reduction. They were developed after the two oil price shocks of the 1970s and for saving electricity consumption in the 1980s (Meier et al., 1982; A. K. Meier, 1982). Later on, this tool finds application in a variety of areas; energy efficiency improvements (Olivier et al., 1983), pollutants emissions reduction (Hyman et al., 2002; Rentz et al., 1994; Silverman, 1985; US EPA, 2006), waste management (Beaumont and Tinch, 2004), water availability (Addams et al., 2009; McKinsey, 2009) and forest management (Kindermann et al., 2008; Strengers et al., 2008). The earliest carbon-focused curves were constructed in the early 1990s (Jackson, 1991; Soft, 1995).

Although MAC curves are widely used for illustrating the economics associated with climate change mitigation, related methodological issues have concerned the academic literature (Kesicki and Strachan, 2011; Ward, 2014). Kesicki and Ekins (2012) discussed the weaknesses of the general MAC approach, the flaws inherent to the method of generating the curve proposing some solutions for methodological issues when constructing ‘measure-explicit’ MAC curves. Approaches to overcome the present shortcomings of this analytic tool have been suggested by other studies as well (e.g. Kesicki, 2013).

Based on Vogt-Schilb and Hallegatte (2014) classification, ‘measure-explicit’ MAC curves can be distinguished into two types, ‘full potential’ and ‘achievable potential’ ones. Regarding the ‘full potential’ approach, the measures are used at their technical maximum and are calculated against a reference technology that will be replaced. Rubin et al. (1992) and, more recently, Wächter (2013) used this approach. On the other hand, ‘achievable potential’ curves, as they are built for a specific point in time, account for the time that technologies need to be largely diffused (Grübler et al., 1999). They appear to be more modest regarding the scale of implementation. In a theoretical framework, Vogt-Schilb and Hallegatte (2014) attempted to show the implications to the policy mix if the two approaches are combined. This is proved to be helpful in dealing with the presentation problems that are associated with MAC curves. They are frequently interpreted as supply curves because they rank options according to their cost – from the least to the most expensive. The study suggested that it is important to distinguish available abatement measures by considering three characteristics of each option: their costs, their mitigation potential, and the time it takes to deploy. Thus a new way of reporting information on emission-reduction options can be introduced, including the speed at which each measure can be implemented.

This key parameter reflects the so-called technical inertia, as refereed by Grubb et al. (1995). Further studies using IAMs (e.g. Luderer et al., 2016) and theoretical models (Ha-duong et al., 1997) concluded that this inertia in the deployment of a measure has an apparent effect in the relation between the optimal quantity of short-term abatement and long-term objectives. In this context, ineffective short-term climate policies reduce the available options for future climate policy (e.g. Luderer et al., 2016; Riahi et al., 2015). Even if it appears sufficient for the foreseeable future, short-term actions may miss key economic sectors where mitigation measures are expensive and take time to deploy (Vogt-Schilb and Hallegatte, 2017). This is often called a ‘lock-in’ effect where abatement options that are cheaper and faster to implement are prioritised but do not have sufficient abatement potential to meet ambitious abatement targets (Klitkou et al., 2015; Seto et al., 2016). Knowing the limitation of the economies to switch overnight to low-carbon technologies, the quantity of short-term abatement must be aligned with long-term decarbonisation. This ‘lock-in’ effect can be an implication of weak near-term policies that affect the achievability of long-term climate targets (Bertram et al., 2015; Iyer et al., 2015).

In Article 4.19 of the Paris Agreement (UNFCCC, 2015), countries committed to "formulate and communicate long-term low greenhouse gas emission development strategies". Those long-term strategies for low-emission development can play an important role in reconciling the long-term horizon with the medium-term horizon (Waisman et al., 2019). Such low-emission development strategies are vital for avoiding 'lock-in' effects that will not allow full decarbonisation in the long term (Sachs et al., 2016). A main concern while designing climate policy must be which short-term, sectoral targets are aligned with long-term decarbonisation objective.

Building on that, it has been argued that the quantity of emissions abatement may not be the only metric to inform climate policy. The quality of abatement refers to how the abatement is achieved (in which sector and with which technology) is also essential to a successful decarbonisation pathway (Vogt-Schilb and Hallegatte, 2014). The importance of this detailed sectoral decarbonisation transition is also highlighted by Bataille et al. (2016). In this context, short-term emission reduction options should not only apply in the sectors that are easier and cheapest to decarbonise. Near-term actions must focus on the sectors that will be more difficult to decarbonise, such as road transport (Vogt-schilb et al., 2012; Vogt-Schilb et al., 2015). To enforce this approach, ensuring that progress will be made in all economic sectors, a set of sectoral targets could be useful (Fay et al., 2015). Such sectoral approaches have been developed in the last few years by academic teams for different countries around the world (Calderón et al., 2016; Di Sbroiavacca et al., 2016; Lucena et al., 2016; Veysey et al., 2016). The Deep Decarbonisation Pathways Project aims to encourage in-country national teams to developed similar studies (Bataille et al., 2016).

Decision support methodologies in the field of climate change include, among others, Mathematical Programming, a subtopic of Operations Research, a scientific method of decision making where the aim is to make the optimal choice under a specific set of constraints. The traditional way of dealing with such decision-making problems is single-objective optimisation (SOO). Given that problems of this nature are subject to numerous objectives and criteria, the idea that only one single optimal solution exists that will lead to one particular course of action may not be helpful. The solution of dealing with complex real-world problems that require the simultaneous optimisation of several objectives lies in the identification of a Pareto set of optimal solutions rather than one unique optimal solution (Chiandussi et al., 2012). Multi-objective mathematical programming (MOMP) is concerned with this type of problems. The output of multi-objective optimisation is a set of performances across the various objective functions, which are often in conflict.

MOMP approaches have been widely used across scientific fields. Focusing on climate change mitigation topics, a considerable amount of work has been done for design, planning and control problems in the field of renewable and sustainable energy (Baños et al., 2011), using, amongst others, Pareto-optimisation techniques. Variety of criteria, e.g. economic and environmental performance, can be found in a variety of studies for planning investment in energy sources (Flores et al., 2015), the design and performance of hybrid energy systems (Katsigiannis et al., 2010; Perera et al., 2013a, 2013b) or hybrid bio-refineries (Giarola et al., 2011) and the optimisation of distributed energy supply systems (Buoro et al., 2013). Studies have also considered a third objective, for example, technological (Fazlollahi et al., 2014) or social criteria (Mota et al., 2015). Optimisation over multiple sustainable development goals has also been applied (Van De Ven et al., 2019).

1.4 Research Procedure

The objective of this doctoral thesis is to explore methodologies for the techno-economic assessment of energy and climate policies and measures. The procedure followed is summarised in concrete steps in Figure 1.4. The rectangles placed in the middle present the main four parts of the research and the corresponding thesis's chapters. Three different methods have been used – MAC, SOO and MOMP – for the formulation of climate change policies with a focus on the sectors of the economy outside the EU ETS, i.e. sectors controlled under the ESR, also called non-ETS sectors. The main inputs and outputs of the models are presented in grey-coloured and purple-coloured rectangles, respectively.

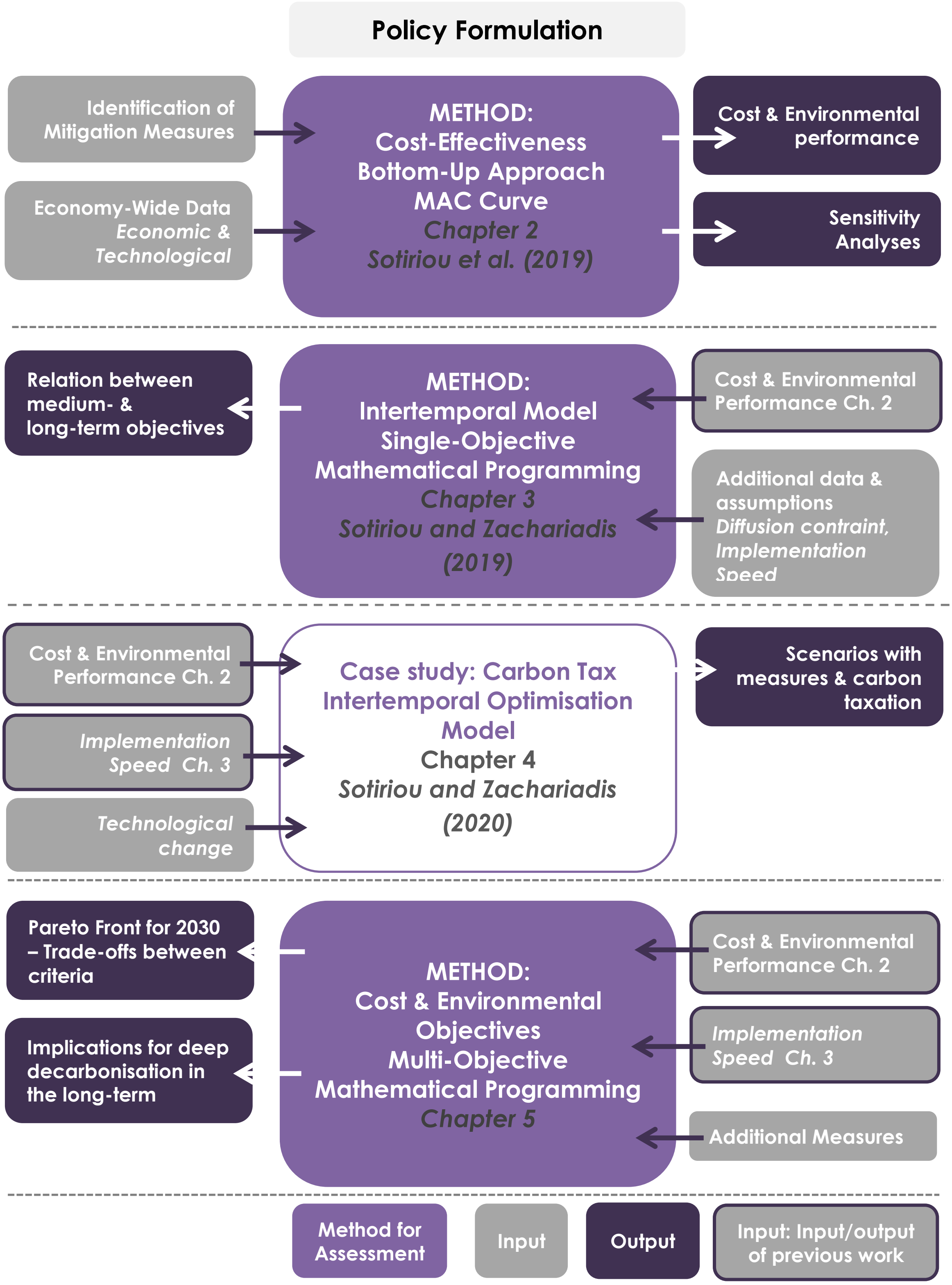

Figure 1.4|**Research steps followed. The figure includes an overview of the procedure followed and the connections between individual studies/chapters. The next chapters of the thesis include modified versions of this figure presenting the inputs/outputs and the relation between the chapters in more depth.**

Keeping in mind the policy needs and difficulties outlined in Section 1.1, the research starts with the development of a bottom-up ‘measure-explicit’ MAC curve for the Republic of Cyprus (Sotiriou et al., 2019) in order to identify a country-specific cost-effective policy mix. A detailed and transparent methodology to assess MAC curves for different economic sectors is provided. This constitutes the first study to analyse the cost-effectiveness of GHG abatement options for Cyprus. An important aspect of this research is that a flexible methodology for the cost-effective assessment of GHG abatement measures is developed, making the analysis similar to other EU countries but also relevant to other countries around the world facing decarbonisation objectives. The diverse set of alternative calculations, in the sense of sensitivity analyses, provides useful policy recommendations while addressing methodological issues of MAC curves, as identified in the literature review.

An extension of this work follows, focusing on the issue of optimal timing, as identified by Vogt-Schilb and Hallegatte (2014), and the interactions between short- and long-term effectiveness of mitigation measures. A single-objective mathematical programming model was developed that deals with the decarbonisation objectives in a dynamic way (Sotiriou and Zachariadis, 2019). The objective of the model is to draw the cost-optimal pathway that will lead to the fulfilment of the emissions reduction targets. New variables featuring the abatement measures are introduced in the analysis. At the same time, the relationship between medium- and long-term targets is explored through different levels of ambition for the medium-term. The model of Vogt-Schilb and Hallegatte (2014) is expanded to account for a variable speed of implementation of emissions abatement measures over time. The model also includes the assessment of the total discounted abatement costs, with and without externalities of air pollutants, and the investment needs for the corresponding abatement.

This theoretical framework is applied for Cyprus by assessing several scenarios of different levels of ambition for medium-term decarbonisation. To evaluate possible climate change mitigation pathways, this study links the implementation of emissions abatement measures with the introduction of a gradually increasing carbon tax. For this purpose, the single-objective mathematical programming model developed in Sotiriou and Zachariadis (2019) was combined with a long-term energy forecast model. The alternative scenarios were developed and compared to assess their potential to turn Cyprus into a low-carbon economy, as well as the related costs and investment needs in each case (Sotiriou and Zachariadis, 2020).

Expanding the previous modelling work, a MOMP approach has been developed that can provide insights into a climate policy that is far from static (Sotiriou and Zachariadis, 2021). In a more stable policy environment, decision making could be conducted through cost-effectiveness analyses where one seeks the least-cost emission abatement options that lead to the target's attainment. In light of the uncertainty about the increased stringency of the 2030 emissions reduction target in the frame of the 'European Green Deal', a multi-objective approach can be a more suitable method of assessment. In this type of programming, the search will not give one unique optimal solution but a set of them. The aim is to provide these solutions to the decision-maker so as to allow him/her to select the solution that satisfies him/her best by judging the various proposed solutions.

1.5 Contribution of the Thesis to the Literature

Some parts of the research reported in this dissertation were stimulated by real-world policy questions that were posed by national decision-makers in Cyprus. However, the approach followed throughout the thesis was to respond to such questions in a methodologically innovative way that would also be relevant for other national contexts. More specifically:

1. While the analysis of Chapter 2 responds to a specific research question, i.e. how Cyprus can deal with the decarbonisation problem in the very challenging non-ETS sectors in a cost-effective way, the approach is innovative in several ways that allow to address methodological problems associated with MAC curves:

- A transparent and fully documented methodology for the cost-effective assessment of mitigation measures is developed. All the data, economic or technical, associated with the options are published. The assumptions underlying the curves are also presented. Full information is given concerning the source of the assumptions - unlike other MAC studies that do not extensively report their data and assumptions (Kesicki and Ekins, 2012).
- The methodology is flexible, useful for other European countries or other countries around the world seeking guidance in their climate policies. It also explores a variety of mitigation options that apply not only in energy end-use sectors but in all economic sectors that are not subject to the EU ETS.
- The methodology, through alternative calculations, is implemented in ways that are meaningful for the formulation of climate and energy strategies. The central approach was based on a social planner's perspective. These are also called economic assessments, as opposed to financial assessments that provide insights into a private firm's decisions or a household. While other national studies conduct either an economic or a financial appraisal for the cost-effectiveness assessment, Chapter 2 highlights the difference between the two – much beyond a simple differentiation in discount rates – thereby providing interesting policy-relevant results.
- The study takes into account the additional benefits of GHG emission abatement. As a rule, measures intended to reduce GHG emissions also affect the emissions of air pollutants. They thereby have an impact on human health, agricultural production, ecosystems and the built environment. Although air quality improvement is recognised as an important side-benefit of decarbonisation strategies, it has not been addressed explicitly in marginal abatement cost models up to now. Accounting for such side-benefits, a more holistic picture of the social cost-effectiveness of GHG emission mitigation measures can be provided, offering useful information for policymakers.

2. Chapter 3 contributes further to the international literature:
   - The multi-constraint optimisation model developed in the context of this study explores the correlation between short- and long-term optimal strategies by

combining a theoretical approach with real-world engineering and cost data; this enables a realistic assessment of the effects of carbon lock-in with real-world, bottom-up, and nationally appropriate data.

- The theoretical model introduced by Vogt-Schilb and Hallegatte (2014) is expanded by (a) adapting the framework to the real-world EU policy setting and (b) making the implementation speed of each abatement measure variable over time and dependent on the cumulative amount of abatement that has already been deployed up to a given year. The latter improvement is computationally demanding but makes policy simulations much more realistic and hence useful to policymakers.
- The total discounted costs for the different scenarios are calculated, with and without externalities of air pollutants and GHG, together with the associated investment needs; this illustrates that, whereas the required investments to achieve climate stabilisation are substantial, ambitious decarbonisation can be socially beneficial.

3. Finally, the MOMP model developed in Chapter 5 to explore decarbonisation pathways under a dynamic policy context goes beyond existing work in several ways:
    - It expands the application of MOMP to GHG emission abatement beyond energy and across all economic sectors of a country. Thus, a varied mixture of climate change mitigation measures is considered.
    - The modelling framework is tailor-made to address the EU’s climate policy context, focusing on all the sectors of the economy outside the EU ETS, which have common commitments and specific challenges.
    - The approach addresses the EU's latest ambition in its plan to further cut GHG emissions by at least 55% in 2030 under the European Green Deal, with a view to the ultimate carbon neutrality goal of 2050.
    - Apart from trade-offs between decarbonisation and costs, with and without accounting for air pollution externalities, implications for public finances and the level of economy-wide investments are also considered.

Finally, it is worth noting that, although the developed models are applied in the case of Cyprus, the framework presented in this thesis has a much broader application. Firstly, the application corresponds to specific policy needs set by the EU (as regards both the differentiation between ETS and non-ETS sectors and the emission reduction targets for 2030 and 2050), so that this framework can be expanded to any other EU member state. Secondly, although the methods are relatively data-intensive, the overall approach is computationally tractable with today's capacity of personal computers; hence it is suitable for application in any other world country or region seeking policy support to achieve ambitious decarbonisation.

1.6 Structure of Thesis

This doctoral dissertation is organised into six chapters, including this introduction. All of the following Chapters, with the exception of Chapter 6, represent each research step taken as briefly explained above and presented in Figure 1.4.

The current Chapter 1 includes a background to the climate change topic and a brief summary of the related work devoted to providing solutions to this problem. The concept and the scope of the research are also stated, and the methods developed for carrying out the aim of the thesis are outlined.

Chapter 2 deals with the determination of the cost-effective policy mix by applying MAC Curve methodology, the first approach used for formulating decarbonisation strategies. Provides a literature review on MAC curves and the way they have been used broadly for policy formulation. It also includes a detailed presentation of the methodology developed and the mathematical formulations. Although the application of this methodology is under a specific policy context, with the data and results corresponding to a particular country, the framework is applicable to every nation or region that seeks decarbonisation advice. Alternative scenarios developed to deal with the main limitations of the MAC curves as a policy tool are also included.

Chapter 3 deals with the determination of the optimal mix and timing by developing a constrained cost-optimisation model; the second approach used for formulating decarbonisation strategies. Presents aspects of mathematical programming and includes a detailed presentation of the single-objective mathematical programming model, and justifies the way that this approach deals with limitations of the MAC curves. Explores, in a theoretical framework, the correlation between climate change mitigation targets set at different points in time and how the level of ambition for the medium-term emissions reduction target can affect the achievability of the long-term climate neutrality objective.

Chapter 4 presents a case study for Cyprus. It combines the cost-optimisation model developed in Chapter 3 with a long-term energy forecast model to insert a carbon tax. Data for the case study are described analytically. Results and policy implications are included.

Chapter 5 deals with the formulation of decarbonisation pathways under a dynamic policy context, presenting the MOMP model. It includes the main aspects of this approach, how it differs from the single-objective mathematical programming model presented in Chapter 3 and the concept of applying this approach to provide insights in a far from stable policy environment. Sensitivity analyses are performed to include the rebound effect and the risk of delayed implementation of the various climate change actions. The source code of the single- and multi-objective model is provided in Appendix II.

Chapter 6 presents the conclusions of the thesis, along with key policy implications and the prospects for future work in the field.

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2 Determining a Cost-Effective Decarbonisation Policy Mix[5]

Abstract

This chapter 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 European Union 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 change towards public transport modes. Nationally appropriate data were applied that are mainly derived from local market information and judgement of national experts. Finally, the results of several sensitivity analyses are presented, which address the main shortcomings of marginal abatement cost curves that have been identified in the literature, and the policy implications of each one of them are discussed. Main results suggest that many of the measures are expected to yield net benefits to society from an economic viewpoint; these benefits become even more pronounced if side-benefits of these measures are taken into account. In order to gain these environmental and economic benefits, governments have to remove financial and regulatory barriers that hinder progress towards decarbonisation. 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. Apart from its relevance for European Union Member States, this assessment is useful for all countries seeking guidance in their decarbonisation strategies.

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[5] A concise version of this chapter was presented in: Sotiriou C., Michopoulos A. and Zachariadis T., On the cost-effectiveness of national economy-wide greenhouse gas emissions abatement measures. *Energy Policy* 128 (2019) 519–529, doi: 10.1016/j.enpol.2019.01.028.

A major part of the work reported here (methodology development, data collection and baseline results) has been conducted within the framework of the project "Evaluation of the Effectiveness of Possible Climate Change Mitigation Policies and Measures" financed by the European Commission Structural Reform Support Service (grant agreement SRSS/C2017/024).

2.1 Policy Context

Governments around the world have made commitments to avoid profound climate change by taking measures to reduce emissions of 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, 2015). Therefore, policymakers 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 the least cost.

One way to determine this cost-effective policy mix is through top-down simulations with the aid of IAM (e.g. Kuik et al., 2009; Morris et al., 2012). 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 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’ 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 study 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 EU, Cyprus has committed to GHG emission reductions in line with EU decarbonisation objectives for the year 2030. Compared to the emissions of the year 2005, by the time of this study, it has to reduce the emissions from heavy industries which are subject to the EU 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 the EU level. Therefore, emission reductions for ETS sectors can be taken for granted. Conversely, national policymakers have the exclusive responsibility for implementing abatement measures in non-ETS sectors. Thus, the work presented in this chapter 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 the 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 CO_2 emission levels of new passenger cars and vans in the years 2020/2021 (OJEU, 2011, 2009); or several EU Directives define energy performance requirements for new buildings. 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), any possible measure that could yield non-negligible GHG emission reductions has been considered. The costs of each measure on the basis of a comprehensive data collection effort have been assessed, 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 evaluated, 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 policymakers.

Apart from being the first study to analyse the cost-effectiveness of GHG abatement options for Cyprus, it contributes to the literature in several ways. First, the study offers 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, all economic sectors are addressed, 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 measures in Wächter (2013). Third, because all economic sectors are covered, all different types of mitigation measures have been considered: improving energy efficiency, switching to low- or zero-carbon fuels, and inducing behavioural changes; and a detailed description of the methodology to assess MAC curves for each one of them has been provided. Finally, the analysis provides 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 study provides sensitivity runs that are meaningful for energy and climate policy discussions and shed light on 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 the measures are examined 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 GHG abatement measures' side benefits. 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, a main criticism of MAC curves is being addressed (e.g. Kesicki and Ekins, 2012), i.e. that ancillary benefits or market barriers should also be considered in these assessments. Another critique of MAC curves is that the cost-effectiveness of measures depends on the order in which they are implemented; this shortcoming, however, is stronger when mitigation measures both in end-use sectors and in energy supply are considered at the same time. This study considers only measures in end-use sectors like buildings, transport and light industry (non-ETS sectors); hence this problem is much less important.

The Chapter is structured as follows: Section 2.2 provides a literature review on how the applied methodology has been used as a policy tool; Section 2.3 gives a detailed description of the adopted approach, the mathematical formulation of the methodology for the different types of mitigation measures and the national data applied in each sector of the Cypriot economy. The results of the cost-effectiveness analysis and the various sensitivity analyses are presented in Section 2.4, and policy implications are discussed in Section 2.5.

2.2 Marginal Abatement Cost Curves as a Policy Tool

A MAC curve is defined as a graph that indicates the cost associated with the last unit (the marginal cost) of emission abatement for varying amounts of emission reduction. This graph depicts the abatement cost on the y-axis and the emission abatement on the x-axis (Kesicki and Strachan, 2011). The measures included are ranked according to their costs of abatement. They come in a wide variety, depends on the time horizon, the regional scope, the abatement measures included and the method used to generate them. Figure 2.1 illustrates an example of a MAC curve. Abatement options are placed from lowest to highest cost-effectiveness, where each measure is represented as rectangular along with the MAC curve plot. The height of each ‘step’ refers to the net present cost of the mitigation measure per unit of emissions abated over the lifetime of the measure. Respectively, the ‘step’ width represents the GHG emissions reduction potential of the mitigation action during the period of study.

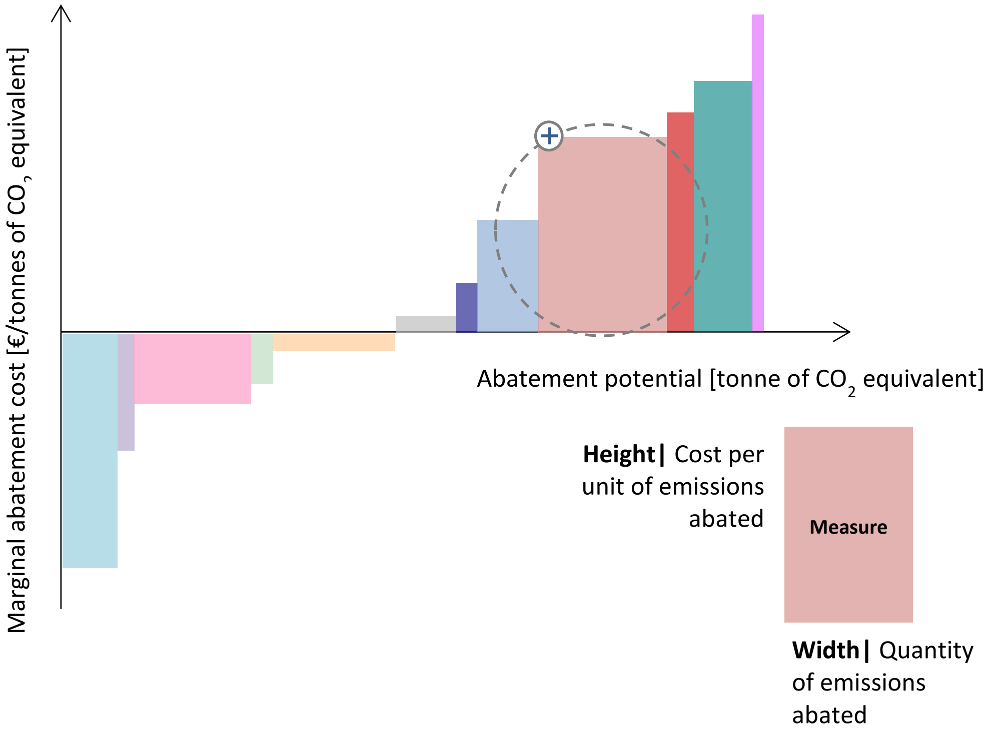

Figure 2.1 | Stylised example of a MAC curve.

Due to the simplicity of the presentation, the MAC curves have become frequently used and powerful tools in evaluating the climate change mitigation options from the economic perspective. It gives direct conclusions on to assessment and comparison of different mitigations options and an opportunity for the decision-makers to design a better-suited mitigation strategy for their country.

The earliest MAC curves were not built in the context of carbon emissions reduction. They were developed after the two oil price shocks of the 1970s, and the aim was the reduction of crude oil consumption in the 1970s and the saving of electricity consumption in the 1980s (Meier et al., 1982; A. K. Meier, 1982). At that point, MAC curves were referred to as conservation supply curves or saving curves. Later on, (Olivier et al., 1983) used this analytical tool for the assessment of energy efficiency improvements in transport, industry and buildings.

Another use of the MAC curves was the valuation of abatement potentials and the associated costs of air pollutants (Silverman, 1985) such as sulphur dioxide (Rentz et al., 1994). The earliest carbon-focused curve was constructed in the early 1990s (Jackson, 1991). MAC curves were also developed for nitrous oxide (Hyman et al., 2002) and methane (US EPA, 2006). Additionally, the application of abatement cost curves expanded to the fields of waste reduction (Beaumont and Tinch, 2004) and water availability (Addams et al., 2009). Examples of studies applying MAC curves for the forest sector are Strengers et al. (2008) and Kindermann et al. (2008).

Moreover, private companies and international institutions have been using the concept of the MAC curve to prioritize climate change mitigation options/technologies, such as McKinsey & Company (McKinsey & Company, 2010, 2009), Bloomberg (Finance B.N.E., 2010) and World Bank. McKinsey and Company established the use of MAC curves as a policy tool for the assessment of climate change. They developed curves for GHG mitigation in 15 countries (Greece, Poland, Russia, Israel, India, Belgium, Brazil, China, Switzerland, Czech Republic, Sweden, Australia, US, UK and Germany).

MAC curve is a strong policy tool with advantages and disadvantages. Among the MAC curve's weaknesses is the exclusion of non – financial costs, as it focuses on the direct costs associated with emissions reductions. This can result in hidden costs. Also, it is a snapshot of one period of time, without giving information about the previous year or the next one (Kesicki and Strachan, 2011). However, MAC curves have been beneficial in the climate policy context for GHG emission sectors due to the demonstration of cost-effectiveness within and among sectors. They can also give the total cost necessary to abate a defined amount of GHG emissions.

2.3 Adopted Approach

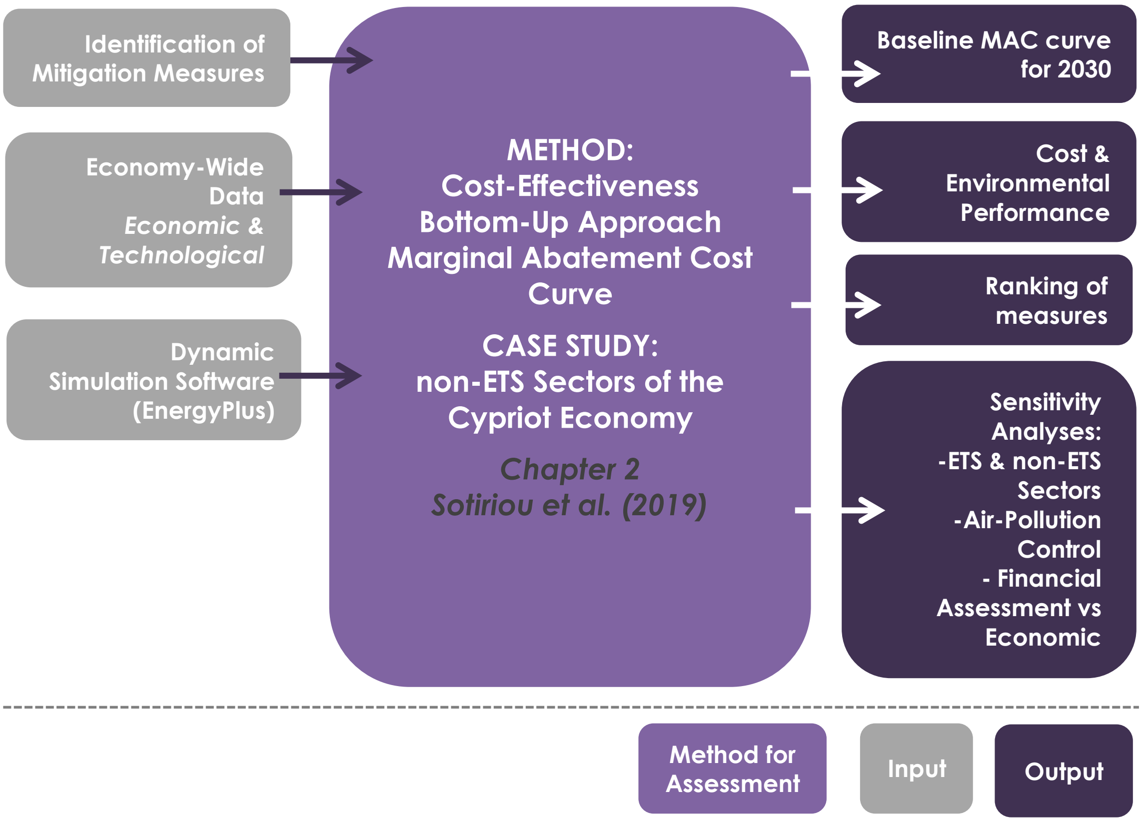

Figure 2.2|Method applied, main input and output included in the determination of cost-effective decarbonisation.

2.3.1 Identification of Mitigation Measures

The following subsections describe the measures considered for Cyprus. As mentioned in Section 2.1, any possible measures that could yield GHG emission reductions, additional to the policies and measures that have already been identified by national authorities of Cyprus by the time of the study, have been considered.

2.3.1.1 Residential Sector

To explore GHG abatement options for residential buildings, this study uses data and results from a recently completed Technical Assistance project that was funded by the European Commission's Structural Reform Support Service and was carried out for the Ministry of Energy, Commerce, Industry and Tourism (MECIT) of Cyprus (Vougiouklakis et al., 2017). This is a detailed national study that applied an engineering methodology to assess the maximum technical potential for energy savings in buildings and then adapted these estimates to consider the national market's realistic financial and technical constraints. Economic data for energy efficiency interventions were collected from the national market and helped to construct diverse cost-effectiveness indices. Finally, that study translated these assessments to aggregate energy demand forecasts and provided policymakers with a ranking of energy efficiency interventions in buildings as regards their cost-effectiveness.

Using technical and physical input parameters and a dynamic bottom-up algorithm, 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 (building construction permits per district provided by the Statistical Service of Cyprus). They distinguished into 84 building typologies based on building type, construction period and climatic area.

This study has extensively relied on data from that detailed modelling work, but they have been aggregated in order to arrive at a meaningful number of building variants that would be appropriate for the purpose of our study. Two building types have been distinguished that turned out to be the most significant: single-family houses and multi-family buildings. Buildings are also classified according to the 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 (two building types and two construction periods with and without refurbishment) is the most significant because energy performance regulations essentially started to be implemented in post-2008 buildings and have continued to evolve thereafter in line with the relevant EU legislation (Vougiouklakis et al., 2017; pp. 17-21).

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. Therefore the following measures are being considered:

- 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[6] (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.

2.3.1.2 *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

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[6] Pilotis are columns or similar structural elements that support a building above ground.

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 this 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 with considerable thermal energy needs for end uses that require hot water. The considered measures are listed below:

- Deep renovation, i.e. renovation of the building envelope so that it becomes a 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;
- Cogeneration (CHP units).

2.3.1.3 Industry Sector

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 (CHP units).

2.3.1.4 Road Transport Sector

The transport sector is responsible for a considerable amount of non-ETS emissions in Cyprus. According to the 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_2 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_2-based vehicle taxation to encourage the purchase of very low-CO_2 cars;
- Infrastructure investments for walking and cycling;
- Infrastructure investments for public transport;
- Use of alternative fuels (e.g. Compressed Natural Gas (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 Section 2.3.2.3. 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.

Since 2013, CO_2 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_2-based vehicle taxation more stringent, a shift to very low CO_2 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 does not change.

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_2 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 the EU level effectively impose a more stringent CO_2-based taxation for passenger cars without the need for additional national measures. More specifically, as of 2019, the CO_2 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_2 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. Hence, it is not further examined in this paper since our study considers mitigation measures that are additional to the existing ones.

Regarding the promotion of 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.

Cyprus has a very low share of public transport in passenger mobility (around 2%); hence, increasing buses' modal share 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 considerable 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.

For the last measure listed, it is assumed that a fraction of new cars sold each year uses a low-carbon or zero-carbon powertrain due to subsidies or a regulatory obligation. 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. Hence, it is also the average emission factor of all cars in use. In the case of passenger cars, a fuel switch is assumed to take place from conventional (petrol and diesel powered) cars to fully electric cars. In the case of freight transport, a fuel switch is assumed to occur from diesel powered to CNG-powered trucks.

2.3.1.5 Agriculture

The only agricultural emission mitigation measure considered in this study – 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 full exploitation of the biogas production capacity of existing animal waste processing plants, b) or through an investment in new anaerobic digesters.

2.3.1.6 Waste Management

Initially, the implementation of planned GHG emission mitigation measures for waste management in line with national policies described by MARDE (2016) was considered, 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 of in landfills; and separate collection of biodegradable waste. To collect information about the above measures and eventual additional policies, interviews were conducted 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, any measures to reduce GHG emissions from waste management were not considered; all realistic measures in this sector are already implemented, so there was currently no scope for additional measures to be included in this study.

2.3.2 Methodology

2.3.2.1 Outline

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 GHG, 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) the emissions abatement potential of each measure. 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 implementing a mitigation measure. This emission abatement is associated with the costs of the measure compared to the reference technology or device, or process. For each measure, the cost per unit of emissions abated can be calculated with the following formula:

$$CPA\,(j) = \frac{c_j^{mit} - c_j^{ref}}{E_j^{ref} - E_j^{mit}}$$

Equation 2.1 | Cost-effectiveness index.

The symbols *c* and *E* denote total discounted costs and emissions, respectively, and the superscripts *mit* and *ref* refer to the mitigation and reference scenario. The costs and emissions in Equation 2.1 are discounted using the same rate. This is a standard method used in marginal GHG abatement cost analysis or economic analysis of electricity generation using the common metric of Levelised Cost of Electricity (Baker and Khatami, 2019). *CPA* is expressed in constant Euros per tonne of CO_2 equivalent abated.

There are N abatement options, indexed by *j*. 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 MAC curve for the middle of the 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 substantial differentiation in the relative cost of the various policies considered.

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

$$C_j = \sum_{t=0}^{T} \frac{IC_{j,t}}{(1+r)^t} + \frac{MC_{j,t}}{(1+r)^t} + \frac{FC_{j,t}}{(1+r)^t}$$

Equation 2.2|Cost of mitigation measure.

The symbols *IC* refers to investment cost, *MC* refers to maintenance costs for each year and FC denotes the annual fuel costs; t relates to time in years, and the summations run from $t = 0$ to $t = T$. *T* indicates 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.

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 being used and calculated with the aid of the following formula; investment cost multiplied by the Capital Recovery Factor (CRF):

$$IC_{j,t} = INV_j \cdot r \cdot \frac{(1+r)^n}{(1+r)^n - 1}$$

Equation 2.3 | Annual investment cost of mitigation measure.

The *INV* is the up-front investment cost of the mitigation option *j*, 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.

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

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

Equation 2.4 | Emissions of CO_2, N_2O and CH_4.

The *A* refers to the relevant activity rate, and *EF* denotes the emission factors of the three main greenhouse gases: CO_2, CH_4 and N_2O; the two latter are multiplied by their Global Warming Potential (GWP) to be expressed in CO_2 equivalent terms. The GWP_{100} values used for CH_4 and N_2O without climate carbon feedback are according to the United Nations Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (IPCC, 2014) and in line with the guidance provided to environmental authorities.

If α_j is the GHG emissions abatement achievable with each measure *j* over a year, then:

$$a_j = \Delta E_j = E_j^{ref} - E_j^{mit} = A^{ref} \cdot EF_{GHG}^{ref} - A^{mit} \cdot EF_{GHG}^{mit}$$

Equation 2.5|Greenhouse emissions abatement.

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

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

Equation 2.6|Greenhouse emissions abatement - reduction in activity and/or in the emission factor.

The symbol EF_{GHG} is the GHG emission factor of the process or fuel, which is related to measure *j*, and ΔA 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.

It is also possible to perform an alternative calculation in which side-benefits of GHG abatement measures are considered. In this case, the air pollution reduction associated with the implementation of GHG emissions mitigation options is being considered. External costs must be included in such an assessment, which are intended to reflect all long-term damages related to climate change (e.g. on agricultural production, human health, ecosystems etc.), and are called ‘social cost of carbon’. These externalities 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.

This alternative cost-effectiveness assessment performed in this study – results presented in Section 2.4.2.2 – includes the external costs of GHG, nitrogen oxides (NOx) and sulphur dioxide (SO_2) emissions. For such a calculation, it is necessary to estimate the emissions of each gas 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. Therefore, the pollutants' emission factors and the marginal damage costs from the emission of an additional tonne of CO_2, NOx and SO_2 in the atmosphere must be selected or calculated based on national data. More information about the data used is provided in Section 2.3.3.

2.3.2.2 Building Interventions

As shown in Section 2.3.1.1 and 2.3.1.2, 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 annual fuel cost *FC* included in Equation 2.2 is related to the energy demand of the building expressed in thousands of Watt-hours (Wh) and the price of the corresponding fuels expressed in Euros per thousands of Wh with the following way:

$$FC = ED \cdot P_f$$

Equation 2.7|Fuel costs of building interventions.

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

$$\Delta FC = FC^{ref} - FC^{mit} = ED^{ref} \cdot P_f^{ref} - ED^{mit} \cdot P_f^{mit}$$

$$\Delta FC = \Delta ED \cdot P_f + ED \cdot \Delta P_f$$

Equation 2.8|Fuel costs savings - reduction in energy demand and/or change in the fuel price.

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 *j*, emissions of GHG are calculated by multiplying energy demand, *ED* by the corresponding emission factor, *EF*. The energy demand corresponds to the appropriate activity data described in the previous section and is measured in thousands of Wh per year.

The following equation is used to estimate the emissions abatement α_j, which is the change in emissions between the reference and mitigation scenario.

$$a_j = \Delta E_j = E_j^{ref} - E_j^{mit} = ED^{ref} \cdot EF_{GHG}^{ref} - ED^{mit} \cdot EF_{GHG}^{mit}$$

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

Equation 2.9|Greenhouse emissions savings - reduction in energy demand and/or change in the fuel price.

Emissions can also be estimated as the product of fuel consumption (on a mass or volume basis, i.e., in tonne/y or m^3/y) and an emission factor expressed in an appropriate unit (e.g., tonne of CO_2 equivalent per tonne of fuel).

As already explained, the above relationship shows that emissions abatement can be attained through a reduction in final energy demand (*ΔED*), keeping the fuel used the same as before, by a decrease in the emission factor (*ΔEF*) 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 in Section 2.3.1.1 and 2.3.1.2, and only to a limited extent by fuel substitution.

2.3.2.3 Modal Shift

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 with the use of the general Equation 2.4, 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 the product of fuel sold (fuel consumed), *FS* in a given time period, and the composite emission factor, *EF* of the three main GHG; carbon dioxide, methane and nitrous oxide for the specific fuel.

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

Equation 2.10|Greenhouse gas emissions from mobile combustion – type and amount of fuel consumed basis.

If the activity parameter is the distance travelled, *D* (kilometres travelled in a given time period), then emissions are calculated as follows:

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

Equation 2.11|Greenhouse gas emissions from mobile combustion – distance travelled basis.

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). The following section provides details on the underlying figures used for this analysis.

The measures applicable for the road transport sector are not as heterogenic as the ones found in the household and tertiary sectors. Thus the general equations presented above are modified depending on the basic mechanism involved in the reduction of GHG emissions. The rest of this section presents the methodology separately for the main types of mitigation measures evaluated.

Infrastructure investments for a) public transport and b) walking and cycling are some of the main mitigation measures for road 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 related to the investment cost, maintenance cost and fuel cost of new buses. It is also accompanied by significant 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 (ΔPKT) 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 (ΔVKT^{ref}) and a rise in the distance travelled with buses (ΔVKT^{mit}). Based on international and local experience, OR_{car} is assumed to be equal to 1.5 passengers per vehicle and OR_{bus} equal to 15 passengers per vehicle.

$$\Delta VKT^{ref,car} = \Delta PKT \ / \ OR_{car}$$

Equation 2.12 | Conversion of passenger kilometres into vehicles kilometres travelled by private cars.

$$\Delta VKT^{mit,bus} = \Delta PKT \ / \ OR_{bus}$$

Equation 2.13 | Conversion of passenger kilometres into vehicles kilometres travelled by public mode.

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 (ΔFS). Regarding the mitigation scenario, the additional fuel costs is a function of the extra fuel consumed by the price of the given fuel P_f, in this case, automotive diesel. Therefore, public modes' fuel costs can be calculated with the aid of the following formula:

$$\Delta FC^{mit,bus} = \Delta FS^{bus} \cdot P_f$$

Equation 2.14 | Additional fuel costs of public transport modes.

The fuel consumption is a relation between the additional kilometres travelled by public transport modes, ΔVKT^{mit} and the average fuel consumption of the buses, AFC expressed in litres of fuel per kilometre travelled.

$$\Delta FS^{bus} = \Delta VKT^{mit,bus} \cdot AFC_{bus}$$

Equation 2.15 | Additional fuel consumption of public transport modes.

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

$$\Delta FC^{avoided} = \sum_{f} \left(\Delta FS_{f}^{avoided} \cdot P_{f} \right)$$

Equation 2.16 | Avoided fuel costs - lower use of private cars.

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

$$\Delta FS_{f}^{avoided} = \sum_{f} \left(\Delta VKT_{f}^{ref,car} \cdot AFC_{cars,f} \right)$$

Equation 2.17 | Avoided fuel consumption - lower use of private cars.

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

$$\Delta FC = \Delta FC^{bus} - \Delta FC^{avoided} = \Delta FS^{bus} \cdot P_{f} - \sum_{f} \left(\Delta FS_{f}^{avoided} \cdot P_{f} \right)$$

Equation 2.18 | Total fuel costs - additional penetration of public transport modes.

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

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

Equation 2.19 | Greenhouse gas emissions abatement - enhanced public transport system.

Improving the infrastructure for walking and cycling is associated with an investment cost and maintenance cost. Although there is no fuel costs associated with the implementation of this measure, there is an avoided fuel costs because of the reduced use of private cars due to the increased share of walking and cycling.

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

Equation 2.20 | Avoided fuel costs due - increased share of walking and cycling.

The fuel consumption avoided can be calculated as the product of vehicle kilometres avoided by cars using a specific type of fuel and the average fuel consumption of cars using the corresponding fuel.

$$\Delta FS_f^{avoided} = \sum_f \Delta VKT_f^{ref,car} \cdot AFC_f$$

Equation 2.21 | Avoided fuel consumption - increased share of walking and cycling.

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

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

Equation 2.22 | Greenhouse gas emissions abatement - increased share of walking and cycling.

As mentioned in previous Section 2.3.1.4, due to significant uncertainties of the needed data, the effect of walking and cycling infrastructure was not further examined in this study.

Regarding mitigation measures that entail the use of alternative fuels for cars and/or trucks, 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. Hence, it is also the average emission factor of all cars in use.

In order to calculate the total discounted cost of such a measure, one needs to calculate the change in each cost item. The change in investment and maintenance costs will be:

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

Equation 2.23|Difference in investment cost - alternative fuelled vs conventional vehicles.

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

Equation 2.24|Difference in maintenance cost - alternative fuelled vs conventional vehicles.

where *NEW* denotes the number of newly registered vehicles per year that run on an alternative instead of conventional fuel and the *alt, conv* indices denoting alternative fuelled and conventional vehicles, respectively.

The difference in fuel cost will be:

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

Equation 2.25 | Difference in fuel cost - alternative fuelled vs conventional vehicles.

The fuel consumed, *FS* can be calculated with the following general equation, with the distanced-based activity remaining the same for both scenarios. For this approach, national data regarding the average distance travelled per vehicle, *KMV* will be required.

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

Equation 2.26 | Fuel consumption - distanced-based activity.

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

$$\boldsymbol{\alpha = \Delta E = VKT \cdot (EF_{GHG}^{ref} - EF_{GHG}^{mit}) = NEW \cdot KMV \cdot (EF_{GHG}^{ref} - EF_{GHG}^{mit})}$$

Equation 2.27 | Greenhouse gas emissions abatement - distanced-based activity.

The reduction here is achieved through the difference in the emission factor ΔEF_{GHG} due to the use of a lower-carbon fuel. In the case of passenger cars, a fuel switch is assumed to take place from conventional (petrol and diesel powered) cars to electric cars. In the case of trucks, a fuel switch is assumed to occur from diesel powered to CNG-powered trucks.

2.3.2.4 Manure Management

As mentioned in Section 2.3.1.5, the only agricultural emission mitigation measure considered in this study is the reduction of emissions from manure management from the promotion of anaerobic digestion for animal waste. Based on an estimation of the amount of GHG emissions to be reduced provided by MARDE (2016), it was possible to assess the amount of additional animal waste that has to be fed to anaerobic digesters to achieve these emission reductions. This calculation 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. Sources of these data are provided in Section 2.3.3.5.

When knowing the additional amount of waste that needs to be directed to anaerobic digesters, it is possible to assess the investment and operation cost of installations that will have to use this additional waste. More details are given in Section 2.3.3.5.

2.3.3 Data and Assumptions on Policies and Measures

The cost-effectiveness analysis performed in the context of this study includes the assessment of possible mitigation measures applicable to all economic sectors of Cyprus from an economic and environmental point of view. As a result, a set of climate change mitigation actions will be described by a) the emissions abatement cost and b) emissions abatement potential and ranked in ascending cost order illustrating them graphically in a bottom-up 'measure-explicit' MAC curve.

Summarizing the previous Section 2.3.2, the total abatement cost of a measure is the sum of the discounted investment, maintenance and fuel costs compared to a "reference scenario" without mitigation measures. 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 after the implementation of a mitigation measure and comparing them with the calculated GHG emissions of a "reference scenario" without mitigation. Then, for each measure, the cost per unit of emissions abated is calculated by dividing the cost difference by the difference in GHG emissions. Regarding the emission factors of the three main GHGs included in the assessment, those are sector and process-specific, and they will be presented by sector in each one of the sections below.

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 the 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 MAC curve for intermediate years during the decade in order to determine a more realistic mix of cost-effective mitigation policies. However, this re-calculation was not conducted in the study because (despite foreseen reductions in the absolute costs of mitigation measures) there are no clear indications for substantial differentiation in the relative cost of the various policies considered in the analysis. Indeed, different technologies have different learning curves, so that differentiation of the relative cost-effectiveness of technologies may result in the future if a different technical change is assumed for each measure. However, a year-by-year calculation would greatly increase the computational burden without leading to essentially different policy conclusions compared with our baseline approach. To be presented in Section 2.4.2, sensitivity analyses 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 IEA's World Energy Outlook 2016 (IEA, 2016).

Since the study follows a social planner's approach, an economic (and not a financial) assessment is conducted; costs and benefits are evaluated from a public policy perspective. Hence fuel and electricity prices are net of taxes and duties (Ea Energy Analyses, 2011). For this reason, 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).

Emission calculations for air pollutants were based on the internationally accepted methodology recommended in the European Monitoring and Evaluation Programme (EMEP)/ European Environment Agency (EEA) Emissions Inventory Guidebook (EEA, 2013) with the aid of national data on fuel quality and power generation emission. Regarding the power generation emission factors, the NO_x emission factor was calculated based on the power generation mix of Cyprus by the time of conducting this study. Respectively, the SO_2 emission factor was estimated based on the weighted average sulphur of fuels used. More details on this estimation are provided in Appendix II of Zachariadis et al. (2018a).

Table 2.1 | External costs of GHGs and the two pollutants considered – NO_x and SO_2.

Gas	Year					Units
	2020	2025	2030	2035	2040	
GHG	35.4	38.6	42.7	46	50.1	€/tonne of GHG
NO_x	7,624	8,286	9,006	9,392	9,793	€/tonne of NO_x
SO_2	13,923	15,121	16,425	17,122	17,849	€/tonne of SO_2

As far as external costs are concerned, for GHG emissions, the assessment of marginal damage costs made by the United States (US) Environmental Protection Agency (EPA) has been used (IWG, 2013). For assessing the cost of NOx and SO_2 emissions, calculations of the European studies were used–results from the Cost Assessment for Sustainable Energy Systems (CASES) project (FEEM, 2008). The total cost of each pollutant is the sum of the effect of damages on human health, crops, materials and biodiversity. Marginal damage costs for the case of Cyprus have been adapted from those relevant international studies by Zachariadis and Hadjikyriakou (2016), presented in Table 2.1.

2.3.3.1 Residential Sector

The implementation of the measures listed in Section 2.3.1.1 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 Section 2.3.2.2, 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.

Table 2.2 and Table 2.3 present the cost data and energy savings for each individual measure for the four different classes of buildings considered in our study. For the assessment of the mitigation measure related to the replacement of heating and cooling systems with modern, highly efficient heat pumps, the energy demand that satisfies optimal thermal comfort requirements for each constructing period included in Table 2.2 and Table 2.3 and the data reported in Table 2.4 are required.

Note that the savings shown in Table 2.2 and Table 2.3 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, Table 2.5 shows the main technologies and their corresponding average thermal efficiency used for space heating and cooling in residential buildings in Cyprus by construction period. To calculate final energy savings by abatement option, the predominant technology was compared 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. Under the non-ETS assessment, the measures applied in buildings after 2008 are excluded as the heat pump is the predominant technology used for both heating and cooling needs; thus, any intervention will affect the ETS emissions. For buildings before 2008, the heating aspect of the intervention is included as it is related to reduced direct emissions, in contrast with the cooling needs, which are also covered by heat pumps and are associated with indirect emissions. Note that the energy savings shown in Table 2.2 and Table 2.3 refer to the operation of equipment that satisfies optimal thermal comfort requirements.

For the case of mitigation measures involving a reduction in electricity use, the savings reported in Table 2.2 and Table 2.3 refer to the final consumption of electricity. Since emissions are generated during the production of electricity, conversion of the respective quantities into power production is necessary with the use of transmission and distribution system's loss coefficient (EAC, 2015).

Table 2.6 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 Table 2.2, Table 2.3, Table 2.4, Table 2.5 and Table 2.6, 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 2.7 shows the GHG emission factors applied for the residential sector; these are primarily based on guidance provided by the IPCC (IPCC, 2006).

Table 2.2|Input for MAC methodology – Data including a) costs savings, b) energy savings and c) lifetime for each measure considered in single-family buildings constructed before and after 2008, and d) energy demand that satisfies optimal thermal comfort requirements for each constructing period retrieved from Vougiouklakis et al. (2017).

Measure	**Variation in energy demand** [kWh$_{th}$] **for:**		**Investment Cost*** [€]	**Maintenance Cost*** [€]	**Lifespan** [y]
	Heating	Cooling			
Single-Family before 2008 (1990)					
Full renovation	817	-12,493	26,600	1,447.0	30
Roof insulation	359	-9751	4,250	85.0	30
Wall insulation	-360	-978	13,100	262.0	30
Windows replacement	280	-742	9,250	1,100.0	30
Lighting [kWhel]	-1,240		650	19.5	15
Solar Thermal [kWhth]	-2,000		1,200	100.0	20
Energy Demand for: [kWh]	*12,460*	*21,095*			
Single-Family after 2008					
Full renovation	-978	-1,422	34,600	2,787.0	30
Roof insulation	-1,126	-510	2,750	55.0	30
Wall insulation	-440	-842	11,600	232.0	30
Windows replacement	-387	-28	20,250	2,250.0	30
Lighting [kWhel]	-1,595		800	36.0	15
Solar thermal [kWhth]	-2,000		1,200	100.0	20
Energy demand for: [kWh]	*13,300*	*12,680*			

*Cost values w/o VAT

Table 2.3|Input for MAC methodology – Data including a) costs savings, b) energy savings and c) lifetime for each measure considered in multi-family buildings constructed before and after 2008, and d) energy demand that satisfies optimal thermal comfort requirements for each constructing period retrieved from Vougiouklakis et al. (2017).

Measure	**Variation in energy demand** [kWh$_{th}$] **for:**		**Investment Cost*** [€]	**Maintenance Cost*** [€]	**Lifespan** [y]
	Heating	Cooling			
Multi-Family before 2008 (1990)					
Full Renovation	-8,278	-19,581	46,750	3,477.0	20
Roof Insulation	-2,936	-12,943	3,350	67.0	20
Wall Insulation	-1,481	-1,731	15,650	313.0	20
Pilotis Insulation	-3,090	3,426	3,350	67.0	20
Windows Replacement	704	-3,460	24,400	3,000.0	20
Lighting [kWhel]	-3,460		1,750	52.5	15
Solar Thermal [kWhth]	-6,000		3,600	300.0	20
Energy Demand for: [kWh]	15,640	45,560			
Multi-Family after 2008					
Full Renovation	-5,578	-3,341	80,800	6,150.0	20
Roof Insulation	-573	-1,289	5,000	100.0	20
Wall Insulation	-2,526	-2,809	26,800	536.0	20
Pilotis Insulation	-1,317	358	5,700	114.0	20
Windows Replacement	-949	424	43,300	5,400.0	20
Lighting [kWhel]	-6,385		3,250	97.5	15
Solar Thermal [kWhth]	-12,00		7,200	600.0	20
Energy Demand for: [kWh]	*14,777*	*43,285*			

*Cost values w/o VAT

Table 2.4| Input for MAC methodology – Data including a) energy efficiency figures, b) costs and c) lifetime of new heat pumps applicable to the residential sector retrieved from Vougiouklakis et al. (2017).

New heat pump specifications

Type	**Seasonal Energy Efficiency Ratio** (SEER)	**Seasonal Coefficient Performance** (SCOP)	**Comment**	**Investment cost*** [€]	**Maintenance cost*** [€]	**Lifespan** [y]
Split, Air-to-Air	515%	475%	Actual data; applicable to residential single-family buildings before 2008	3,200	128	15
Split, Air-to-Air	515%	475%	Actual data; applicable to residential single-family buildings after 2008	4,000	160	15
Split, Air-to-Air	515%	475%	Actual data; applicable to residential multi-family buildings before 2008	9,600	384	15
Split, Air-to-Air	515%	475%	Actual data; applicable to residential multi-family buildings after 2008	14,400	576	15

*Cost values w/o VAT

Table 2.5|Input for MAC methodology – Data including a) technologies and b) fuels used in residential buildings of Cyprus by the construction period and their corresponding efficiency figures and c) shares of each technology in the stock of appliances of the corresponding building types retrieved from Vougiouklakis et al. (2017).

Technology	Fuel	Efficiency	Share in the total stock of appliances
Heating Systems – Before 2008			
Central heating	Diesel	80%	23.6%
Heat pump	Electricity	320%	15.2%
Stove	Electricity	100%	17.1%
Stove	LPG	70%	23.0%
Fireplace	Biomass	30%	7.3%
Storage	Electricity	100%	4.5%
Heating Systems – After 2008			
Central heating	Diesel	80%	9.1%
Heat pump	Electricity	320%	38.6%
Stove	Electricity	100%	18.2%
Stove	LPG	70%	4.5%
Fireplace	Biomass	30%	8.0%
Storage	Electricity	100%	9.1%
Cooling Systems – Before 2008			
Heat pump	Electricity	250%	100.0%
Cooling Systems – After 2008			
Heat pump	Electricity	320%	100.0%

Table 2.6|Input for MAC methodology – Data including the number of interventions for each mitigation measure proposed for the residential sector in Cyprus up to 2030 retrieved from Vougiouklakis et al. (2017).

Intervention	Number of intervention up to 2030	Fraction of current building stock
Single-Family Buildings		
Full Renovation	1,000	0.3%
Roof Insulation	12,000	3.9%
Wall Insulation	2,500	0.8%
Window Frame System Upgrade	3,500	1.1%
Lighting and Electronic Appliances	21,000	6.8%
Solar Thermal Water Heaters	3,500	1.1%
Heat Pumps	2,500	0.8%

Intervention	Number of intervention up to 2030	Fraction of current building stock
Multi-Family Buildings		
Full Renovation	500	0.4%
Roof Insulation	3,500	2.8%
Wall Insulation	600	0.5%
Pilotis Insulation	300	0.2%
Window Frame System Upgrade	2,000	1.6%
Lighting and Electronic Appliances	5,500	4.4%
Solar Thermal Water Heaters	500	0.4%
Heat Pumps	1,500	1.2%

Table 2.7|Input for MAC methodology – Data including GHG emission factors applied for the residential sector retrieved from IPCC (2006) for the case of gas oil and MARDE (2017) for electricity.

	CO_2	N_2O	CH_4	CO_2 equivalent	Units
Gas oil	0.267	2.160×10^{-6}	1.08×10^{-5}	0.2677	Kg/kWh
Electricity	0.741	5.64×10^{-6}	2.847×10^{-5}	0.7431	Kg/kWh

Table 2.8|Input for MAC methodology – Data including pollutants emission factors applied for the residential sector.

	NOx	SO_2	Units
Power Generation	0.00129	0.00394	Kg/kWh
Heating gas oil	0.0001836	0.000166	Kg/kWh

Table 2.8 includes the emission factors of the pollutants NO_x and SO_2 for the power generation and gas oil for heating purposes. For the electricity, the NO_x emission factor was estimated based on the power generation mix of Cyprus at the time of this study. The SO_2 emission factor was calculated based on the weighted average sulphur content (equal to 0.68%) of fuels used for power generation in Cyprus. These data were obtained from information provided by the Electricity Authority of Cyprus to national air quality authorities and reported by Zachariadis and Hadjikyriakou (2016). The corresponding emission factors for gas oil were retrieved from EEA (2013).

2.3.3.2 Tertiary Sector

Cost and energy savings data for this sector are presented in Table 2.9. As already mentioned for the residential sector, energy savings refer to the demand for useful energy, and efficiency figures of Table 2.5 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. Regarding the replacement of heating and cooling systems with modern, highly efficient heat pumps, data are included in Table 2.10.

Table 2.11 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 presented in Table 2.12.

Regarding the cogeneration measure, it was assumed that up to 30 CHP units could be realistically installed, with a nominal electricity capacity of 100 thousand Watt (W) each. To achieve the maximum possible emission savings, it was assumed that the CHP units would be fuelled by liquefied petroleum gas (LPG) and replace gas oil fired boilers (Table 2.13). In line with relevant industrial information, the 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.

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 concerning the non-ETS assessment.

Table 2.9|Input for MAC methodology – Data including a) costs savings, b) energy savings and c) lifetime for each measure considered in office buildings constructed before and after 2008, and d) energy demand that satisfies optimal thermal comfort requirements for each constructing period retrieved from Vougiouklakis et al. (2017).

Measure	**Variation in energy demand** [kWh$_{th}$] **for:** Heating	Cooling	**Investment Cost** [€]	**Maintenance Cost** [€]	**Lifespan** [y]
Office building before 2008 (1990)					
Full Renovation	-9,720	-21,300	141,000	6,520	20
Roof Insulation	-2,515	-7,270	12,000	240	20
Wall Insulation	-4,010	-490	55,000	11,000	20
Pilotis Insulation	-3,115	4,480	9,000	180	20
Windows Replacement	1,470	-12,890	65,000	5,000	20
Lighting [kWhel]	-12,200		7,600	228	18
Solar Thermal [kWhth]	-6,000		3,600	300	20
Energy Demand for: [kWh]	*16,890*	*84,185*			
Office building after 2008					
Full Renovation	-3,460	570	128,000	6,260	20
Roof Insulation	-415	-665	9,500	190	20
Wall Insulation	-1,890	-960	47,000	940	20
Pilotis Insulation	-720	755	6,500	130	20
Windows Replacement	-490	1,270	65,000	5,000	20
Lighting [kWhel]	-12,000		7,600	228	18
Solar Thermal [kWhth]	-12,000		7,200	600	20
Energy demand for: [kWh]	*18,875*	*60,800*			

Table 2.10|Input for MAC methodology – Data including a) energy efficiency figures, b) costs and c) lifetime of new heat pumps applicable to the tertiary sector retrieved from Vougiouklakis et al. (2017).

Type	**Seasonal Energy Efficiency Ratio** (SEER)	**Seasonal Coefficient Performance** (SCOP)	**Comment**	**Investment Cost** [€]	**Maintenance Cost** [€]	**Lifespan** [y]
Package, VRV	500%	460%	Actual data; applicable to commercial buildings for both construction periods	92,500	3,700	15

Table 2.11|Input for MAC methodology – Data including the number of interventions for each mitigation measure proposed for the tertiary sector in Cyprus up to 2030 retrieved from Vougiouklakis et al. (2017).

Intervention	Total number of interventions up to 2030	Fraction of current building stock
Deep renovation (nZEB)	800	0.9%
Roof insulation	3,000	3.5%
Wall insulation	600	0.7%
Pilotis insulation	150	0.2%
Window frame system upgrade	800	0.9%
Lighting and electronic appliances	7,000	8.2%
Heat pumps	3,500	4.1%
Solar thermal system for hot water production	2,500	2.9%

Table 2.12|Input for MAC methodology – Data including GHG emission factors applied for the tertiary sector retrieved from IPCC (2006) for the case of gas oil, LPG and MARDE (2017) for electricity.

	CO_2	N_2O	CH_4	CO_2 equivalent	Units
Gas/diesel oil	0.267	2.160×10^{-6}	1.08×10^{-5}	0.2677	Kg/kWh
LPG	0.227	3.600×10^{-7}	3.600×10^{-6}	0.2274	Kg/kWh
Electricity	0.741	5.694×10^{-6}	2.847×10^{-5}	0.7431	Kg/kWh

Table 2.13|Input for MAC methodology – Data including cost data of the CHP units to be installed in the tertiary sector retrieved from Vougiouklakis et al. (2017).

	Electricity Production [kWh/y]	Heat Production [kWh/y]	Gas Oil Substitution [kWh/y]	Investment Cost [€]	Maintenance Cost [€]	Lifespan [y]
CHP 100 kWel - LPG	815,760	1,322,640	1,765,000	165,000	4,950	15

2.3.3.3 *Industry*

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. The emission factors used are included in Table 2.14. Emissions calculations of air pollutants were made based on data provided in Table 2.15. Table 2.16 illustrates the costs and assumed energy savings for the industry-related measures, taking into account the diversity of uses and operation modes of equipment in industrial plants of Cyprus.

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 25 CHP units could be realistically installed in industrial plants across Cyprus, with a nominal electricity capacity of 100 thousand W each. To achieve the maximum possible emission savings, it was assumed that the CHP units would 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. The rest of the measures, except for the replacement of fuel oil fired burners with modern, efficient ones, are related to electricity-generation emissions reduction and are excluded for the non-ETS assessment.

Table 2.14|Input for MAC methodology – Data including GHG emission factors applied for the industry sector retrieved from IPCC (2006) for the case fuel oil, LPG and MARDE (2017) for electricity.

	CO_2	N_2O	CH_4	CO_2 equivalent	Units
LFO	0.279	2.160×10^{-6}	1.080×10^{-5}	0.2796	Kg/kWh
LPG	0.227	3.600×10^{-7}	3.600×10^{-6}	0.2274	Kg/kWh
Electricity	0.741	5.694×10^{-6}	2.847×10^{-5}	0.7431	Kg/kWh

Table 2.15|Input for MAC methodology – Data including pollutants emission factors applied for the industry sector.

	NOx	SO_2	Units
Power Generation	0.00129	0.00394	Kg/kWh
Fuel Oil	0.00185	0.00162	Kg/kWh

Table 2.16|Input for MAC methodology – Data including a) energy saving and b) cost savings for each measure considered in the industry sector retrieved from Vougiouklakis et al. (2017).

Measure	**Savings** [kWh/kW/y]	**Investment Cost*** [€/kWh]	**Maintenance Cost*** [€/kWh]	**Lifespan** [y]	**Overall Savings** [kWh/y]	**Overall Investment cost*** [€]	**Overall Maintenance cost*** [€]
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
Burner Replacement	224	4.60 - 8.50	0.34	10	1,325,940	56,500	2,933

*Cost values w/o VAT

Table 2.17|Input for MAC methodology – Data including a) investment cost, b) maintenance cost and c) lifetime for each measure considered in the road transport sector.

Measure	Investment Cost [€]	Maintenance Cost [€]	Lifetime [y]	Source
Promotion of Public Transport	100,000,000	2,000,000	12	Assumed expenditures for public transport infrastructure and purchase of additional buses for the entire period 2020-2030
Introduction of Electric Cars				
Conventional Car	18,918	1,000	12	European Commission recommended data for “ordinary” technology
Electric Car	25,839	1,000	12	European Commission recommended data for “ordinary” technology, assuming an extra premium in the retail price of battery electric cars
Introduction of CNG Trucks				
Difference: CNG-powered truck - Diesel-powered truck	30,000	-	12	Based on European Commission recommended data, assuming extra cost for CNG trucks because currently, no CNG infrastructure exists

Table 2.18|Input for MAC methodology – Data including the suggested extend of implementation for each measure considered in the road transport sector.

Measure	Savings occurring from:	Source
Promotion of Public Transport	Amount of passenger kilometres shifted up to 2030 from cars to buses: 7% that accounts for 434,000,000 pkm	Assumption: according to European Commission (2017)
Introduction of Electric Cars	Fraction of new cars sold up to 2030 using low-carbon powertrain: 50%	Assumption
Introduction of CNG Trucks	Fraction of new trucks sold up to 2030 using CNG as a fuel: 50%	Assumption

Table 2.19|Input for MAC methodology – Data including average fuel consumptions by different mode and fuel.

	Average Fuel Consumption	Units	Source
Passenger Cars			
Gasoline	7.7	l/100 km	European Commission recommended data for “ordinary” technologies
Diesel	5.9	l/100 km	
Electricity	0.2	kWh/km	
Buses			
Diesel	28	l/100 km	National estimates used in the Odyssee-Mure database
Trucks			
Diesel	32	l/100 km	National estimates used in the Odyssee-Mure database
CNG	14	MJ/km	Copert model (personal communication with Emisia S.A.)

Table 2.20|Input for MAC methodology – Data including a) average kilometres travelled each year, b) national estimates on the number of yearly new registrations and c) occupancy rate of different modes.

Parameter	Value	Units	Source
Average kilometres travelled by:			
Passenger car	12,000	km/car	National estimates used in the Odyssee-Mure database
Truck	25,000	km/truck	
Newly registered:			
Passenger car	25,000	cars/y	National estimates used in the Odyssee-Mure database
Truck	500	trucks/y	
Occupancy Rate:			
Passenger car	1.5	passengers/car	Assumption
Bus	15	passengers/bus	Assumption

Table 2.21|Input for MAC methodology – Data including GHG emission factors applied for road transport retrieved from IPCC (2006) for the case of gas oil, diesel, CNG and MARDE (2017) for electricity.

	Emission Factor	Units	Source
Gasoline			
CO_2	69,300	kg/TJ	(IPCC, 2006)
CH_4	25	kg/TJ	(IPCC, 2006)
N_2O	8	kg/TJ	(IPCC, 2006)
CO_2 equivalent	2.398	$kgCO_{2\text{-}e}/l$	Calculated
Diesel			
CO_2	74,100	kg/TJ	(IPCC, 2006)
CH_4	3.9	kg/TJ	(IPCC, 2006)
N_2O	3.9	kg/TJ	(IPCC, 2006)
CO_2 equivalent	2.759	$kgCO_{2\text{-}e}/l$	Calculated
Electricity			
CO_2	0.7407	$kgCO_2/kWh_{el}$	Cyprus GHG Inventory Report (MARDE, 2017)
CH_4	2.847×10^{-5}	$kgCH_4/kWh_{el}$	Cyprus GHG Inventory Report (MARDE, 2017)
N_2O	5.694×10^{-6}	kgN_2O/kWh_{el}	Applies to the current power generation mix of Cyprus
CO_2 equivalent	0.743	$kgCO_{2\text{-}e}/kWh_{el}$	Calculated
CNG			
CO_2	56,100	kg/TJ	(IPCC, 2006)

2.3.3.4 Road Transport

Table 2.17, Table 2.18, Table 2.19 and Table 2.20 summarise the main data and assumptions used for the cost-effectiveness calculations in the road transport sector, limited to the measures eventually assessed as explained in Section 2.3.1.4. 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 2.21 includes the appropriate factors for emission calculations in the road transport sector.

For the assessment of the air pollution control, emission factors of the pollutants were estimated based on EEA methodology (EEA, 2013) – average weighted emission factors for the Cypriot vehicle stock calculated with the assistance of a) the Department of Labour Inspection of the Republic of Cyprus and b) Emisia S.A. for emission factor for diesel buses is for new (Euro VI) vehicles, which are assumed in the study to replace part of passenger car mobility. All the above are included in Table 2.22.

Table 2.22|Input for MAC methodology – Data including pollutants emission factors applied for the road transport sector.

	NOx	SO_2	Units
Transport emission factors			
Gasoline Car	0.00208	0.0000741	kg/l
Diesel Car	0.00929	0.0000844	kg/l
Diesel Bus (Euro VI)	0.00200	0.0000844	kg/l
Diesel Truck	0.0145	0.0000844	kg/l
CNG Truck	0.002	-	Kg/km

2.3.3.5 Agriculture

This section describes the approach and data used to assess costs and emission reduction from manure management from the promotion of anaerobic digestion for animal waste as discussed in Section 2.3.1.5.

As regards the amount of GHG emissions to be reduced, MARDE (2016) estimated a decrease of 15.3 thousand tonnes of CO_2 equivalent by 2020, or 8.5% compared with the baseline situation without measures; this decrease is assumed to remain the same up to 2030.

Table 2.23|Input for MAC methodology – Data including animal population growth forecast.

	Type of animal:				Type of animal:		
Year	**Cattle**	**Pigs**	**Poultry**	**Year**	**Cattle**	**Pigs**	**Poultry**
2020	62,521	307,863	3,309,359				
2021	62,521	307,863	3,309,359	2036	62,521	307,863	3,309,359
2022	62,521	307,863	3,309,359	2037	62,521	307,863	3,309,359
2023	62,521	307,863	3,309,359	2038	62,521	307,863	3,309,359
2024	62,521	307,863	3,309,359	2039	62,521	307,863	3,309,359
2025	62,521	307,863	3,309,359	2040	62,521	307,863	3,309,359
2026	62,521	307,863	3,309,359	2041	62,521	307,863	3,309,359
2027	62,521	307,863	3,309,359	2042	62,521	307,863	3,309,359
2028	62,521	307,863	3,309,359	2043	62,521	307,863	3,309,359
2029	62,521	307,863	3,309,359	2044	62,521	307,863	3,309,359
2030	62,521	307,863	3,309,359	2045	62,521	307,863	3,309,359
2031	62,521	307,863	3,309,359	2046	62,521	307,863	3,309,359
2032	62,521	307,863	3,309,359	2047	62,521	307,863	3,309,359
2033	62,521	307,863	3,309,359	2048	62,521	307,863	3,309,359
2034	62,521	307,863	3,309,359	2049	62,521	307,863	3,309,359
2035	62,521	307,863	3,309,359	2050	62,521	307,863	3,309,359

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 relied on a forecast of the evolution of the animal population in Cyprus by animal type (Table 2.23) and on specific waste-related information (Table 2.24) 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.

Table 2.24| Input for MAC methodology – Data including animal waste data.

	Waste Density [tonnes/m^3]	**Waste generated** [tonnes/animal/y]
Cattle	1.551	2.591
Pigs	0.973	3.094
Poultry	0.546	0.013

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. Therefore it is assumed that, for the other plants to exploit their capacity fully, 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 2,700 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. It is 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 million Wh per year (MWh/y), 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. However, under the non-ETS assessment that electricity-related emissions much be excluded from the abatement calculations. The additional thermal energy to be generated by biogas CHP plants was ignored in the analyses because a large part of the thermal energy produced already now is wasted as there is a limited thermal capacity that 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.

The diagram of Figure 2.3 summarises the procedure followed on the cost-effectiveness approach presented in all the above sections.

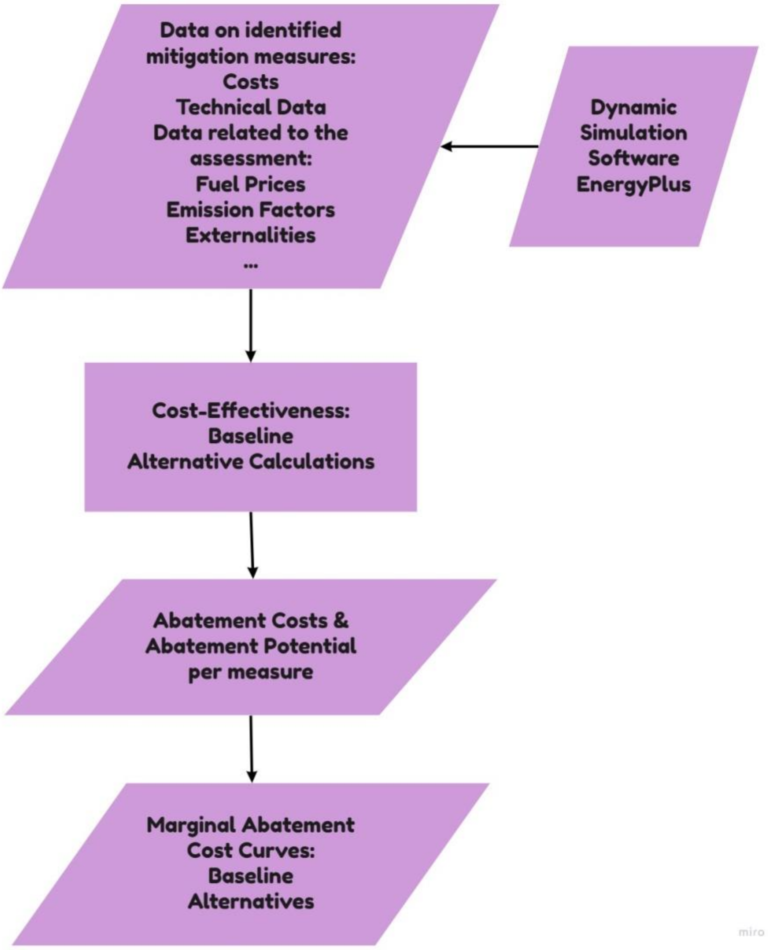

Figure 2.3|Schematic presentation of the methodology used for the determination of cost-effective decarbonisation policy mixes.

2.4 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 Section below, 2.4.1, reports the results of the baseline calculations. Section 2.4.2 describes three sensitivity cases and shows the corresponding alternative results.

2.4.1 Baseline MAC Curve

Figure 2.4 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 effect on emissions due to changes 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;
- the use of cogeneration in the industrial and tertiary sector;
- the roof insulation in pre-2008 residential multi-family buildings;
- the increased use of anaerobic digestion for animal waste;
- the replacement of burners in the 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 2.4 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 (Kesicki and Ekins, 2012; Taylor, 2012). 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 decarbonisation 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.

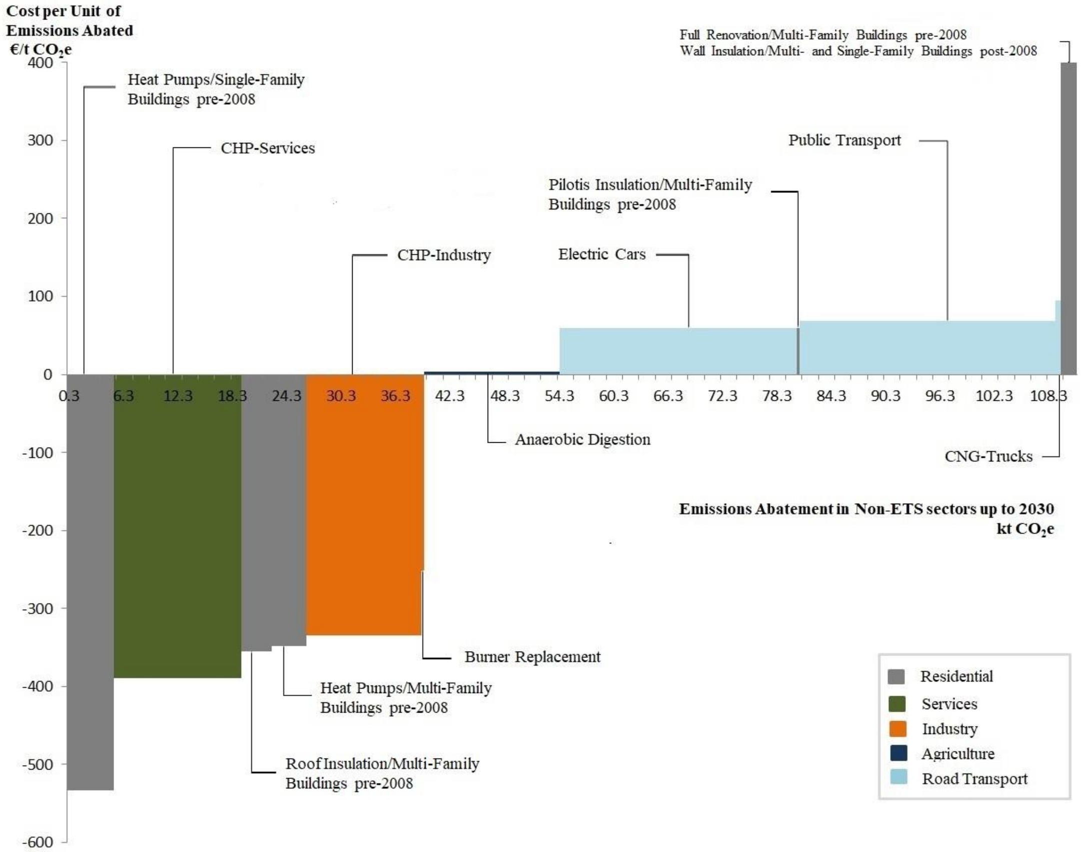

Figure 2.4|Marginal GHG emissions abatement cost curve for Cyprus, taking into account the emissions abatement potential in non-ETS sectors. Each measure is coloured according to the economic sector to which it belongs, as shown in the legend of the graph.

These results are similar to those coming out from other national studies. Despite several national particularities such as different needs for heating and cooling in buildings or different energy price structure, the studies of Toleikyte et al. (2018) for

Lithuania and Timilsina et al. (2017) for Armenia and Georgia display a similar ranking of measures, showing several types of building energy renovations to be the most cost-effective. This is also the case with the results of Wächter (2013) for Austria as regards building renovations; that study, however, shows that energy efficiency measures in cars and trucks are also very cost-effective, which is not confirmed by our results. The difference lies in the definition of measures for road transport: the Austrian study focuses on technical improvements in the existing types of car and truck engines and does not include fuel switch or modal shifts (Wächter, 2013; p.1119), whereas our study examines more radical measures (electric cars, CNG-powered trucks and shift to public transport) because these have a more long-term effect and can offer substantial benefits in view of long-term decarbonisation commitments. Finally, Tomaschek (2015), studying mainly transport-related measures, concludes that transport is not the sector with the most cost-effective measures – which is confirmed in our study as well.

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 2.4 alone will meet the national commitments of EU energy and climate policy up to 2030. However, observing the horizontal axis of Figure 2.4, 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 thousand tonnes of CO_2 equivalent, which amounts to merely 2.1% of the 2005 GHG emissions of non-ETS sectors. 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 most other EU Member states as well: According to the latest assessment of the EEA, the decarbonisation policies and measures foreseen by EU Member states remain insufficient compared with the 30% reduction that EU non-ETS sectors should achieve by 2030, as a contribution to delivering the EU target of an at least 40% domestic reduction in GHG emissions by 2030 compared with 1990. 11 out of 28 EU Member

States are not on track to meet their non-ETS targets (European Environment Agency, 2018).

2.4.2 Sensitivity Analyses

2.4.2.1 Composite Effect in both non-ETS and ETS Sectors

As mentioned above, Figure 2.4 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 – primarily emissions of power plants. 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 the fuel consumption of conventional vehicles but increases electricity generation (and thus emissions of power plants). Moreover, there are important GHG abatement measures that involve a 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 changes 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. For this purpose, the average GHG emission factors of the current thermal power generation mix of Cyprus were used, as they appear in Table 2.7, and were assumed to remain constant up to 2030. As the contribution of renewable power generation is relatively low (it was below 10% in 2017 and is expected to remain below 25% by 2030), we assumed that any savings of electricity from a non-ETS mitigation measure will not affect renewable power generation but will lead to reduced fossil-fuelled power generation.

Figure 2.5 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_2 equivalent. Because a larger number of measures is considered in this case, total emission abatement amounts to almost 850 thousand tonnes of CO_2 equivalent – more than seven times higher than in the baseline case; and if measures of even higher cost – not shown in Figure 2.5 – are taken into account, total abatement exceeds 1,000 thousand tonnes of CO_2 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 are 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 the industry as well as replacement of lighting equipment both in industry and in the building sector.

As regards the former effect (reduction in cost-effectiveness when extra electricity consumption is accounted for), other national studies have not conducted assessments of this change in cost-effectiveness; hence no direct comparisons with their results can be made. As regards fully electricity-related abatement measures, the high cost-effectiveness of some of them (e.g. lighting) has been confirmed by Toleikyte et al. (2018) and Wächter (2013).

Some useful policy implications from this sensitivity analysis are the following:

- Cost-effectiveness of specific non-ETS GHG emission abatement measures may be overestimated if the side-effects of these measures on ETS emissions are ignored. Although European governments treat ETS and non-ETS emissions separately because they have different legal commitments for each one, it is important to keep in mind the repercussions of decarbonisation measures in non-ETS on the prospects of ETS sectors and vice versa.
- Several ETS-related policies may be economically more favourable than non-ETS measures; this has to be taken seriously into account by governments when designing cost-optimal GHG abatement, as long as some trading between non-ETS and ETS emissions is possible.

- If this analysis considers the whole EU, the above finding may also have implications for the ETS allowance price. On the one hand, the trend towards electrification (especially of transport and space heating) will increase the demand for electricity and may increase allowance prices due to the rise in power plant emissions, to the extent that the transition to carbon-free electricity is slow. On the other hand, the existence of several cost-effective electricity saving options in non-ETS sectors can reduce the demand for electricity, thereby decreasing demand for allowances and driving allowance prices down. Which one of these effects dominates will depend on the carbon content of power generation in each country and the speed of electrification of energy end-use sectors.

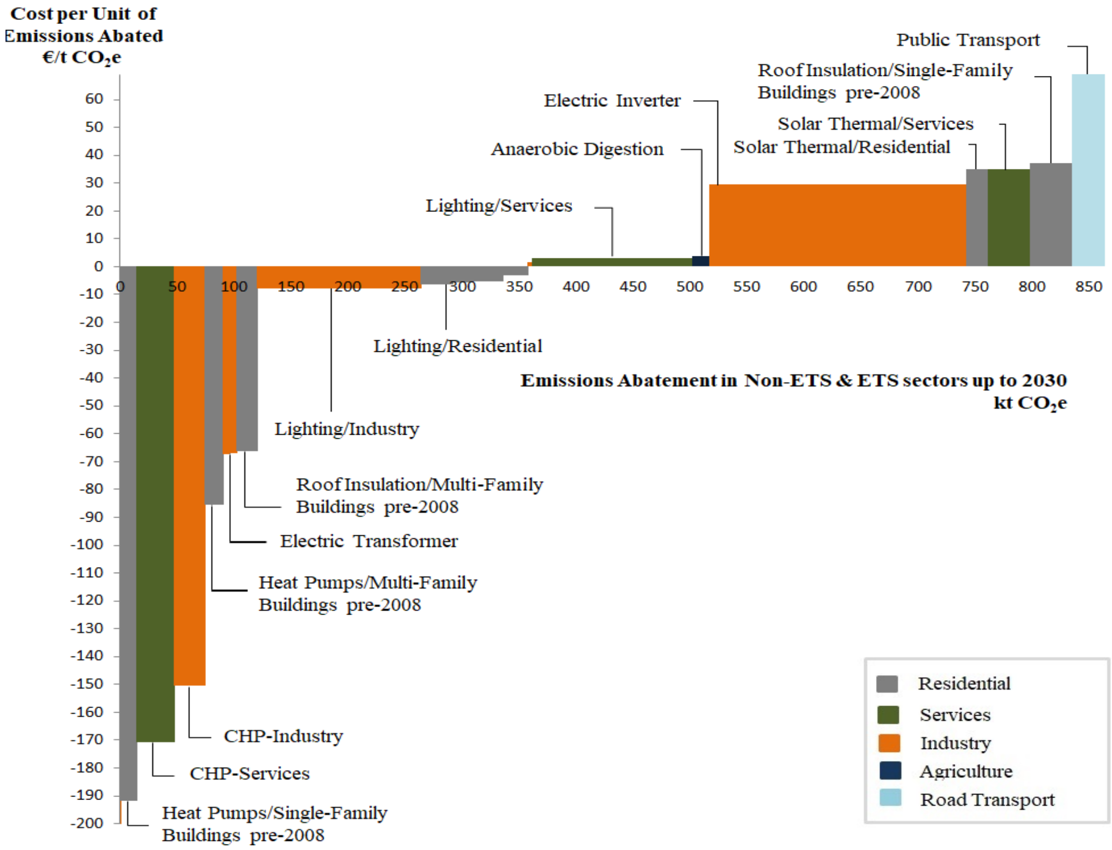

Figure 2.5|Marginal GHG emissions abatement cost curve for Cyprus, taking into account mitigation measures for both non-ETS and ETS sectors.

2.4.2.2 Inclusion of GHG and Air Pollution Costs

As a rule, measures intended to reduce GHG emissions also affect the emissions of air pollutants. They 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 are 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. This alternative cost-effectiveness assessment includes the external costs of GHG, NOx and SO_2 emissions. More information about this approach is provided in Section 2.3.2.1.

Figure 2.6 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 2.4. Similarly, anaerobic digestion, which displayed slightly positive net costs in Figure 2.4, 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. Other national studies have not accounted for pollution damage costs; hence a comparison with the relevant literature is not possible.

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. In any case, Figure 2.6 provides a more holistic picture of the social cost-effectiveness of GHG emission mitigation measures and offers useful information for public policymakers.

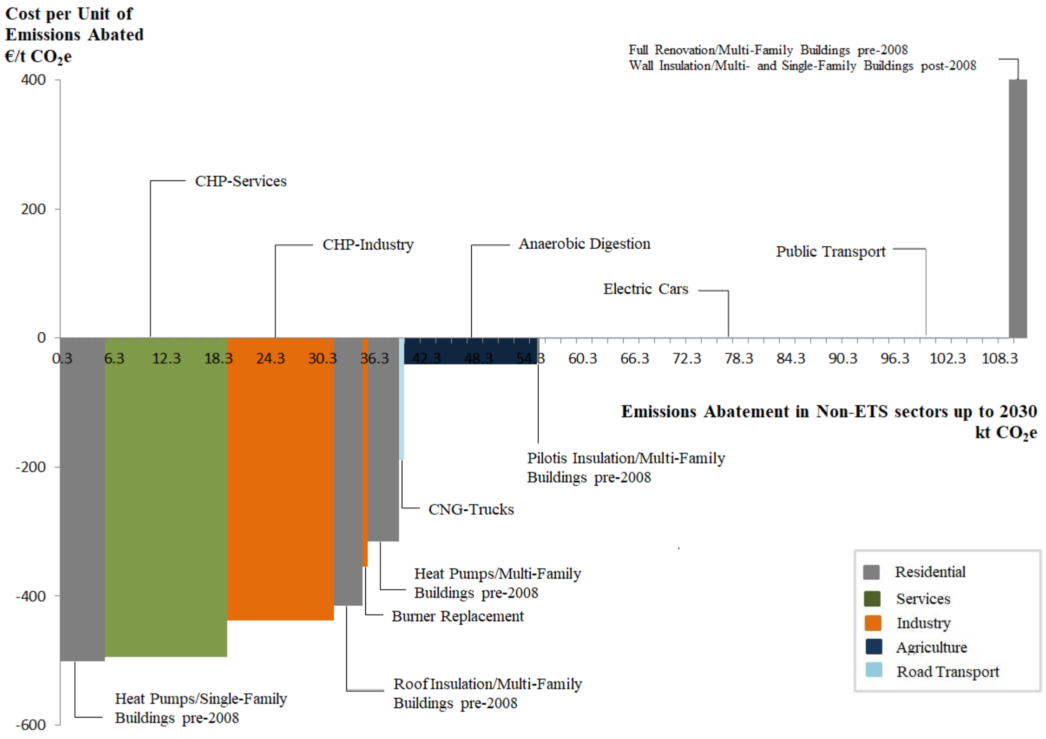

Figure 2.6 | Marginal non-ETS GHG emissions abatement cost curve for Cyprus, taking into account the external damage costs from emissions of CO_2, NO_x and SO_2.

2.4.2.3 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 that provide insights into a private firm's decisions or a household (Ea Energy Analyses, 2011; pp.12). Contrary to economic assessments, a financial assessment includes all taxes and subsidies, takes the actual financing conditions of a project into consideration, and ignores environmental or other social costs and benefits. To gain a better understanding of the difference between the two approaches in our case, the cost-effectiveness calculations have been repeated from a private (financial) 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 (VAT) 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 that 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, sector-specific discount rates which were applied that 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 2.7. 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 2.4. 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 fossil fuel with electricity that has a high retail price, such measures become less attractive compared to Figure 2.4; 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).

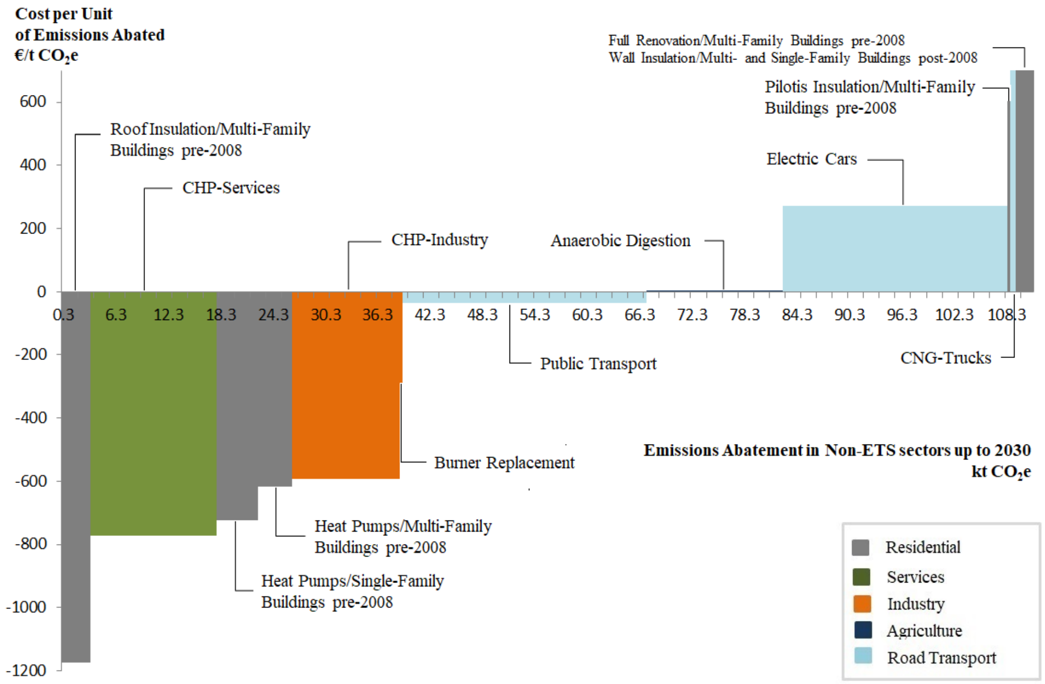

Figure 2.7|Marginal non-ETS GHG emissions abatement cost curve for Cyprus under a financial appraisal approach.

Comparing the results of this case with baseline results, a useful 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 that 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 that appear to be more costly from a private perspective than for society (i.e. they move to the right in Figure 2.7 compared to their position in Figure 2.4) 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 2.6, such strong economic incentives may be welfare-improving and should therefore be pursued by governments.

Other national studies conduct either an economic or a financial appraisal for the cost-effectiveness assessment. Hence, it is not possible to make a direct comparison of those studies with the differences we find between our baseline and our private-investor-perspective sensitivity case. Those studies mention the well-known issue of the existence of several financial and behavioural barriers for the adoption of energy efficiency investments (Gillingham and Palmer, 2014) and provide recommendations for overcoming these barriers. Some studies contain sensitivity analyses with different discount rates (e.g. Löffler and Hecking, 2017; Timilsina et al., 2017), but as mentioned before, this is not the most interesting policy-relevant result because the main difference driving the results, in this case, are not due to the change in the discount rate but due to the use of end-user energy prices that includes all duties and taxes.

2.5 Conclusions and Policy Implications

This chapter has presented an approach to construct bottom-up 'measure-explicit' MAC 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. This study provides a generic methodological approach and has 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 – despite national particularities as regards climatic conditions, power generation mix etc. – the methodology can be used to assess the most cost-effective GHG emission abatement options in that region too.

The 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. Less costly alternatives have relatively limited abatement potential, and since the long-term target is for a strong decarbonisation of the European and global energy system, high-potential measures should be explored already now in order to avoid lock-in in carbon-intensive transport modes.
- 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 industry should focus on the installation of modern, highly efficient LPG-fuelled burners and the promotion of industrial cogeneration.

As illustrated in Figure 2.4, Figure 2.5, Figure 2.6 and Figure 2.7 of this chapter, 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, governments have to remove financial and regulatory barriers that hinder progress towards decarbonisation. At the same time, the results highlight that 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 as 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 or alternative calculations such as those 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. The data enable the development of an intertemporal optimisation model in order to find the optimal mix and optimal timing of measures that can meet a decarbonisation for the year 2050 at the least cost.

Moreover, the optimal timing also depends on the speed of implementation of measures – something that can be addressed 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, the collection of real-world data on the costs and potential of measures to abate air pollutants such as NOx, $SO_{2,}$ and particulate matter can lead to the creation of a multi-criteria optimisation 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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3 Determining the Optimal Timing of Emission Abatement Measures towards Long-Term Decarbonisation[7]

Abstract

Decarbonisation by the mid-21st century requires a strong commitment to greenhouse emission abatement measures, but national emission reduction pledges are made for the medium term. Achieving medium-term targets without taking into account the long term can lead to a lock-in effect, binding countries in pathways that cannot lead to strong decarbonisation. This chapter sheds light on this issue by combining a theoretical approach with real-world engineering and cost data. A single-objective constrained optimisation model was developed to examine least-cost greenhouse gas emission abatement pathways, taking into account (a) emission reduction objectives for two years: 2030 and 2050; and (b) the potential speed of implementation of each measure, which expresses technical and behavioural inertia in the deployment of a measure. The focus is on European countries and economic sectors that are not subject to the European Union Emissions Trading System. Relationships between 2030 abatement targets of varying ambition and the possibility for a country to achieve a strong 2050 target were derived. It is evidenced that more ambitious European Union-wide targets have to be set by 2030 so that Europe delivers deep decarbonisation by 2050. Moreover, if air pollution costs are taken into account, strong decarbonisation by 2050 has lower social costs than less ambitious policies.

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[7] A concise version of this chapter was presented in Sotiriou C. and Zachariadis T., Optimal Timing of Greenhouse Gas Emissions Abatement in Europe. *Energies* 12 (2019), 1872; doi: 10.3390/en12101872.

3.1 Policy Context

Looking ahead from the short- and medium-term horizon, many governments, committed themselves to increasingly stringent energy and climate-related targets for the long term as well in order to bring their policies in line with the Paris agreement on climate change. Such commitments are usually expressed as a pledge to curb greenhouse gas emissions by a certain percentage rate up to 2030, 2040 or 2050, compared to a reference year of the past. Following the declarations of some European countries, in late 2018, the European Commission (the executive body of the European Union) declared that it would aim to achieve ‘climate neutrality’ by 2050, i.e. achieve zero net GHG emissions into the atmosphere (European Commission, 2018).

In order to fulfil such pledges, policymakers have to design proper and cost-effective decarbonisation strategies. This involves deciding an appropriate mix of GHG abatement policies and measures that can be implemented so as to meet the emission reduction objective in the target year, at the least cost to society. Such analyses are often carried out with the aid of IAE or national forecast models, which lead to a cost-optimal set of policies. Sometimes the optimisation procedure concludes with the development of a MAC curve, which ranks all abatement measures according to their cost per tonne of GHG abated and can serve as a guide to policymakers for prioritizing specific measures (Vogt-Schilb and Hallegatte, 2014).

Being simplified representations of socio-technical systems, all modelling approaches are subject to uncertainties and weaknesses, which become more pronounced under a complex political reality. For example, EU Member States have committed to a specific emissions reduction target for the year 2030: 40% lower GHG emissions compared to 1990. At the same time, there are political declarations for 2050 as well: EU leaders have expressed their intention to achieve 80-95% lower emissions by the year 2050, and the European Commission has stated its 2050 climate-neutrality target mentioned above. This means that European policymakers need to find cost-optimal decarbonisation policies which can fulfil the pledges for both 2030 and 2050. Even ignoring the uncertainties in the evolution of costs and abatement potential of specific technologies up to 2050, such an optimisation is not straightforward because investments made up to 2030 with a long lifetime will affect the emissions of 2050 as well. As the 2050 decarbonisation target is much more ambitious than the one for 2030, meeting the 2030 objective without keeping in mind, the longer term may make it impossible – or very costly – to fulfil the 2050 commitment. This is often called a 'lock-in' effect – prioritizing abatement options that are cheaper and faster to implement but do not have sufficient potential to meet ambitious abatement targets (Klitkou et al., 2015; Seto et al., 2016).

Similar challenges apply to any country in the world. It has been argued that the long-term GHG development strategies required by the Paris agreement on climate change have to be formulated in such a way that enables reconciling the long-term and global nature of the climate objective with the medium-term horizon and national scale of the Nationally Determined Contributions provided by each country (Waisman et al., 2019).

In this study, the aim is to shed light on this issue by combining a theoretical approach with empirical work in order to contribute to the design of policies for simultaneously achieving decarbonisation targets in the medium and the long term. We develop a cost-optimisation model to examine least-cost GHG emission abatement pathways, taking into account a) emission reduction objectives for two years: 2030 and 2050; and b) the potential speed of implementation of each measure, which expresses technical and behavioural inertia in the deployment of a measure.

The challenge of meeting emission abatement targets in two different periods has been identified in the past. Vogt-Schilb and Hallegatte (2014) developed an optimisation model for two theoretical emission reduction measures which have different costs and different potential to meet 2030 and 2050 targets and have introduced a variable to capture the speed of implementation of each measure. They applied this approach in a real-world setting by developing an improved MAC curve for Brazil (Vogt-Schilb et al., 2015). This study expands their approach by a) adapting it to the EU policy setting, as explained below, and b) making the implementation speed of each abatement measure variable over time and dependent on the cumulative amount of abatement that has already been deployed up to a given year.

As mentioned before, the EU's approach is to treat decarbonisation targets separately for heavy industry and the rest of the economy. Heavy industrial installations (including power generation) are subject to the EU ETS, a cap-and-trade system in which most emission allowances will be auctioned from 2021 onwards. All other sectors of the economy (light industry, transport, agriculture, residential and commercial sectors) are subject to an aggregate emission reduction objective for 2030, which is different for each country. The optimisation model developed focuses on all these non-ETS sectors, which comprise a diverse mix of economic activities and GHG abatement options.

A further contribution of this study is that it takes into account the additional benefits of GHG emission abatement. These benefits are expressed in monetary terms, i.e. the avoided damage costs because of lower emissions of GHG and major air pollutants NOx, SO_2 and Particulate Matter (PM). Although air quality improvement is recognized as an important side-benefit of decarbonisation strategies, it has not been addressed explicitly in climate policy models up to now.

The starting point of this modelling work was the development of a static MAC curve for Cyprus – an EU country that is faced with a demanding non-ETS decarbonisation target, as presented in Chapter 2 (Sotiriou et al., 2019). The initial technical and economic data were collected in the frame of that work. However, this study distances itself from the specific case study of Cyprus; although it uses the same data as a starting point, the assumptions to be presented in the following section about the future evolution of costs, abatement potential and speed of implementation are more generic, as the optimisation model is intended to be relevant for any country seeking cost-optimal decarbonisation pathways in its non-ETS sectors.

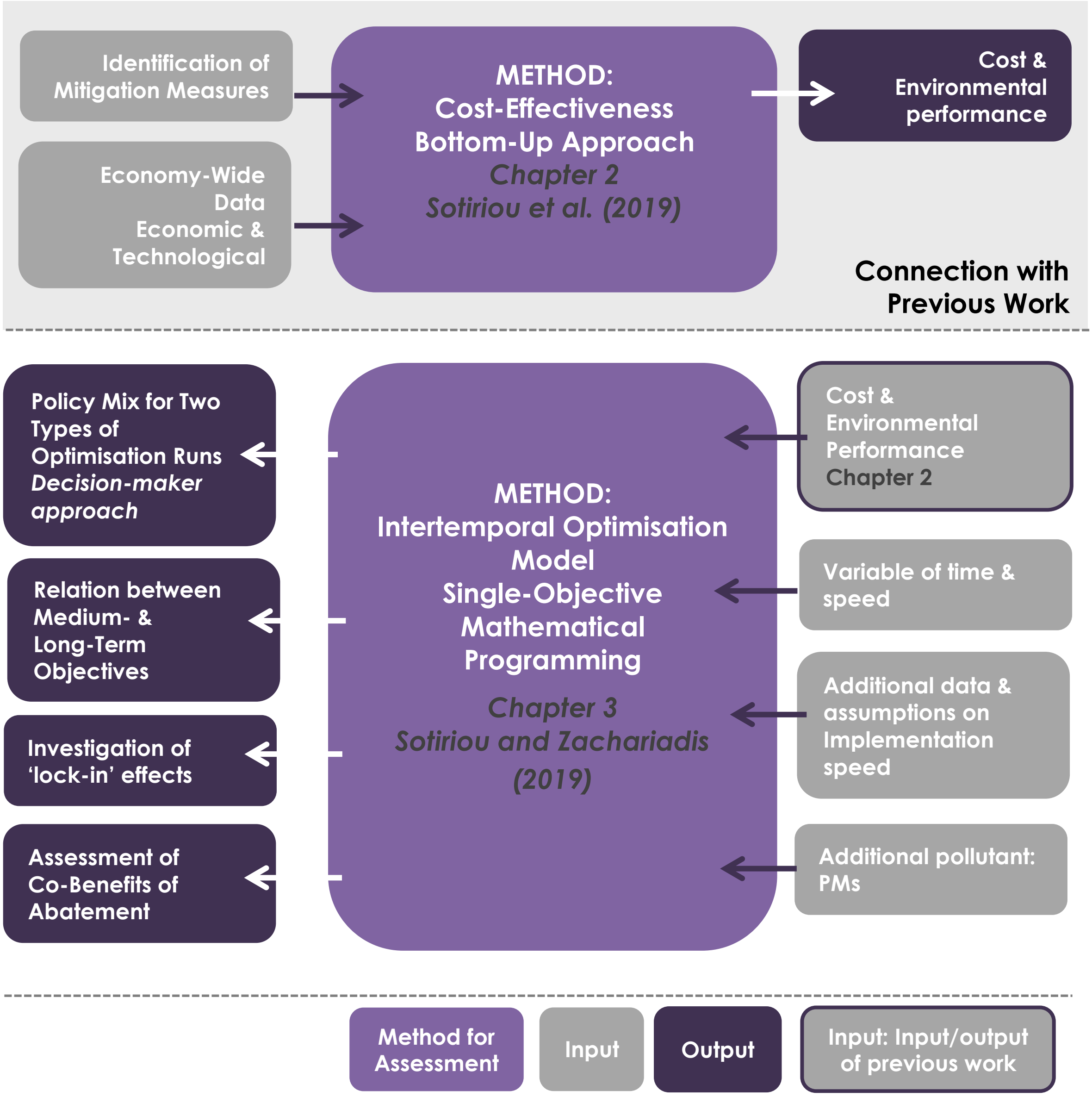

Figure 3.1 | Methods and models applied, main input and output included in determining the optimal timing of emissions abatement measures.

This chapter is structured as follows: Section 3.2 gives an overview of the methodology used, while a full description of the model and its equations together with the data and assumptions used are being provided in Section 3.3. The results of the different types of simulations and the main policy conclusions are presented in Section 3.4 and 3.5, respectively.

3.2 Operations Research and Mathematical Programming

In a more broad context outside climate change, mankind was always been confronted with the problem of deciding the best course of action under the circumstances. This process, well known now as decision making, refers to this approach where a decision is being made based on various criteria. A systematic approach to the decision problem becomes to emerge under the 'New Deal' in the US in the 1930s and other attempts to deal with economic depression. Operations Research constitutes a scientific method of decision making originated from the methodology applied by scientists during the World War II for dealing with research on military operations; thus, the name. This scientific method was later on applied in industry, business, management and many other areas. One of the most important operations research techniques is Mathematical Programming (Sinha, 2006); the word 'programming' is used in the sense of 'planning'. A mathematical programming problem is concerned with the efficient use of limited resources to meet desired objectives, and the developed models involve optimisation. Main classification of mathematical programming models is linear programming, non-linear programming, integer programming and multi-objective programming. Linear programming is perhaps the most important as it has been widely used throughout the business and scientific world.

Usually, a mathematical programming model has an objective function that expresses the optimisation criterion, the decision variables that are the unknown of the problem, and the parameters representing the data. The relationship between the unknown values and the data is described through the constraints of the problem. A general optimisation problem (minimisation) can be described in mathematical terms as follows (Collette and Siarry, 2003):

$$\min f(\vec{x}) \ s.to.$$

$$\vec{g}(\vec{x}) \leq 0 \ and$$

$$\vec{h}(\vec{x}) = 0$$

where $\vec{x} \in \mathbb{R}^n$, $\vec{g}(\vec{x}) \in \mathbb{R}^m$ and $\vec{h}(\vec{x}) \in \mathbb{R}^p$.

The objective function (the quantity that we wish to maximize or minimize) is represented by $f(\vec{x})$. Decision variables are included in the vector $\vec{x}$. With the modification of this vector, the search of the optimum of the objective function is performed. The vectors $\vec{g}(\vec{x})$ and $\vec{h}(\vec{x})$ represent m inequality constraints and p equality constraints, respectively. The constraints determine the solution area for the search of the optimal solution. In the case of a Linear Programming problem, the objective function and constraints are linear with respect to the decision variables.

3.3 Adopted Approach

3.3.1 Problem Formulation

A full description of the model and its equations is provided in this Section. In the context of reducing GHG emissions by designing appropriate and efficient strategies, the decision-maker additional to (a) the emissions abatement cost, (b) the emissions abatement potential of available options requires information about (c) the implementation speed of each measure. The aim is to meet the emission reduction objective in the target year at the least cost to society.

3.3.1.1 Objective Function

The objective function that needs to be minimized is the total present cost of abatement, *TC*.

$$TC = \sum_{j} \sum_{t} \frac{TC_{j,t}}{(1+r)^t}$$

Equation 3.1 | Objective function - minimisation of the total cost of abatement.

There are N abatement options, indexed by *j*. The model runs with a time step of a year, *t*.

$$TC_{j,t} = AC_{j,t} \cdot \sum_{i} \frac{a_{j,t}}{(1+r)^{i}}$$

Equation 3.2|Cost of abatement for each measure.

Each abatement measure *j* has an abatement cost *AC* expressed in Euro per tonnes of CO_2 equivalent and an abatement potential α expressed in avoided annual emissions in thousand tonnes of CO_2 equivalent. The latest represents the decision variables. The optimisation problem to be solved is the selection of the amount of abatement to be implemented by measure each year in order to achieve future emission reduction targets at the minimum cost. As a result, the annual implementation of each measure, i.e., the number of buildings to be renovated, passenger kilometres shifted from private cars to buses etc., is determined.

For each measure, the emissions abatement cost is given based on prior calculations or literature data and is calculated as follows:

$$AC_{j,t} = \frac{\sum_{i} \left[\frac{IC_{j,t} + MC_{j,t} + FC_{j,t}}{(1+r)^{i}} \right]}{\sum_{i} \frac{a_{j,t}}{(1+r)^{i}}}$$

Equation 3.3|Cost per unit of emissions abatement for each measure.

where *IC* refers to investment cost, *MC* refers to maintenance costs for each year, *FC* denotes the annual fuel costs, and α represents the abatement achieved through the implementation of each measure in a specific year. All values are discounted at rate *r* over the measure's lifetime *i*.

3.3.1.2 *Subject to Constraints*

For each measure, there is a maximum abatement potential *A*, that is expressed in avoided emissions in thousand tonnes of CO_2 equivalent. The cumulative abatement of each measure up to 2050 must be less than or equal to the full abatement potential *A*.

$$\sum_t a_{j,t} \leq fa_j$$

Equation 3.4|Maximum abatement potential constraint for each measure.

Each abatement measure takes time to realize. For example, energy renovations of buildings cannot happen overnight for the whole building stock because of constraints in financial, human and raw material resources; deployment of electric vehicles requires adequate infrastructure investments, changes in the regulatory environment and adaptation of consumer habits. Therefore, irrespective of the full abatement potential, each measure has a maximum implementation speed *s*, expressed in maximum annual abatement that can be achieved per year [tonnes CO_2 equivalent/y/y]. This has been introduced by Vogt-Schilb and Hallegatte (2014).

$$a_{j,t} \leq s_{j,t}$$

Equation 3.5|Maximum speed of implementation per year constraint for each measure.

A new feature in this model is that *s* can change over time to reflect inertia in the uptake of low-carbon technologies and in consumer behaviour and develops differently for the available measures. For example, adoption of electric vehicles or shift of passenger mobility to public transport modes will most probably start at low speed, based on some pioneering initiatives (e.g., the first charging stations that will serve the first few purchasers of electric cars; or the first municipalities to use smart public transit and other facilities to attract car drivers to shift to public transport; etc.). It will take years for such measures to diffuse in the economy to a sufficient extent, and the more one delays implementation of these measures, the longer it will take for a measure to achieve its maximum implementation speed.

Finally, for a subset of measures associated with strong economic and behavioural barriers, an additional constraint assumes that annual values of *s* to depend on the cumulative amount of abatement that has already been deployed up to that year:

$$s_{j,t} = f\left(\sum_{i=1}^{t} a_{j,t}\right)$$

Equation 3.6 | Dependence of implementation speed and the cumulative amount of abatement.

Also, abatement achieved thanks to measure *j* at time *t* is always positive.

$$a_{j,t} \geq 0$$

Equation 3.7 | Positive decision variables.

The model computes the least-cost implementation schedule of the various mitigation measures for succeeding the desirable emissions targets. The emissions objectives for given points in time *m* (2030 and 2050) that needed to be satisfied, are set with the following emission constraint:

$$\sum_{j}\sum_{t=1}^{m} a_{j,t} \geq a_{m}^{objective}$$

Equation 3.8 | Emissions abatement constraint for specific milestones.

The cumulative emissions, *E,* at time *t* are calculated from the cumulative baseline emissions $E_{baseline}$, expressed in thousand tonnes of CO_2 equivalent and the cumulative emissions abatement achieved through the implementation of the available mitigation measures.

$$E_t = E_{baseline,t} - \sum_j \sum_t a_{j,t}$$

Equation 3.9 | Emission levels after the implementation of the selected policy mix.

The optimisation problem becomes to select annual abatement by measure in order to minimize discounted social costs in line with Equation 3.1, subject to the constraints shown in Equation 3.4, Equation 3.5, Equation 3.6, Equation 3.7 and Equation 3.8. This linear problem has been solved with the use of a spreadsheet model. Table 3.1 summarizes the optimisation problem formulated in the context of this study.

Table 3.1 | Problem definition – Single-objective optimisation programming.

Models' Component	Description
Sets	
j	Mitigation measures available for consideration
t	Time step of a year
Decision Variables	
$a_{j,t}$	Emissions abatement achieved through the implementation of measure *j* for the time period *t*
Objective Function	
minimize TC	Minimisation of the total discounted cost of emissions abatement, Equation 3.1
Constraints	
Maximum emissions abatement	Achievable maximum abatement potential for each measure, Equation 3.4
Maximum implementation speed	Maximum speed of implementation that can be achieved per measure for the time period *t*, Equation 3.5
Dependence of implementation speed and selected abatement	Dependence of implementation speed and the cumulative amount of abatement that has already been deployed up to the time period *t-1*, Equation 3.6
Positive abatement	Positive decision variables, Equation 3.7
Emissions reduction target	Desirable emissions abatement level to be satisfied, Equation 3.8

3.3.2 Data and Assumptions on Policies and Measures

A detailed list of GHG emission abatement measures, along with the associated investment, maintenance and fuel costs and the emission abatement potential of each one, is provided in Chapter 2, Section 2.3.3 (Sotiriou et al., 2019).

In summary, the following measures were considered for reducing GHG emissions from non-ETS sectors:

- In residential buildings, emission reductions are mainly due to the implementation of specific energy renovations in buildings that were constructed before 2008 and complied with low or no energy performance requirements. Such measures comprise: renovation of the building so that it becomes a nZEB, also called 'deep renovation'; roof insulation; wall insulation; insulation of pilotis (columns or similar structural elements that support a building above ground); and investment in modern, very energy efficient heat pumps which replace older space heating and space cooling systems.
- In buildings of the tertiary sector, the use of CHP in hotels and hospitals was considered, which have considerable hot water requirements.
- In non-ETS industrial sectors, the two main measures considered were to replace fuel oil fired burners with modern ones, thereby attaining an efficiency of over 90%; and industrial cogeneration.
- Infrastructure investments for promoting public transport that will reduce the use of passenger cars correspondingly.
- Use of alternative fuels in road transport: promoting the purchase of (a) all-electric passenger cars and (b) trucks powered with CNG.
- Promotion of anaerobic digestion in the waste sector in order to reduce emissions of methane; this applies to both animal waste (i.e., manure management) and municipal solid waste and can be realized by exploiting the full biogas production capacity of existing plants that process animal waste, and through investments in new anaerobic digesters.

Table 3.2 presents the initial abatement costs for each policy and measure considered. Details on the methodology and the assumptions underlying these figures are provided in Sections 2.3.2 and 2.3.3. It should be reminded that the analysis is performed from the perspective of a social planner who attempts to maximize social welfare, i.e., from a public policy viewpoint. Therefore, costs are net of taxes and duties, and a real social discount rate of 4% is used to determine the present value of future cash flows. Measures displaying a negative abatement cost seem to be beneficial to the country from a public policy perspective, even if they may require economic incentives to enable their uptake by private investors.

While the third column of Table 3.2 shows the estimated monetary costs, the last column adds to these the associated external costs of each measure. This is the net effect of the damage costs due to additional emissions of pollutants and/or greenhouse gases because of the introduction of an abatement measure, minus the damage costs that will be avoided thanks to reduced emissions of these measures. For example, the introduction of electric cars saves emissions from conventional fossil fuel powered cars but leads to additional emissions from the thermal power plants generating the corresponding amount of electricity to operate these cars. External costs are calculated on the net difference of these emissions. Details on this calculation are provided in Section 2.3.2. This assessment has been expanded here by including additional to GHG, NOx, and SO_2 emissions, the PM. Also, some NOx emission factors have been revised after discussion with the Department of Labour Inspection of the Republic of Cyprus (Table 3.3).

As far as external costs are concerned, for GHG emissions, the assessment of marginal damage costs made by the US EPA has been used. For assessing the cost of NOx, PM and SO_2 emissions, calculations of the European studies were used–results from the CASES project (FEEM, 2008) for emissions from power plants and from Ricardo-AEA (2014) for road transport emissions. The total cost of each pollutant is the sum of the effect of damages on human health, crops, materials and biodiversity. All values were transformed to constant Euros per tonne of pollutant and are shown in Table 3.4.

Table 3.2|Input data – Abatement costs of identified mitigation measures as retrieved from the model developed by Sotiriou et al. (2019).

Measure	Abatement Cost [€'2015/ tonnes of CO_2 equivalent]	Abatement Cost with Externalities [€'2015/ tonnes of CO_2 equivalent]
Residential		
Full Renovation, Multi-Family building constructed pre-2008	1,967.1	1,907.1
Roof Insulation, Multi-Family building constructed pre-2008	-354.8	-414.8
Wall Insulation, Multi-Family building constructed pre-2008	2,528.4	2,468.4
Wall Insulation, Single-Family building constructed pre-2008	7,904.8	7,837.4
Pilotis Insulation, Multi-Family building constructed pre-2008	59.4	-37.8
Heat Pumps, Multi-Family building constructed pre-2008	-348.0	-315.0
Heat Pumps, Single-Family building constructed pre-2008	-533.6	-500.7
Services		
Cogeneration (CHP) in the services	-389.2	-593.8
Industry		
Cogeneration (CHP) in industry	-334.9	-533.1
Replacement of industrial burners	-251.1	-449.3
Road Transport		
Promotion of public transport	69.0	-8.2
Introduction of electric cars	59.1	-22.1
Introduction of CNG-powered trucks	95.2	-645.5
Agriculture & Waste		
Anaerobic digestion for animal and municipal waste	3.9	-40.6

Table 3.3|Pollutant emission factors modified and added in the alternative assessment when including the co-benefits of air pollution control.

	NOx	PM	Units
Gasoline Car	0.00156	0.000129	kg/l
Diesel Car	0.00900	0.000714	kg/l
Diesel Bus (Euro VI)	0.00200	0.000720	kg/l
Diesel Truck	0.0191	0.000688	kg/l

Table 3.4|External costs of GHGs and the three pollutants considered – NOx, PM and SO_2.

Gas	Year					Units
	2020	2025	2030	2035	2040	
GHG	35.4	38.6	42.7	46	50.1	€/tonne of GHG
NO_x	7,624	8,286	9,006	9,392	9,793	€/tonne of NO_x
PM	135,000	137,500	140,000	142,500	145,000	€/tonne of PM
SO_2	13,923	15,121	16,425	17,122	17,849	€/tonne of SO_2

Damage costs increase over the years because the disposable income is projected to continue increasing in the following decades; this raises the corresponding willingness of populations to pay for reducing pollutant-induced risks. In the case of GHG emissions, an additional reason for rising damage costs over the years is associated with the accumulation of GHG in the atmosphere, so that a tonne of GHG emitted in the future is expected to cause more damages than a tonne of GHG emitted today.

Comparing the two last columns of Table 3.2, it is evident that the inclusion of external costs reduces the cost of most mitigation measures. The difference in costs when accounting for externalities is particularly noteworthy in the three transport-related measures, whose abatement cost is initially positive and turns to negative when pollution damages are accounted for; this is obviously due to the strong benefits thanks to avoided emissions of air pollutants, especially in urban areas. Similarly, abatement costs of cogeneration measures and anaerobic digestion of waste are strongly reduced when air pollution costs are taken into consideration, thanks to the avoided emissions of air pollutants because of reduced needs to produce electricity from conventional thermal power plants. On the other side, there are few measures whose abatement costs increase when pollutant emissions costs are included; this is the case with heat pump installation, as this is expected to increase thermal power generation and hence the associated pollutant emissions. It has to be reminded that most power generation in Cyprus comes from power plants burning fuel oil and gas oil, which are scheduled to be gradually converted to natural gas fired plants.

As described in Section 3.3.1, the model also requires information about variable *s*, the speed of implementation of each measure, which was not included in Sotiriou et al. (2019). Table 2.5 provides an overview of these assumptions. The concept of how this speed differs is based on the following considerations:

- In the specific case of energy renovations in buildings constructed before 2008, the speed of implementation up to 2030 was based on technical and financial constraints – see Table 2.6 and Table 2.11 of Sections 2.3.3.1 and 2.3.3.2. From 2031 onwards, it was assumed that no further energy renovations would take place because it would not be realistic to perform such renovations in buildings over 25 years old.
- For emission abatement measures that require modest public or private investments, we assumed that *s* remains essentially constant or rises slightly over the years of the period 2021-2050; this is the case of industrial and commercial cogeneration and the replacement of industrial burners. The annual speed depends on the technical capacity available in the country for proceeding with such investments, based on information collected by industrial experts.
- Abatement measures that require substantial investments in infrastructure were assumed to be implemented with relatively low initial speeds, which gradually increase over the years, depending on the cumulative abatement achieved up to a specific year. This is the case with anaerobic digestion of animal and municipal waste, which requires both the construction of additional digesters and sufficient facilities to transport and store waste from different locations. This is also the case with the promotion of public transport, electric cars and CNG trucks because each one of these measures needs large investments in relevant infrastructure — smart bus systems and bus lanes; sufficient electric charging stations for cars; and adequate CNG refuelling stations. The existence of such infrastructure is expected to gradually enable behavioural changes that will induce increased use of public transport and steadily rising purchases of electric cars and CNG trucks.

Table 3.5 | Input data – Speed of implementation of identified mitigation measures.

Measure	Initial Implementation Speed [ktonnes of CO_2 equivalent/y/y]	Comments
Residential		
Full Renovation, Multi-Family building constructed pre-2008	0.42	150 buildings renovated each year in 2021-2030, no renovations post-2030
Roof Insulation, Multi-Family building constructed pre-2008	1.38	1,400 buildings renovated each year in 2021-2030, no renovations post-2030
Wall Insulation, Multi-Family building constructed pre-2008	0.09	180 buildings renovated each year in 2021-2030, no renovations post-2030
Wall Insulation, Single-Family building constructed pre-2008	0.09	750 buildings renovated each year in 2021-2030, no renovations post-2030
Pilotis Insulation, Multi-Family building constructed pre-2008	0.09	90 buildings renovated each year in 2021-2030, no renovations post-2030
Heat Pumps, Multi-Family building constructed pre-2008	1.14	450 buildings renovated each year in 2021-2030, no renovations post-2030
Heat Pumps, Single-Family building constructed pre-2008	1.51	750 buildings renovated each year in 2021-2030, no renovations post-2030
Services		
Cogeneration in the services	3.34	Approximately 200 CHP units installed in total, mainly in hotels and hospitals; slightly increasing implementation speed up to 2050
Industry		
Cogeneration in industry	3.34	Approximately 200 CHP units installed in total, slightly increasing implementation speed up to 2050
Replacement of industrial burners	0.07	Burners of total thermal capacity of 12,000 kW to be replaced; constant implementation speed up to 2050
Road Transport		
Promotion of public transport	2.79	Total number of passenger kilometres shifted from private

Measure	Initial Implementation Speed [ktonnes of CO_2 equivalent/y/y]	Comments
		cars to buses: 7% up to 2030 with constant speed, and then 30% up to 2050 with constant speed
Introduction of electric cars	2.08	(1,000 +1,000*t) new electric cars sold each year t of period 2021-2040, then constant speed up to 2050; post-2040, all newly registered private cars are electric
Introduction of CNG-powered trucks	0.50	New trucks sold up to 2050 use CNG as a fuel, gradual increase of implementation speed through the years
Agriculture & Waste		
Anaerobic digestion for animal and municipal waste	1.55	Extra amount of waste per year to be directed to anaerobic digestion, increase of speed through the years

3.4 Simulation Results

Two types of optimisation runs were performed with the model. One is a joint optimisation for both target years 2030 and 2050. In other words, the model is forced to solve the dynamic abatement problem satisfying both emission constraints. This enables policymakers to design a decarbonisation policy that meets the 2030 objective as well as the 2050 commitment. This is called ‘joint optimisation’. In the second type of run, which is called ‘split optimisation’, the model is initially solved for the period 2021-2030, with the 2030 emissions target as the only constraint; then, at a second stage, the model solves for annual abatement in the period 2031-2050, taking into account the solution of 2021-2030 and having as a constraint the 2050 emissions target.

Based on initial trials of the model with the data that have been included and the assumptions explained in Section 3.3.2, the available measures can arrive at a maximum emissions abatement value of 1,602 tonnes of CO_2 equivalent in the year 2050; this corresponds to an approximately 60% reduction in non-ETS GHG emissions of a base year. Keeping the 2050 constraint fixed at this value, we then employed the two types of runs for different emission constraints for the year 2030. The 2030 abatement constraints were 100, 150, 200 and 280 tonnes of CO_2 equivalent, respectively, which correspond to increasing levels of ambition for emission reduction in the year 2030.

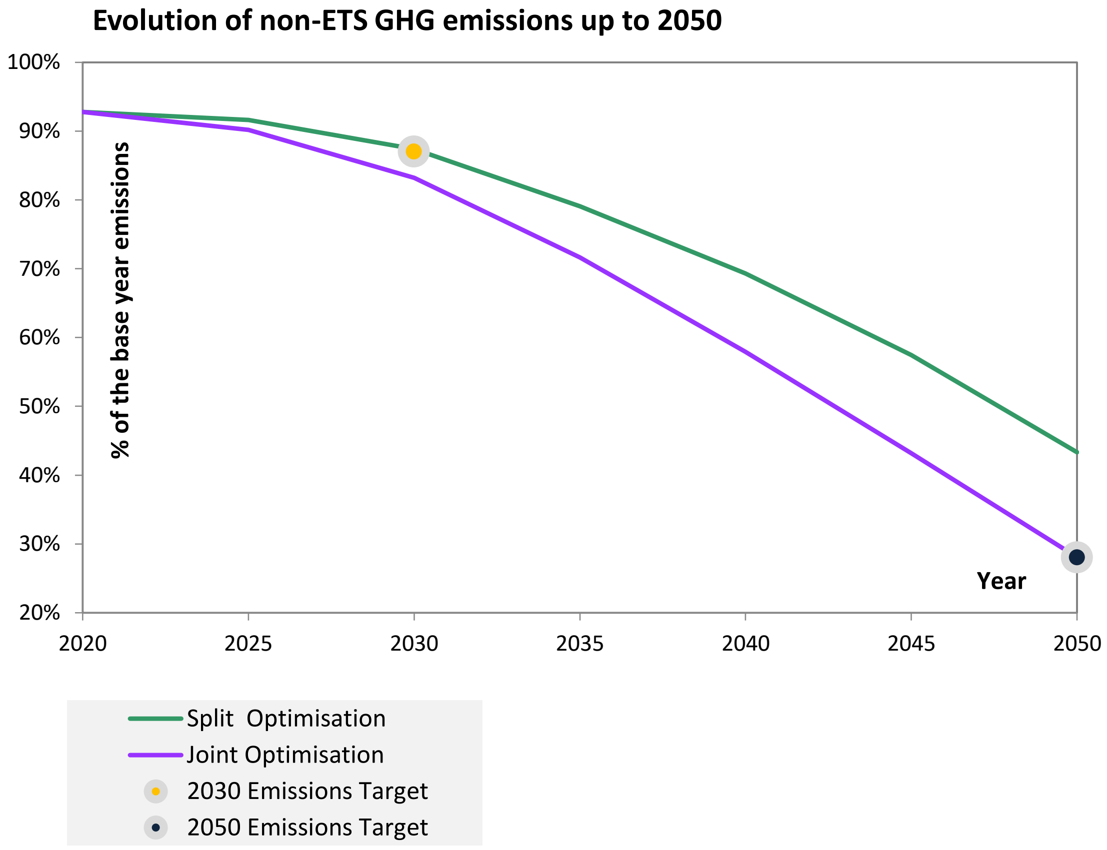

Figure 3.2| Evolution of non-ETS GHG emissions with an unambitious abatement target for 2030, depending on whether policymakers optimise jointly for years 2030 and 2050 or at two stages, i.e., one optimisation in 2020 for the 2030 target and one in 2030 for the 2050.

Figure 3.2 presents the evolution of GHG emissions up to 2050 according to the two types of runs, for the case of 100 tonnes of CO_2 equivalent abatement in 2030. In order to abstract from specific numbers (which in this study are relevant for Cyprus only) and highlight the main policy message that is relevant for all countries, this 2030 abatement level is defined as ‘unambitious’ and express all values as a fraction of the base year emissions. It is evident that if the 2030 objective is unambitious, the decarbonisation target of 2050 can only be met if one solves the joint optimisation problem. The latter strategy may overachieve the 2030 objective– joint optimisation leads to lower emissions in 2030 than what is required by the constraint.

Conversely, if a policymaker designs a strategy in 2020, keeping in mind only the 2030 target, deep decarbonisation of the year 2050 cannot be achieved. The reason for this failure is that abatement measures with high potential which take time to mature, such as electric cars or public transport, cannot deliver their full potential until 2050 if deployed after 2030; early deployment of seemingly expensive measures is necessary in order to achieve serious decarbonisation in 2050. This is highlighted in Figure 3.3, which compares cumulative abatement up to 2050 for the two approaches.

In the absence of an ambitious 2030 target, the split optimisation approach achieves much less abatement in 2050 because measures whose implementation does not start early enough (electric cars, CNG trucks, public transport, anaerobic digesters) reach about half of their full potential in 2050. Figure 3.4 zooms specifically in the year 2030 and presents the same result with Figure 3.3, highlighting both the different level of cumulative abatement and the different mix of policies that a policymaker chooses, depending on whether her focus is on attaining both 2030 and 2050 targets (joint optimisation) or the 2030 target only (split optimisation). It has to be stressed that these values refer to non-ETS emission reduction objectives only; attaining a 2030 or 2050 target in non-ETS sectors does not imply anything about meeting the objectives of ETS sectors, which is also a demanding task (ECF, 2010).

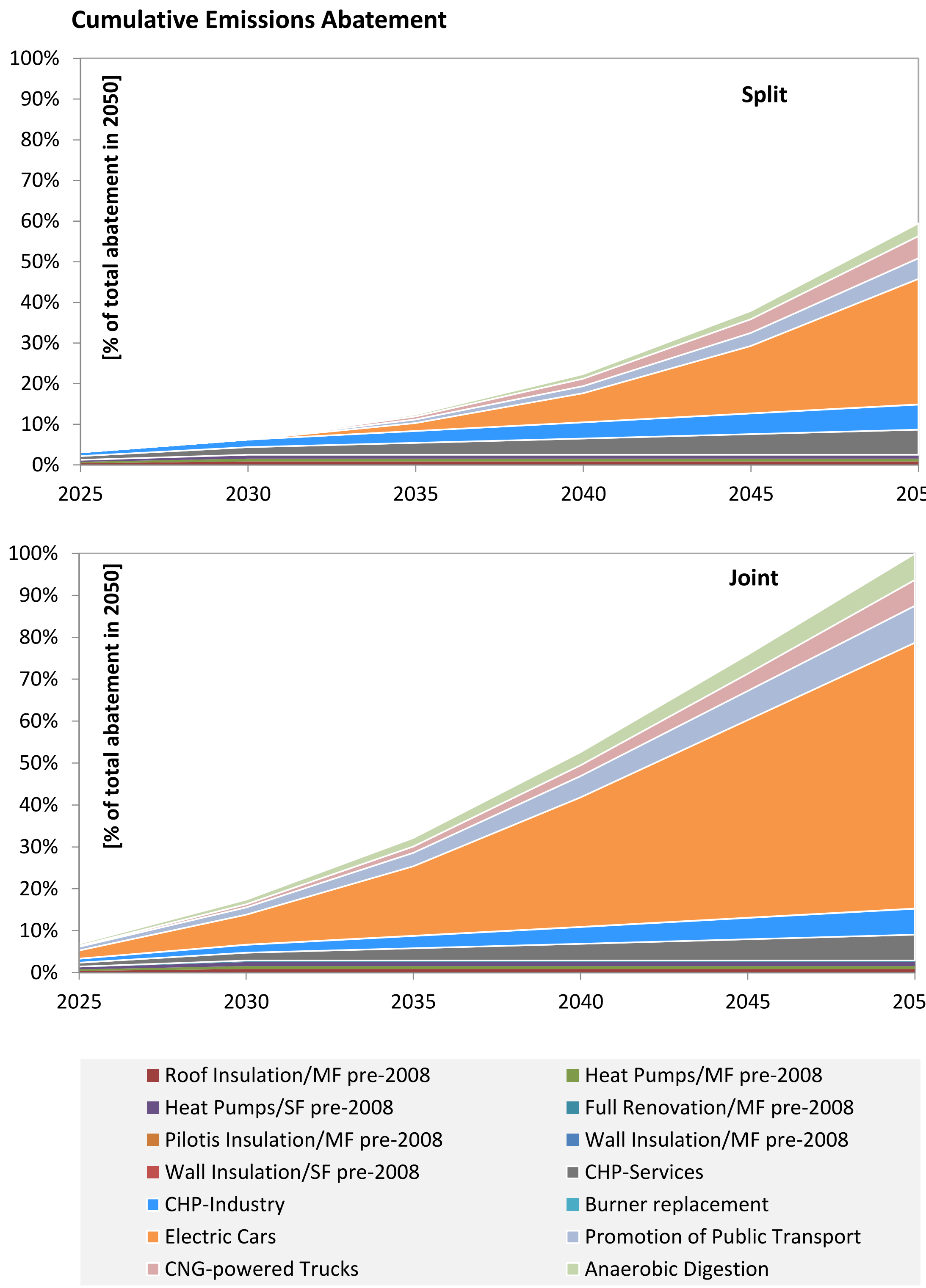

Figure 3.3|Emission abatement in non-ETS sectors up to 2050 by type of measure, when the 2030 target is unambitious: (a) Joint optimisation which reaches the full abatement target in 2050, (b) Split two-stage optimisation, which falls short of the 2050 target because measures that take time to mature develop less than their full potential up to 2050.

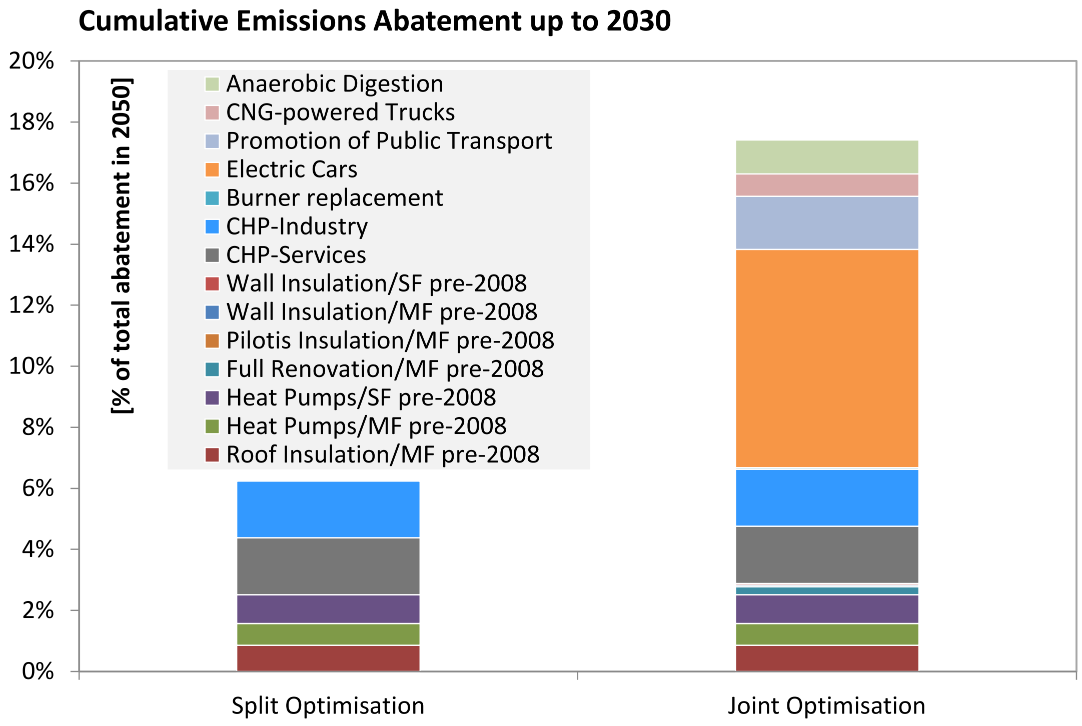

Figure 3.4 | Non-ETS GHG emission abatement achieved in the year 2030 for an unambitious 2030 target. Left column: split optimisation keeping in mind the 2030 objective only. Right column: joint optimisation, which has been designed to attain the 2030 target and also reach the full abatement target in 2050.

For comparison, Figure 3.5 shows the corresponding evolution for the case of 200 tonnes of CO_2 equivalent abatement in 2030. This can be considered a clearly more ambitious target. Here again, the joint optimisation is the only one achieving the 2050 objective, and to do this, it is necessary to overachieve the 2030 target. However, the emissions gap in 2050 is much smaller than in Figure 3.2. Because of the need to attain the ambitious target of 2030, many high-potential abatement measures start being deployed before 2030. As a result, it makes little difference whether the policymaker designs a strategy keeping both targets in mind already in 2020 or develops the strategy in two stages.

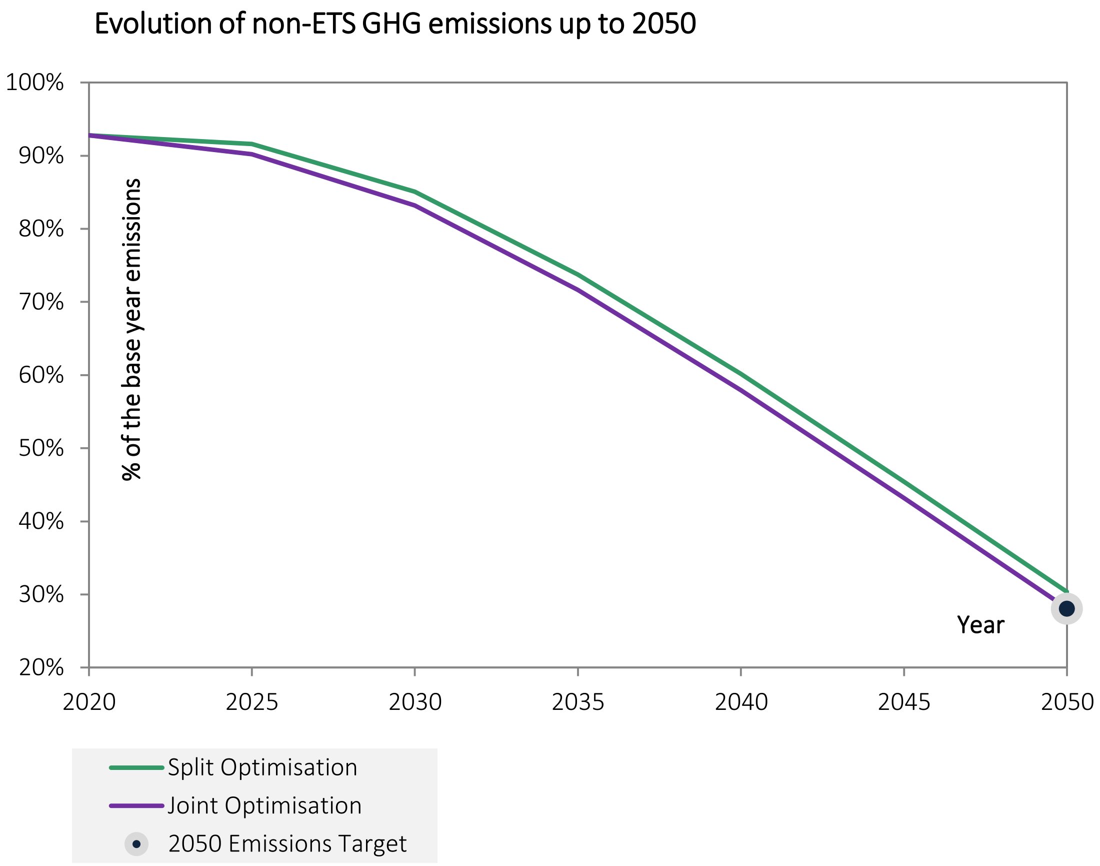

Figure 3.5 | Evolution of non-ETS GHG emissions with an ambitious abatement target for 2030, depending on whether policymakers optimise jointly for years 2030 and 2050 or at two stages, i.e., one optimisation in 2020 for the 2030 target and one in 2030 for the 2050.

Figure 3.6 highlights this message. With an even more ambitious target for 2030, both optimisation strategies lead to the same result, and the 2050 emissions difference between the two approaches becomes zero. Conversely, the less ambitious the 2030 strategy is, the more important it is to design a strategy already in 2020, keeping in mind the 2050 target as well. Otherwise, ignoring the 2050 target in 2020 leads to an underachievement of the 2050 objective by more than 35%.

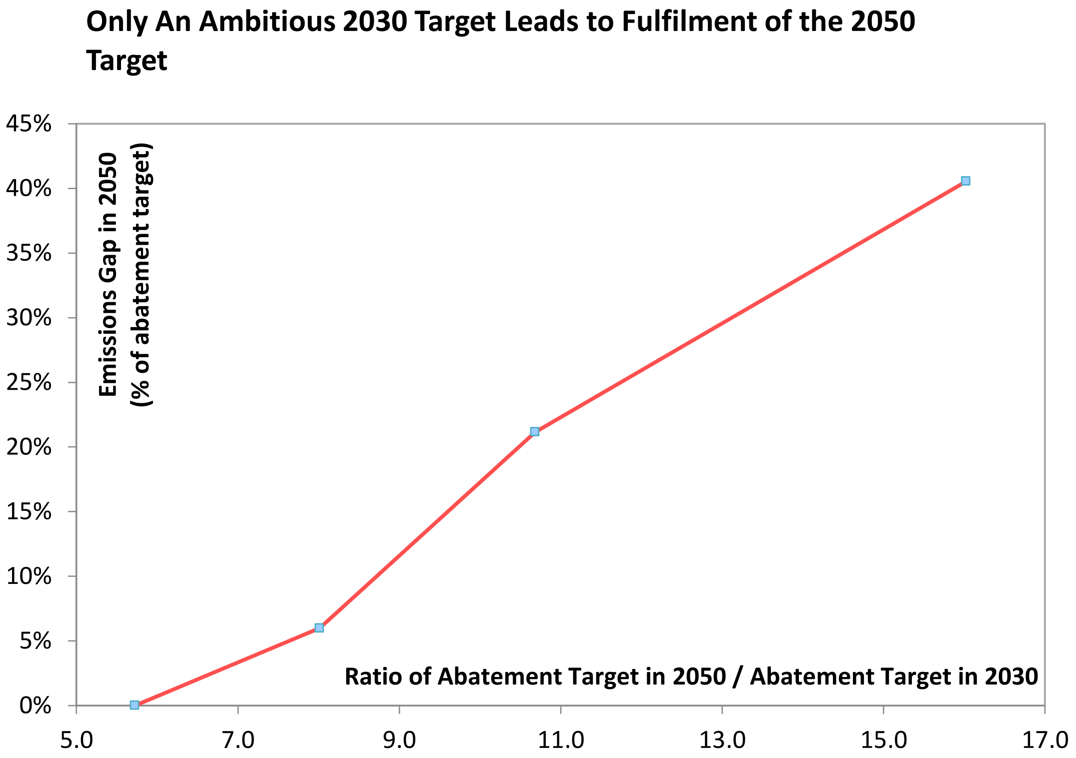

Figure 3.6 | Emissions gap in 2050, depending on the ambition level of emissions abatement in 2030. The gap is defined as the difference between the desired abatement in 2050, and the abatement realised when the optimal policy is determined in two stages. The lower the ratio on the horizontal axis, the more ambitious the 2030 abatement target.

Apart from differences in aggregate emission abatement, the two optimisation approaches lead to different aggregate costs. This is obvious because split optimisation in most cases leads to lower total abatement, and therefore to lower total investments in the corresponding abatement measures. However, as shown in Figure 3.7, this is not the socially optimal approach. An unambitious abatement target for 2030 (the rightmost grey column) leads to 8% lower discounted aggregate costs, but if one takes into account external costs of emissions of GHG and air pollutants NOx, PM and SO_2, the difference in cost becomes essentially zero. Keeping in mind that other externalities, such as emissions of other pollutants, road congestion and noise, have not been accounted for in these calculations, it becomes evident that the full GHG emissions abatement is also the economically preferable solution. This finding is consistent with work presented by the World Bank (2014), where the multiple benefits of climate change mitigation were monetized.

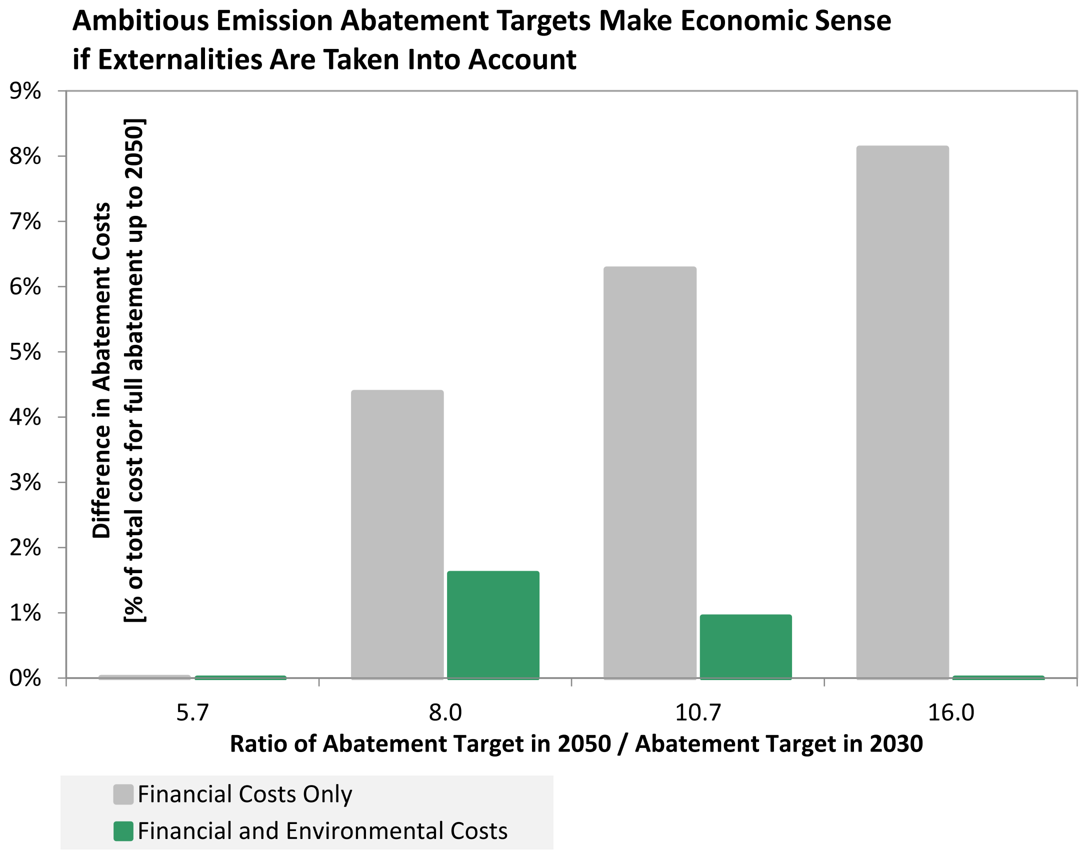

Figure 3.7 | Difference in total discounted abatement costs up to 2050, depending on the ambition level of emissions abatement in 2030. The lower the ratio on the horizontal axis, the more ambitious the 2030 abatement target. Environmental costs include damages from GHG, NO_x, PM and SO_2 emissions.

3.5 Conclusions and Policy Implications

Decarbonisation by the mid-21st century requires a strong commitment to greenhouse emission abatement measures, but national emission reduction pledges are made for the medium term. Achieving medium-term targets without taking into account the long term can lead to a lock-in effect, whereby policies to reduce emissions in the medium term bind countries in pathways that cannot lead to strong decarbonisation in the longer term. This study attempts to shed light on this issue by combining a theoretical approach with real-world engineering and cost data from the EU Member State of Cyprus. The development of a multi-constrained optimisation model helps to examine least-cost greenhouse gases emission abatement pathways, taking into account: (a) emission reduction objectives for two years: 2030 and 2050; and (b) the potential speed of implementation of each measure, which expresses technical and behavioural inertia in the deployment of a measure. Our focus is on European countries and non-ETS sectors, i.e., economic sectors that are not subject to the EU Emissions Trading System. Therefore the study abstracts from the specific emission calculations of that particular country and expresses costs and emissions in relative terms. The analysis also considers the environmental side-benefits of greenhouse gas emission abatement by accounting for measure-specific external costs from the emissions of air pollutants.

The simulations offer evidence that if the 2030 objective is unambitious, the decarbonisation target of 2050 can only be met if a policymaker–already in 2020–decides jointly on the optimal pathway for meeting both 2030 and 2050 objectives. Conversely, if a policymaker designs a strategy in 2020, keeping in mind only the 2030 target, deep decarbonisation of the year 2050 cannot be achieved. The reason is that abatement measures with high potential which take time to mature, such as electric cars or promotion of public transport, cannot deliver their full potential until 2050 if deployed after 2030; early deployment of seemingly expensive measures is necessary in order to achieve serious decarbonisation in 2050.

This is in line with findings from other national case studies mentioned in Vogt-Schilb and Hallegatte (2017) and recommendations from international organisations (OECD/The World Bank/UN Environment, 2018). Road and freight transport as well as waste management are the sectors that are particularly vulnerable to unambitious 2030 objectives because deployment of new vehicle technologies and anaerobic digestion/biogas plants takes time to materialize.

It is also found that an unambitious abatement target for 2030 leads to lower discounted aggregate costs up to 2050; however, the cost difference becomes negligible if one takes into account external costs of emissions of GHG and air pollutants NOx, PM and SO_2. Keeping in mind that other externalities, such as emissions of other pollutants, road congestion and noise, have not been accounted for in these calculations, it becomes evident that the full GHG emissions abatement is also the economically preferable solution, as also highlighted by the World Bank (2014).

As the Paris Agreement (UNFCCC, 2015) refers to “carbon budgets” that are compatible with a global warming of a certain temperature (e.g., 1.5 °C or 2 °C), it is important to note that our analysis takes as granted the EU policy that was first decided in 2014 (as regards 2030 objectives) and has been recently extended to pledges for climate neutrality (European Commission, 2018). As demonstrated, e.g., by Perissi et al. (2018), the trajectories for achieving the 2030 and 2050 emission goals, which we take for granted here, are not necessarily compatible with the global carbon budget that underlies the Paris Agreement. To improve this analysis, country-specific optimal emission reduction paths need to be developed – which is an interesting avenue of future research.

In terms of governance, policy experts have found that the current EU energy and climate policies are generally effective, and there are good prospects that the 2030 targets will be achieved (Oberthür, 2019; Ringel and Knodt, 2018) – although the EEA’s assessment is less optimistic in this regard (European Environment Agency, 2019). This study does not evaluate these aspects but assesses implicitly how adequate the 2030 targets are in order to attain the EU’s long-term decarbonisation objective. As regards the latter question, although the analysis is not explicitly based on data from all EU member states and hence its general conclusions should be treated with caution, our finding is that more ambitious EU-wide targets have to be set by 2030 in order for Europe to stay on track to deliver deep decarbonisation by 2050.

The message of this chapter is that the long-term net-zero emissions goals need to be translated into short-term ambition in order to achieve the long-term temperature goals of the Paris Agreement. The development of the national plans for 2030 must be consistent with the climate-neutrality goal. This goal must be transformed into short- and medium-term action and not be deal with as a problem for the next day.

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4 The Importance of a Carbon Tax for Cost-Effective Emissions Abatement [8]

Abstract

In European countries, greenhouse gas emissions abatement seems to be most challenging in those sectors of the economy which are not subject to the European Union’s Emissions Trading System. In this chapter, decarbonisation options for the European Union Member State of Cyprus are examined. To assess possible climate change mitigation pathways, the adoption of emissions abatement measures is considered coupled with the implementation of a gradually increasing carbon tax in those sectors outside the European Union’s Emissions Trading System. A long-term energy forecast model that is used for national energy planning is combined with an optimisation model that examines least-cost abatement pathways for the medium- and the long-term objective. Several alternative scenarios were developed and compared to assess their potential to turn Cyprus into a low-carbon economy, as well as the corresponding costs and investment needs in each case. The simulations provide evidence that the lack of ambition in the medium-term will lock the economy into a carbon-intensive trajectory. Taking into account the environmental side-benefits of emission abatement, more ambitious policies turn out to be the socially optimal approach and can narrow down the emissions gap of the demanding long-term objective. However, even with an ambitious policy mix, the mitigation measures alone cannot secure the zero-emissions trajectory. For this purpose, it is found that a carbon tax in the order of 120 Euros per tonne of CO_2 *can facilitate a transition to a low-carbon economy.*

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[8] A concise version of this chapter was presented in: Sotiriou C. and Zachariadis T., The Importance of a Carbon Tax for Timely and Cost-effective Decarbonisation – A Case Study from Cyprus. *Economic Instruments for a Low-carbon Future.* Critical Issues in Environmental Taxation XXII, Edward Elgar Publishing, 2020. doi: 10.4337/9781839109911.

4.1 Policy Context

Limiting global warming to no more than 2°C above pre-industrial levels requires the strong commitment of governments to GHG emission abatement measures. Apart from technical and economic barriers to decarbonisation, the attainment of long-term targets is further complicated by the fact that national emission reduction pledges are usually made for the medium term, e.g. for 2030; achieving medium-term targets without taking into account the long term perspective can lead to a lock-in effect, such that policies to reduce emissions in the medium term may bind countries in pathways that cannot lead to strong decarbonisation in the long term – discussed in Chapter 3.

In this chapter, the importance of a carbon tax for achieving cost-effective emission abatement in the Republic of Cyprus is analysed. To assess abatement options, a long-term energy forecast model that is used for national energy planning is combined with a dynamic optimisation model that examines optimal mitigation pathways under a specific set of constraints as presented in Chapter 3 (Sotiriou and Zachariadis, 2019). The latter takes into account emission reduction objectives for two future years; 2030 and 2050, years that correspond to medium- and long-term milestones of EU emissions reduction strategy, and incorporates assumptions on the speed of implementation of each measure, which expresses technical and behavioural inertia in the deployment of a measure. Environmental side-benefits of greenhouse gas emission abatement as also been considered. In the context of this study, a number of alternative scenarios are developed and compared according to their potential to turn Cyprus into a low-carbon economy, as well as the corresponding costs and investment needs in each case.

The simulations offer evidence that if the medium-term strategy is not ambitious, deep decarbonisation by 2050 will be highly unlikely to achieve. ‘Weak’ medium-term scenarios result in under-investment in ambitious options in the medium term, which are, however, absolutely necessary to create a zero-emissions trajectory for the long term. More ambitious policy mixes result in the highest investment needs but seem to be the socially optimal approach, taking into account climate stabilisation as well as side benefits such as air pollution improvement.

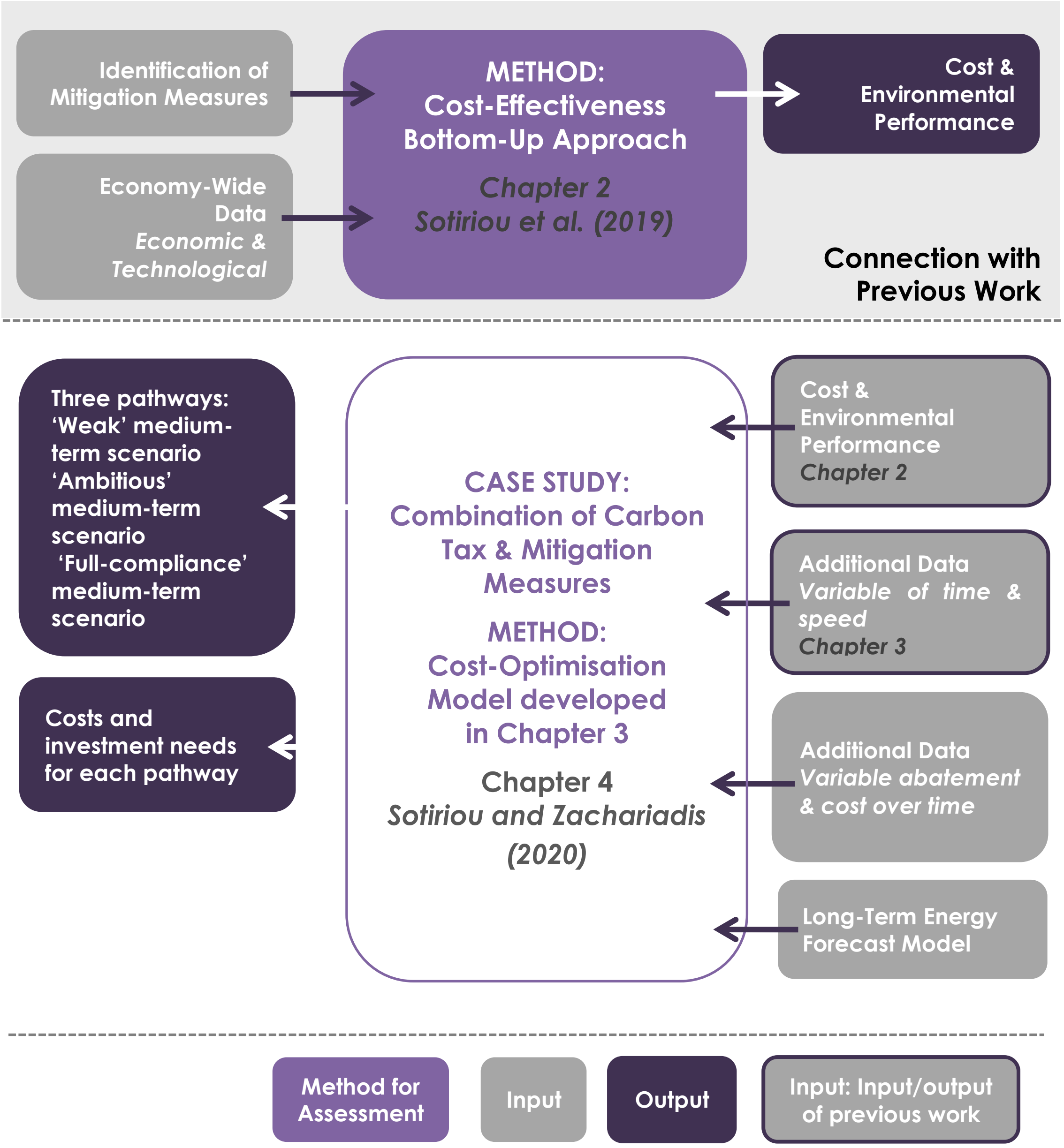

Figure 4.1|Methods and models applied, main input and output included in the assessment of the importance of carbon tax for a cost-effective decarbonisation pathway.

4.2 Study Design

4.2.1 Models

Policymakers facing climate change mitigation targets need to design a comprehensive mitigation strategy through a set of options described by their (a) emissions abatement cost and (b) emissions abatement potential. As mentioned in Chapter 3, Vogt-Schilb and Hallegatte (2014) proposed a new way of reporting information on mitigation measures, including additionally the speed at which each option can be implemented. The social planner's aim is to fulfil climate-related commitments by deciding the appropriate mix and the optimal timing of abatement measures.

In the case of Cyprus, the core of this approach is a cost-optimisation model whose mathematical formulation has presented in Section 3.3.1 (Sotiriou and Zachariadis, 2019). The model determines a least-cost emissions reduction pathway, taking into account (a) emission reduction objectives for the medium and long term: 2030 and 2050; and (b) the time-varying speed of implementation of each measure. The objective is to comply with the abatement targets, minimising the total discounted present cost of abatement. The model runs for the period 2020-2050 with a time step of five years and identifies the cost-optimal policy mix by selecting the specific amount of abatement to be implemented by each measure expressed in avoided annual emissions in a tonne of CO_2 equivalent per year.

The model needs as input the abatement cost, the maximum abatement potential and the diffusion speed of each measure. The abatement cost is expressed in Euros per tonne of CO_2 equivalent and consists of the annual investment, maintenance and fuel costs discounted over the measure's lifetime. The maximum abatement potential, expressed in tonne of CO_2 equivalent per year, suggests that cumulative abatement of each measure up to 2050 cannot exceed that value. However, since measure-specific abatement requires time to be realised depending on implementation barriers, this is modelled as a speed of implementation expressed in maximum abatement that can be achieved per year. Factors that limit the speed of each measure are taken into account; for example, the deployment of electric vehicles, apart from cost factors, requires adequate infrastructure investments, changes in the regulatory environment and adaptation of consumer habits. Expanding the approach of Vogt-Schilb et al. (2015), the model presented in Chapter 3 assumes that the speed of implementation changes over time, and annual implementation speed depends on the cumulative abatement achieved by a measure up to that specific year. This simulates the acceleration in the diffusion of a technology because of the build-up of enabling infrastructure and gradual behavioural changes. The optimisation model also considers non-climate external costs associated with the implementation of mitigation measures, thereby allowing accounting for additional benefits of decarbonisation related to the reduction in local air pollution.

To assess the effect of implementing a carbon tax on aggregate energy use and carbon emissions, as a first step, a long-term energy forecast model was employed that is being used by energy authorities of Cyprus for national planning (Vougiouklakis et al., 2017). This determines the emissions in future years and hence the required GHG abatement in order to reach emission targets of 2030 and 2050. The study experiments with different levels of carbon taxes, as will be explained in the next section. For different carbon tax scenarios, the energy forecast model assesses the changes in fuel consumption and carbon emissions up to 2050. The carbon emission reductions are then used as an exogenous input to the optimisation model described in the previous paragraphs in order to determine cost-effective decarbonisation pathways. In this second step, the analysis is carried out from the perspective of a social planner, which means that costs and benefits are net of taxes and duties (Ea Energy Analyses, 2011).

It is important to note that the abatement potentials and costs may evolve through time due to technological advances. In the previous application of the model (Sotiriou and Zachariadis, 2019), these features had been kept fixed over time. In this chapter, the model input is extended to allow for variable abatement potentials and costs during the study period; this leads to more realistic assessments of the cost-optimal mix of policies and measures for the long term.

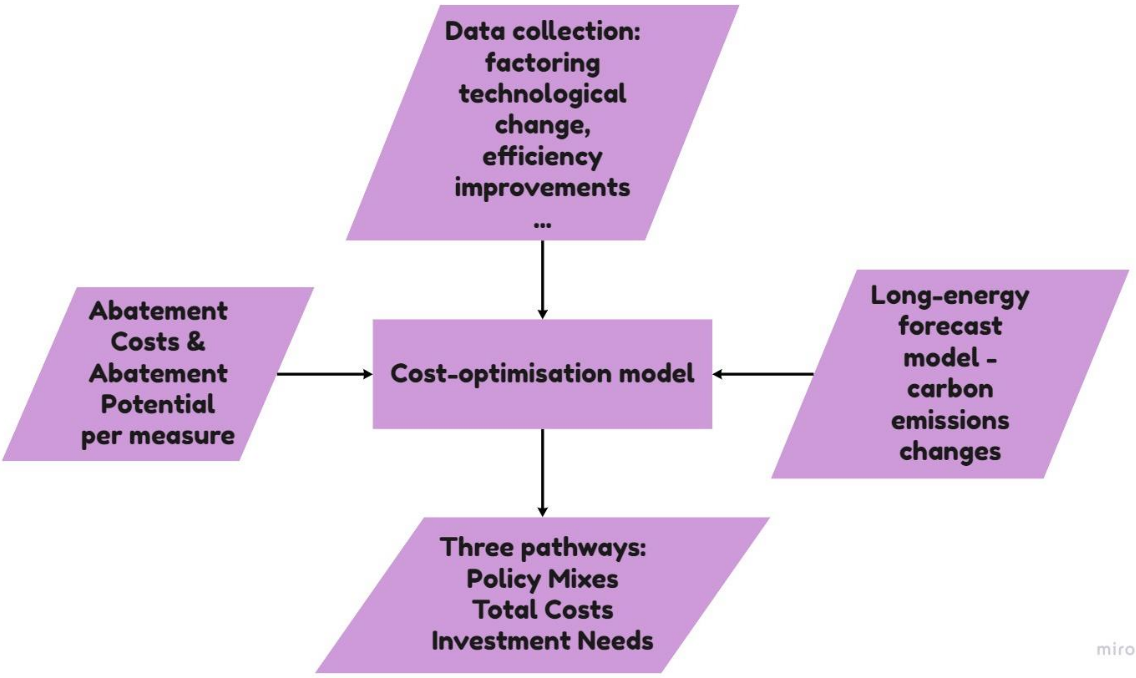

Figure 4.2|Schematic presentation of the methodology used for assessing the importance of carbon taxation on non-ETS emissions for a cost-effective decarbonisation.

4.2.2 Data and Assumptions

The available mitigation measures and the initial technical and economic data were selected in the frame of the study of Sotiriou et al. (2019), which explored cost-effective GHG abatement options for Cyprus through the development of a bottom-up ‘measure-explicit’ MAC curves as presented in Chapter 2. The list of measures identified by that study was used directly in the optimisation model. Thus the options considered for reducing non-ETS GHG emissions are the following:

- In the residential sector, we considered energy renovations in single- and multi-family buildings that were constructed before 2008 because those buildings did not have to comply with any energy performance regulations. Renovation measures considered were: deep renovation of the building envelope so that it becomes a near-Zero Energy Building (nZEB); roof insulation; wall insulation; insulation of pilotis; replacement of old space heating systems powered by diesel with modern highly efficient heat pumps.

- In the services sector, the use of cogeneration in hospital and hotels was considered, with CHP units, will be fuelled by LPG and replacing gas oil fired boilers. Other energy renovation measures were excluded because they only involved changes in electricity consumption of these buildings, but electricity is part of the EU ETS and therefore not considered in our model that focuses on non-ETS abatement only.
- In the industrial sector of Cyprus, cogeneration was taken into account and the replacement of old fuel oil-fired burners with modern, efficient ones burning LPG.
- In road transport, r the modal shift in passenger mobility was accounted as well as fuel substitution. As regards the former, a shift of a certain amount of passenger kilometres from private cars to buses was considered through infrastructure investments for public transport; regarding the latter, the use of alternative fuels was also evaluated through the promotion of (a) electric private cars and light good conveyance vehicles (replacing petrol- and diesel-powered cars) and (b) trucks powered with CNG and electricity (replacing diesel-powered trucks).
- In the agriculture and waste sectors, the promotion of anaerobic digestion was considered for both animal waste (i.e. manure management) and municipal solid waste. This requires the full exploitation of the biogas production capacity of existing plants that process animal waste, as well as investments in new anaerobic digesters.

Table 4.1 | Emission abatement measures considered, ranked by their abatement cost – Abatement costs retrieved from the model developed by Sotiriou et al. (2019).

Measure	Sector	Abatement Cost [€'2015/ tonnes of CO_2 equivalent]	Cost Category
Heat Pumps, Single-Family building constructed pre-2008	Residential	< 0	Net social benefit
Cogeneration in Services	Services	< 0	
Roof Insulation, Multi-Family building constructed pre-2008	Residential	< 0	
Heat Pumps, Multi-Family building constructed pre-2008	Residential	< 0	
Cogeneration in Industry	Industry	< 0	
Replacement of industrial burners	Industry	< 0	
Anaerobic Digestion for Animal and Municipal Waste	Agriculture	4	Modest abatement cost
Pilotis Insulation, Multi-Family building constructed pre-2008	Residential	59	
Introduction of Electric Private and Light Good Conveyance Vehicles	Road Transport	59	
Promotion of Public Transport	Road Transport	69	
Introduction of Low-Carbon Trucks	Road Transport	95	
Full Renovation, Multi-Family building constructed pre-2008	Residential	> 1,000	High abatement cost
Wall Insulation, Multi-Family building constructed pre-2008	Residential	> 1,000	
Wall Insulation, Single-Family building constructed pre-2008	Residential	> 1,000	

Table 4.1 presents the measures mentioned above, ranked according to their estimated abatement costs and classified into three groups: those with negative costs, which are immediately beneficial to society if certain implementation barriers are removed, those with modest abatement costs and those with very high costs, whose adoption is difficult to justify on mere cost-effectiveness grounds.

These costs refer to the implementation of such measures around the year 2020. In the optimisation model used in this chapter, we assumed a gradual change in the costs and abatement potential during the 2020-2050 period to account for the anticipated reduction in the costs of specific technologies and the expected improvement in the efficiency of some measures, which enhances their emissions reduction potential. Based on data and assumptions that were made available by the European Commission to EU governments in 2018 as guidance to their energy and climate modelling[9], we assumed the following changes:

- For all interventions in pre-2008 buildings, the abatement cost remains the same for the ten-year period 2020-2030. It is assumed that no energy renovations will take place after 2031, as Vougiouklakis et al. (2017) concluded that – depending on the age of the building – it is too costly or not realistic to perform such renovations in buildings that will be more than 25 years old.
- For the measures related to the introduction of electric private cars and light good conveyance vehicles, we assume a 15% reduction in abatement costs every 5 years in line with the recommendations mentioned above by the European Commission.
- For all other measures except electric vehicles, we assume a gradual decrease of the abatement cost over the 30-year period 2020-2030 by introducing a 10% reduction in abatement costs every 5 years.

The optimisation model requires information on the full abatement potential and the implementation speed of each measure. The abatement potential up to 2030 was derived from Sotiriou et al. (2019). The residential sector is considered to reflect the realistic potential based on earlier empirical work of Vougiouklakis et al. (2017). In the frame of this study, it was necessary to assess the full potential of each measure beyond 2030 and up to 2050. This is reported in Table 4.2, taking into account the pre-2030 data and the assumed changes in costs and efficiency of each measure over the years, as mentioned above.

As regards the speed of implementation, which is also a necessary input to the optimisation model, the initial speed is presented in Table 4.2, along with assumptions

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[9] Unpublished information provided by the European Commission to the governments of EU Member states, which were made available by the government of Cyprus.

about its evolution up to 2050. There may be different reasons that limit the speed of implementation of an abatement measure. For example, energy renovations in buildings face technical and financial constraints (Sotiriou et al., 2019); road transport measures (modal shifts to public transport and electrification of vehicles) require substantial investments in infrastructure and also depend on behavioural changes (Sotiriou and Zachariadis, 2019). Table 4.2 provides the initial speed of implementation for each measure and reports on the related assumptions about its evolution up to 2050.

Table 4.2 | Input data – Full abatement potential and the implementation speed of identified mitigation measures.

Measure	**Full Abatement Potential** [ktonnes of CO_2 equivalent]	**Comments**	**Implementation Speed** [ktonnes of CO_2 equivalent/y/y]	**Assumptions on speed**
Full Renovation, Multi-Family building constructed pre-2008	4.16	1,500 buildings renovated; no renovations post-2030	0.42	constant up to 2030
Roof Insulation, Multi-Family building constructed pre-2008	13.79	14,000 buildings renovated; no renovations post-2030	1.38	constant up to 2030
Pilotis Insulation, Multi-Family building constructed pre-2008	0.93	900 buildings renovated; no renovations post-2030	0.09	constant up to 2030
Wall Insulation, Multi-Family building constructed pre-2008	0.89	1,800 buildings renovated; no renovations post-2030	0.09	constant up to 2030
Wall Insulation, Single-Family building constructed pre-2008	0.91	7,500 buildings renovated; no renovations post-2030	0.09	constant up to 2030

Measure	**Full Abatement Potential** [ktonnes of CO_2 equivalent]	**Comments**	**Implementation Speed** [ktonnes of CO_2 equivalent/y/y]	**Assumptions on speed**
Heat Pumps, Multi-Family building constructed pre-2008	11.37	4,500 buildings renovated; no renovations post-2030	1.14	constant up to 2030
Heat Pumps, Single-Family building constructed pre-2008	15.10	7,500 buildings renovated; no renovations post-2030	1.51	constant up to 2030
Cogeneration in Services	32.58	50 units installed	0.47	slightly incr. up to 2050
Cogeneration in Industry	33.94	50 units installed	0.49	slightly incr. up to 2050
Replacement of industrial burners	0.74	burners of total thermal capacity of 12,000 kW to be replaced	0.07	constant up to 2050
Promotion of Public Transport	195.03	number of passenger kilometres shifted from private cars to buses: 7% up to 2030, and then 30% up to 2050	2.79	gradually incr. up to 2050
Introduction of Electric Private and Light Good Conveyance Vehicles	1,863.14	all newly registered private & light good conveyance vehicles are electric up to 2040	2.08	gradually incr. up to 2040; constant up to 2050
Introduction of Low-Carbon Trucks	240.64	new trucks sold up to 2040 use CNG as a fuel; introduction of electric trucks up to 2050	2.22	gradually incr. up to 2050
Anaerobic Digestion for Animal and Municipal Waste	43.83	extra amount of waste per year to be directed to anaerobic digestion	1.00	gradually incr. up to 2050

4.3 Model Simulations

After experimenting with various simulations of emission pathways up to 2050, the results of three specific simulations are being presented and compared with the evolution of non-ETS GHG emissions according to the scenario “With Existing Measures” (WEM) that the government of Cyprus prepared in its National Energy and Climate Plan. The National Energy and Climate Plan of the Republic of Cyprus was scheduled to be submitted to the European Commission by the end of 2019, by which time it would also be provided to the public. Information about this plan in the time of performing the simulations has been obtained from governmental authorities.

These four pathways are illustrated in Figure 4.3, which also includes the mandatory emission target for Cyprus for the year 2030 according to the EU regulation mentioned above; this target is 3,008 thousand tonnes of CO_2 equivalent and comprises a 24% reduction in non-ETS emissions compared to those of the year 2005. In Figure 4.3 it is also included an indicative target for the year 2050, in line with the stated objective of the European Commission to achieve “net-zero” carbon emissions by that year; the indicative target is a 90% reduction in non-ETS GHG emissions or 396 thousand tonnes of CO_2 equivalent. Figure 4.4 focuses on the year 2030 and the projected level of emissions after the implementation of the scenarios; the difference from the desirable level based on EU policy for 2030, positive or negative, is also presented.

Main aspects of each one of the four scenarios are also shown in Table 4.3 and Table 4.4. The upper part of Table 4.3 shows costs by scenario up to 2030, including the potential cost for purchasing allowances in order to comply with the binding non-ETS target mentioned above. The lower part of the table shows results for the entire period 2020-2050, which are only relevant for the ‘ambitious’ and ‘full compliance’ scenarios, as only these can lead to approximate fulfilment of the deep decarbonisation target of 2050. Note that since the 2050 objective is still indicative and not mandatory, there are no market mechanisms (e.g. trade of allowances) to ensure compliance. Table 4.4 includes the abatement results of each scenario by presenting the emissions gaps for the medium- and the long-term objective, i.e. emissions gap is defined as the difference between projected GHG emissions abatement under the implementation of the various scenarios and the desirable emissions abatement set by the EU targets.

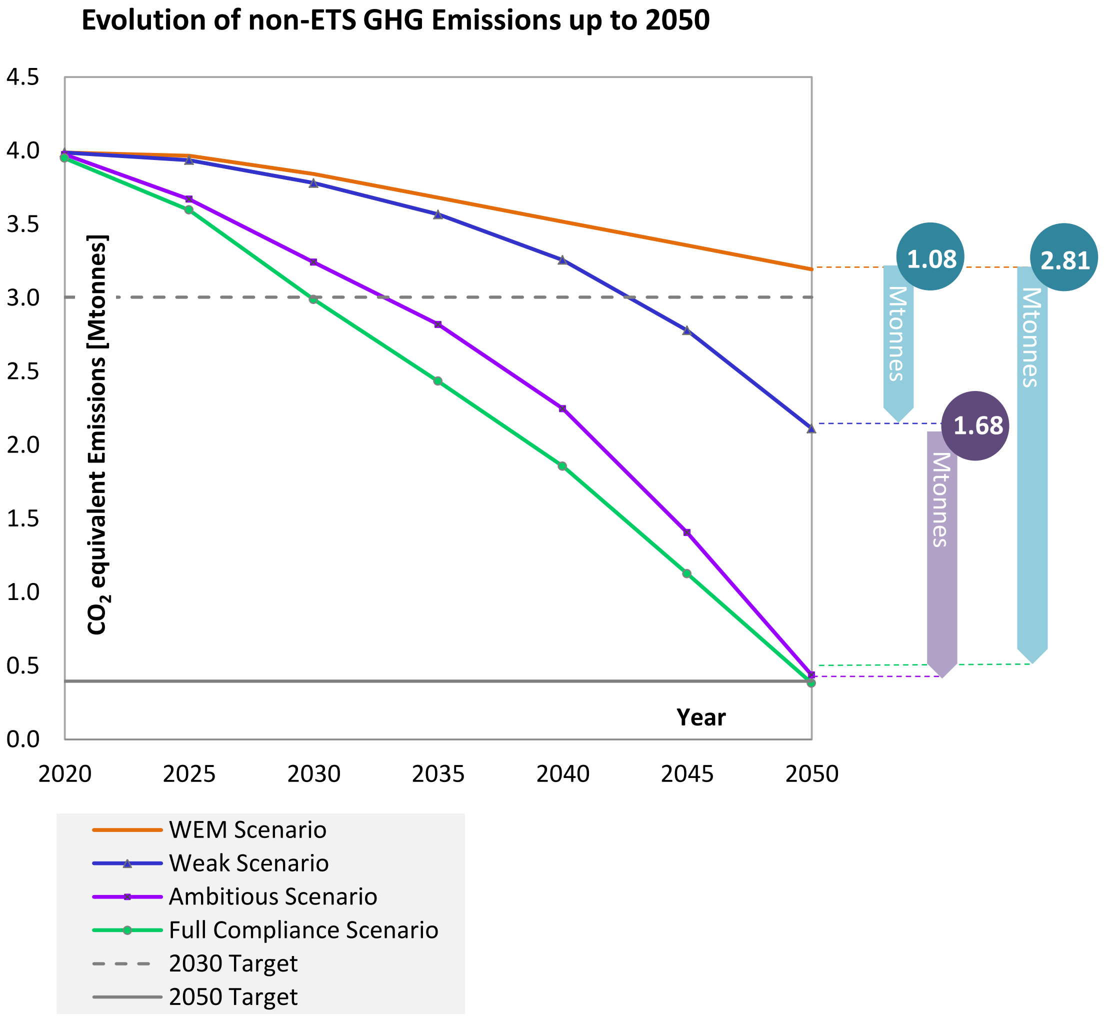

Figure 4.3|Evolution of non-ETS emissions in Cyprus up to 2050 according to the scenarios considered in this carbon taxation case study.

The first scenario, WEM, which comes from the projections of the government of Cyprus and is used as a reference for our simulations, does not include any GHG abatement measures out of those listed in Section 4.2.2. In this case, no additional investments in emission reduction measures are made, and Cyprus falls short of its non-ETS emission reduction commitment of the year 2030. The 2030 emissions gap is large (837 thousand tonnes of CO_2 equivalent as shown in Table 4.4) and has to be covered by purchasing allowances from other countries, in line with the possibility to use ‘flexibility mechanisms’ foreseen in EU Regulation 2018/1999 on the Governance of the Energy Union and Climate Action. Assuming a price level of 30 Euros per tonne of CO_2 equivalent for these allowances, we arrive at a total cost of 105.5 million Euros up to 2030. Obviously, the WEM scenario results in very high emissions in the year 2050 and is nowhere near the 2050 decarbonisation target.

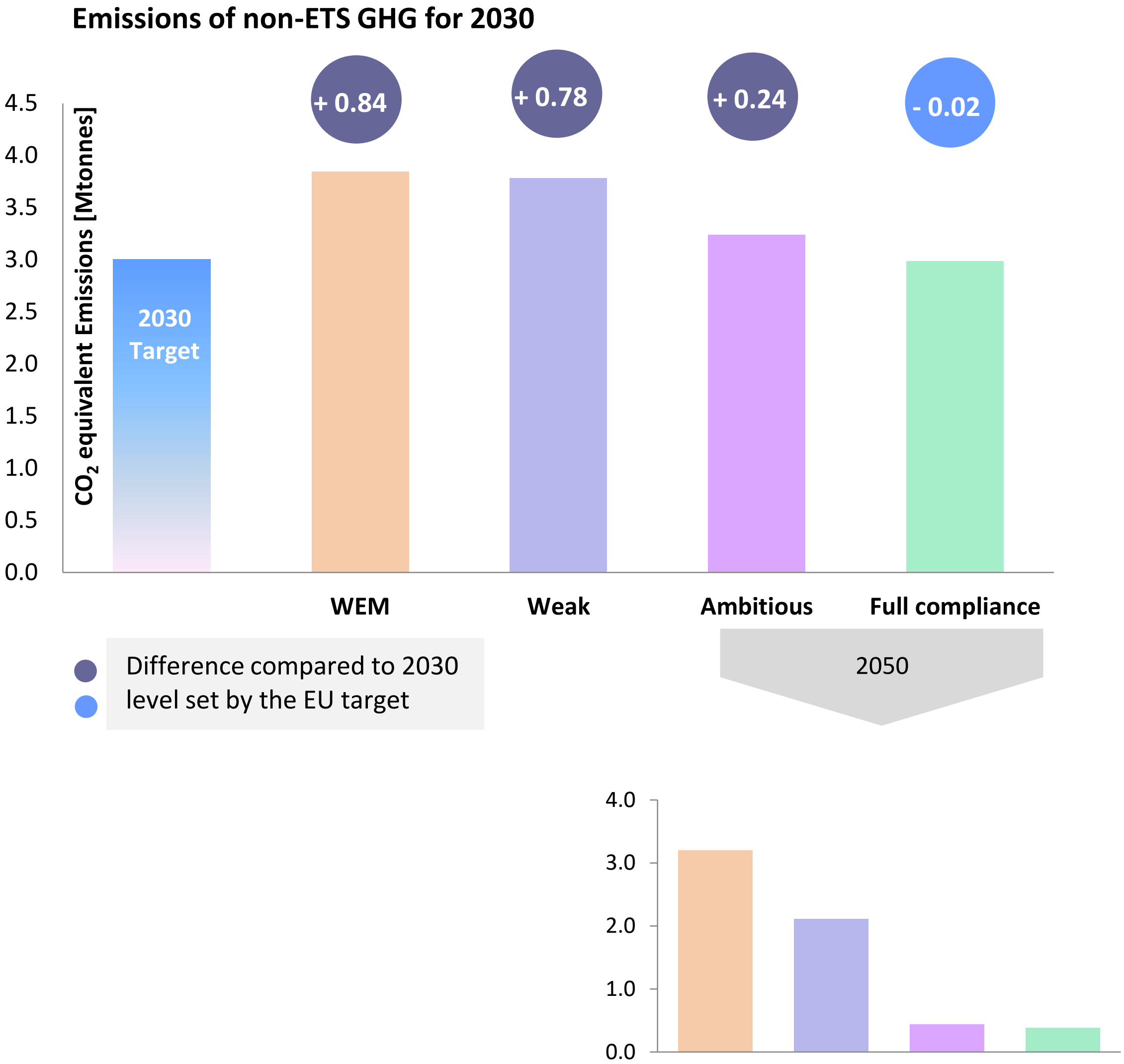

Figure 4.4 | Non-ETS GHG emissions level after the implementation of the various scenarios. The figure also highlights the difference (positive or negative) compared to the 2030 desirable emissions level for Cyprus set by the EU policy. The emissions levels for the year 2050 as also illustrated.

4.3.1 ‘Weak’ Scenario

A ‘weak’ abatement scenario has also been considered in which it is assumed that policymakers adopt some measures in addition to the WEM scenario, but only those measures with an abatement cost up to 30 Euros per tonne of CO_2 equivalent– the cheapest measures that are approximately as costly as the emissions allowance price prevailing in EU ETS sectors by the end of 2019. Based on the data shown in the third column of Table 4.3, seven measures fulfil this cost criterion and are introduced to the optimisation model. Road transport measures are excluded from the policy mix up to 2030 based on this cost criterion, and they are only available from 2031 onwards. Such an approach affects not only the 2030 target, which appears to be unreachable, but also the long-term objective. This is due to the fact that measures such as the introduction of electric vehicles or promotion of public transport, with large abatement potential, take time to be implemented; neglecting these measures during the period 2020-2030 leads to the underachievement of the 2050 target by 1,217 thousand tonnes of CO_2 equivalent. In this ‘weak’ scenario, the resulting gap for the 2030 emissions is covered by purchasing allowances up to 97.7 million Euros.

4.3.2 ‘Ambitious’ Scenario

In the third scenario, which is called the ‘ambitious’ scenario, the optimisation model is forced to exploit for the period 2020-2030 only measures with costs up to 120 Euros per tonne of CO_2 equivalent. This cost threshold has been chosen because it is in line with carbon tax levels applied in some EU countries (e.g. Sweden) and proposed for others (e.g. Germany and Cyprus). In this case, eleven out of the fourteen mitigation options of Table 4.1 are available to deploy. This ‘ambitious’ scenario also includes the implementation of a carbon tax of 120 Euros’2015 per tonne of CO_2 equivalent in the non-ETS sectors, to be introduced gradually over the six-year period 2020-2025, at an annual increase of 20 Euros’2015 per tonne of CO_2 equivalent. After 2025, the carbon tax remains constant at this level up to 2050. The long-term energy forecast model suggests a reduction of emissions by 363 and 307 thousand tonnes of CO_2 equivalent by 2030 and 2050, respectively, due to this tax compared to the WEM scenario developed in the National Energy and Climate Plan. As the carbon tax is implemented gradually, and since it involves modest increases in energy prices and its revenues are considered to be recycled in the economy of Cyprus, we assume that the tax has no cost to society.

The two scenarios, ‘weak’ and ‘ambitious’, obviously lead to different aggregate costs up to 2030 (see the fourth and fifth row of Table 4.3). The first case yields lower total abatement and hence shows lower investment needs. Although the ‘weak’ scenario results in greater net benefits up to 2030 than the ‘ambitious’ scenario (because it does not deploy expensive abatement measures), if one takes into account external costs of GHG emissions and air pollutants, the ‘ambitious’ scenario turns out to be more beneficial for society. From the viewpoint of long-term decarbonisation, the ‘ambitious’ scenario closes considerably the 2050 emissions gap compared to the ‘weak’ scenario. This is not only due to the emissions reduction caused by the carbon tax but also to the number of mitigation measures that enter in the ‘ambitious’ scenario. This is highlighted in Figure 4.5, which presents the different cost-effective mix of policies, depending on the level of ambition for the medium-term. It is evident that only with an ambitious medium-term strategy, as assumed in the ‘ambitious’ scenario, is it possible to approach the demanding 2050 target. Similar results – but not specific to Cyprus – were presented in the theoretical model application of Sotiriou and Zachariadis (2019) in Chapter 3.

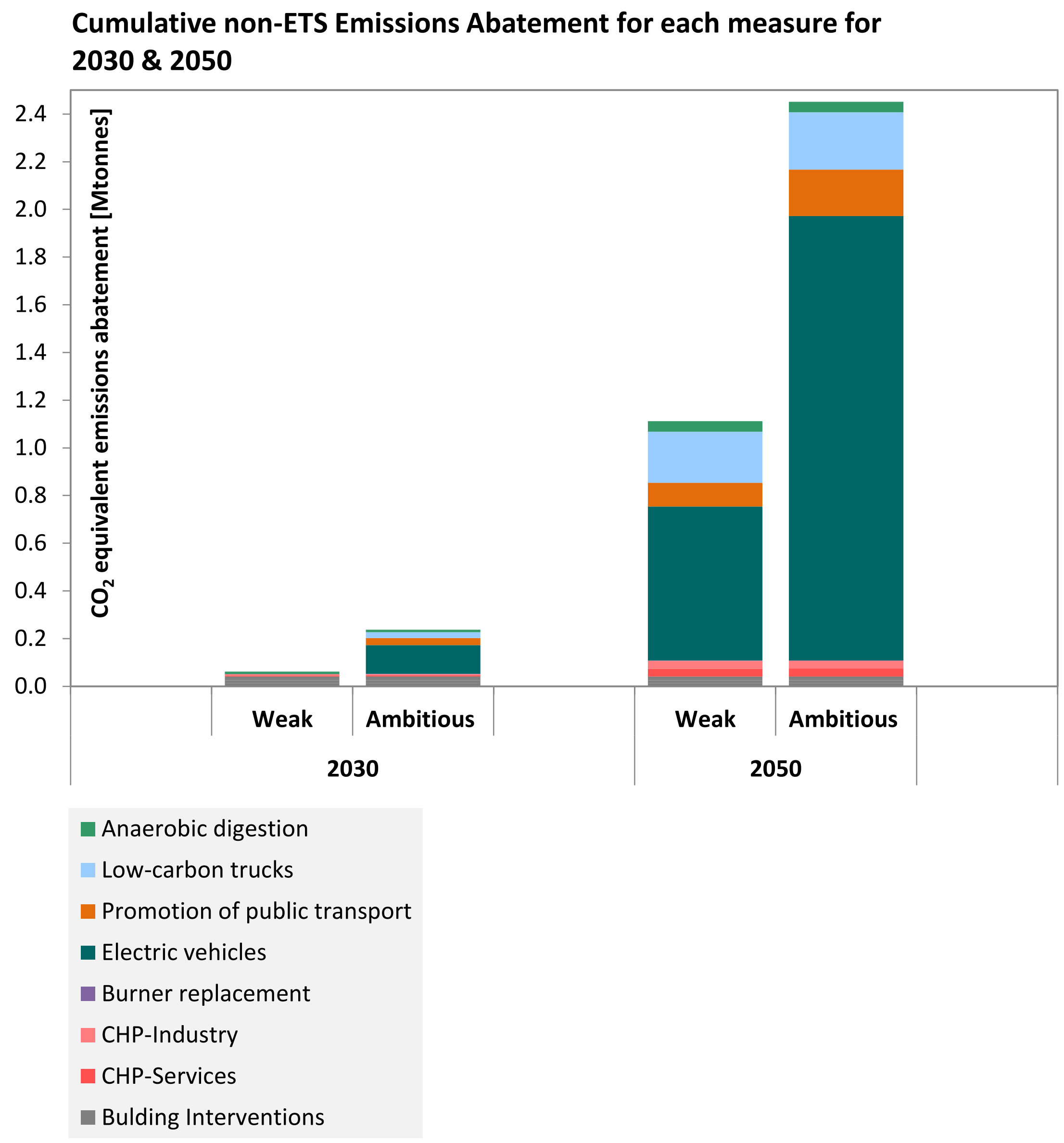

Figure 4.5 | Cumulative GHG emissions reduction in non-ETS sectors of the economy of Cyprus, and the difference in total abatement and in the diffusion of abatement measures depending on the ambition level of policymakers.

4.3.3 ‘Full Compliance’ Scenario

In the last scenario, the so-called ‘full compliance’ scenario, all measures are available to implement regardless of their abatement cost. To meet the decarbonisation target of 2030, a higher carbon tax is necessary compared to the ‘ambitious’ scenario. This tax, which was determined iteratively in our long term energy forecast model, is introduced gradually over the eleven-year period 2020-2030, starting from 27 Euros’2015 per tonne of CO_2 equivalent and reaching 298 Euros’2015 per tonne of CO_2 equivalent by 2030. For the rest of the study period, 2030-2050, the carbon tax remains constant. The corresponding reductions in energy demand due to this draconian tax lower non-ETS emission by 596 and 626 thousand tonnes of CO_2 equivalent by 2030 and 2050, respectively, compared to the WEM scenario. The optimisation model fully exploits the measures up to 2030, which leads to larger investment needs than the ‘ambitious’ scenario. Considering the 2050 objective, due to the large emissions reductions induced by the very high carbon tax, fewer investments up to 2050 are needed in comparison to the ‘ambitious’ scenario (two last rows Table 4.3). However, it has to be noted that such a tax, at almost 300 Euros per tonne of CO_2, is difficult to be adopted as it would raise retail fuel prices by 50% or more.

Moreover, even at gradual implementation, such tax levels can greatly affect the relative prices of goods and services in the economy, may lead to very high costs for parts of society and to a fast replacement of capital in some economic sectors, leading to stranded assets. Therefore, the ‘full compliance’ scenario is almost certain to lead to social costs and can be regarded as a theoretical one. It is presented here in order to exhibit how great the decarbonisation challenge is for an industrialised country with growing income levels. In fact, achieving non-ETS decarbonisation targets is considered very challenging for most EU countries, as shown by (European Environment Agency, 2019).

Table 4.3 | Summary of the cost-related results of the scenarios considering mitigation measures and carbon tax.

Scenario	Investment costs [million €]	Permits to cover 2030 gap [million €]	Total Costs [million €]	Total Costs incl. savings [million €]	Total Costs incl. savings and externalities [million €]
Results for the medium-term target, 2030					
WEM	-	105	105	105	105
Weak	105	98	203	-239	-280
Ambitious	1,619	30	1,649	-139	-637
Full compliance	1,671	-	1,671	114	-391
Results for the long-term target, 2050					
Ambitious	8,186	30	8,216	390	-1,770
Full compliance	7,541	-	7,541	585	-1,502

Table 4.4 | Summary of the abatement-related results of the scenarios considering mitigation measures and carbon tax.

Scenario	**Emissions gap** [ktonnes of CO_2 equivalent] **for:**	
	2030 target	**2050 target**
WEM	837	2,799
Weak	776	1,687
Ambitious	237	41
Full compliance	0	0

4.4 Conclusions

Deep decarbonisation of the economy of most EU countries faces significant challenges. This study has explored emission abatement options for the EU member state of Cyprus, where the already adopted policies and measures are insufficient for meeting mandatory emission reduction commitments for the sectors that are not subject to the EU Emissions Trading System. In view of these challenges, the adoption of additional abatement measures was considered, coupled with the implementation of a gradually increasing carbon tax in the non-ETS sectors of the Cypriot economy. It is widely accepted that, without a sufficiently high carbon tax, Cyprus – like most other EU member states – will not be able to meet its 2030 and 2050 decarbonisation objectives in a cost-effective manner.

The simulations provide evidence that if the medium-term climate strategy is not ambitious, deep decarbonisation required for 2050 will probably be impossible to achieve unless strong technological breakthroughs occur. Weak policies involving the adoption of abatement options with a cost of up to 30 Euros per tonne of CO_2, which is currently the business-as-usual norm in most EU countries, resulting in low investment in ambitious measures, such as those affecting road transport emissions. The resulting emission gap for 2050 suggests that the medium term's lack of ambition will lock the economy to a carbon-intensive trajectory. Therefore, it is important to be more ambitious in the medium term and also deploy more costly measures with higher long-term abatement potential. For this purpose, the results suggest that a carbon tax in the order of 120 Euros per tonne of $CO_{2,}$ which is adjusted for changes in the cost of living and whose revenues are recycled in the economy, can reduce energy demand to a sufficient extent so as to induce green investments that can lead a country to deep decarbonisation in the mid-21st century. Although ambitious policies result in the highest investment needs, they turn out to be the socially optimal approach not only because they can help achieve long-term decarbonisation targets but also because they can improve air quality and human health to a considerable extent while avoiding adverse impacts from climate change.

4.5 References

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5 Trade-Offs between Economic and Environmental Criteria in Climate Policy[10]

Abstract

Climate policy is changing fast in the European Union, with country leaders raising the bloc's ambition to reduce greenhouse gas emissions by 2030 and 2050. However, there is uncertainty about the allocation of decarbonisation effort between European Union member states. This study develops a multi-objective mathematical programming framework to provide insights to decision-makers in this policy context by exploring trade-offs between stronger decarbonisation goals and higher costs. The application of this approach suggests that, unless the 2030 policy objective is very ambitious, small changes in emission abatement do not entail large changes in costs. The picture changes when decision-making explicitly accounts for external costs of emissions of greenhouse gases and air pollutants in the optimisation procedure. In this case, the costs to comply with a specific 2030 target rise faster the more ambitious the target becomes, but most decisions lead to negative social costs, which means that decarbonisation will be beneficial to the national economy. The analysis also addresses the required level of investments and public expenditures for implementing specific policy mixes and the attainability of climate neutrality by 2050 as pledged by the European Union. Sensitivity analyses are performed regarding the direct rebound effect on energy renovation and transportation measures and the risk of delayed implementation. Although the modelling framework has been developed for a specific country and is tailored to the specific European Union policy circumstances, the proposed methodology is entirely suitable for other world regions with a demanding decarbonisation roadmap.

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[10] A concise version of this chapter is available in: Sotiriou C. and Zachariadis T., A multi-objective Optimisation Approach to Explore Decarbonisation Pathways in a Dynamic Policy Context. United States Association of Energy Economics Working Paper No. 21-485, Available at SSRN: https://ssrn.com/abstract=3766455; submitted to *Journal of Cleaner Production*, January 2021, in revision status since March 2021.

5.1 Introduction

Compared to most other parts of the world, the EU has made important commitments to help stabilise the global climate since the 1990s. In order to align their ambitions with the global Paris Agreement on Climate Change (UNFCCC, 2015), EU Member States decided in December 2019 that they would aim to achieve 'climate neutrality' by 2050, i.e. achieve zero net emissions of GHG into the atmosphere by that year. The ambitions related to climate change are part of a broader initiative on a 'European Green Deal' with wide-ranging policy initiatives for the transition to a sustainable economy. In this context, a 'European Climate Law' was proposed in March 2020 and is under negotiation at the time of this writing, with the aim to make the climate neutrality target legally binding across the EU[11].

An earlier decision, adopted by EU leaders in 2014, was to reduce GHG emissions by 40% in the year 2030 compared to those of 1990. However, in view of the European Green Deal, this target is considered inadequate to lead to net-zero emissions by 2050. Therefore, the 2030 objective is currently under revision, with the declared aim to increase the target to at least 55% emissions reduction in 2030; a relevant proposal was tabled in September 2020 (European Commission, 2020) and is negotiated among EU bodies with the aim to be adopted as part of the European Climate Law by summer 2021.

Since the 2014 decision, all EU countries have adapted their energy and environmental strategies in order to reach the 40% GHG emission reduction target by 2030. Separate decarbonisation targets have been set for heavy industry and the rest of the economy. Heavy industrial installations are subject to the EU ETS, whereas all other economic sectors (transport, buildings, light industry and agriculture) are subject to an aggregate emission reduction target for 2030, different by country. Decarbonisation seems to be

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[11] Policy updates are available on the website of the European Commission, the EU's executive body: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

particularly challenging for these non-ETS sectors because it is difficult to decouple their emissions from economic growth, and zero-carbon energy sources are still costly; as a result, very few EU countries are on track to meet their non-ETS 2030 commitments (European Environment Agency, 2019). Strengthening of the 2030 targets, in the frame of the 'European Green Deal' mentioned above, puts further strains on national policies.

In light of the changes mentioned above and the future more challenging targets, the national climate policy framework may need to be redesigned. That raises challenges regarding the identification and evaluation of additional measures and the appropriate selection of the policy mix to be implemented by national climate change decision-makers. In a more stable policy environment, decision making could be conducted through cost-effectiveness analyses where one seeks the least-cost emission abatement options that lead to the attainment of the target. However, the current context of European climate policy is far from static. In addition to the uncertainty regarding the 2030 emission reduction target mentioned above, achieving the long-term decarbonisation goal of 2050 (and at what cost) may crucially depend on the decisions to be taken about the 2030 target. In a previous paper (Sotiriou and Zachariadis, 2019), we demonstrated that ambitious decarbonisation in 2050 could only be achieved with a relatively strong intermediate target for 2030; selecting the least costly abatement measures to attain the minimum 2030 emission reductions will not allow sufficient time for more ambitious (but more costly) measures to take full effect by 2050, making it impossible to comply with the 2050 goal.

Expanding on the previous work, this chapter presents a MOMP approach that takes into consideration the current policy challenges. A Pareto-optimal front (PF) was developed for policies that can achieve varying decarbonisation levels in non-ETS sectors at different costs; this allows policymakers to identify trade-offs between a more ambitious and costly decarbonisation policy and a cheaper mix of abatement measures that can achieve a less ambitious target. Then we re-calculate this front by considering not only the direct costs of each measure but also the change in external costs because of changes in air pollution induced by the measures; this enables an assessment of decarbonisation strategies up to 2030 in a way that is closer to the socially optimal solution. Finally, the investment needs and public expenditures required for implementing specific policy mixes were assessed, and the feasibility of these mixes to lead to climate neutrality goal by 2050.

MOMP approaches have been widely used across scientific fields. Focusing on climate change mitigation topics, a considerable amount of work has been done for design, planning and control problems in the field of renewable and sustainable energy (Baños et al., 2011), using, amongst others, Pareto-optimisation techniques. Similar criteria to ours, i.e. economic and environmental performance, can be found in a variety of studies for planning investment in energy sources (Flores et al., 2015), the design and performance of hybrid energy systems (Katsigiannis et al., 2010; Perera et al., 2013a, 2013b) or hybrid bio-refineries (Giarola et al., 2011) and the optimisation of distributed energy supply systems (Buoro et al., 2013). Studies have also considered a third objective, for example, technological (Fazlollahi et al., 2014) or social criteria (Mota et al., 2015). Optimisation over multiple sustainable development goals has also been applied (Van De Ven et al., 2019).

This study goes beyond existing work in several ways. A main feature is that it adopts a tailor-made modelling framework to address the EU policy context, focusing on emissions outside of the EU ETS, i.e., the non-ETS emissions, controlled by the ESR, which have specific commitments and challenges, as explained above. There is no clear distinction in similar studies between the two key EU policies tools mentioned above to the best of our knowledge. Consequently, dealing with the non-ETS emissions of a country enabled us to assess variant mitigation measures across all non-ETS economic sectors, such as transport, buildings, light industry, and agriculture. As Table 5.1 indicates, the applications of multi-objective optimisation methods in emissions reduction and climate change mitigation appear to focus mainly on a specific sector.

Furthermore, the approach addresses the new challenging EU-wide climate targets for 2030 as part of a broader European Green Deal programme with a view of the ultimate carbon neutrality goal of 2050, considering implications for public finances and the level of economy-wide investments. An alternative assessment has also been followed, where the optimisation procedure is being driven by the cost performance of the various mitigation options when including the avoided external costs of air pollution. This study constitutes the first to follow a MOMP approach for exploring decarbonisation pathways for Cyprus' non-ETS sectors.

The modelling framework is applied for an EU member state with a population of about one million people, which – similarly to most other EU nations – is faced with serious challenges to decarbonising its non-ETS sectors, as demonstrated in the country's National Energy and Climate Plan (Republic of Cyprus, 2020). Data to be presented in this chapter come from an in-depth exploration of the emissions abatement potential in that country. However, with an appropriate extension of the available dataset, the proposed methodology is entirely suitable for any other EU member state, as well as for any other country with a demanding decarbonisation roadmap.

The remaining chapter is structured as follows: Section 5.2 gives an overview of the applied methodology, and the following Section 5.3 includes a detailed description of the formulation of the problem and the data and assumptions used. The application and the results of the proposed approach in a real-world case study are illustrated in Section 5.4, which also includes sensitivity analyses that account for uncertainties in behavioural aspects and the speed of implementation of the abatement measures. Finally, concluding remarks and implications for policy are given in Section 5.5.

Table 5.1 | Applications of multi-objective optimisation methods in emissions reduction and climate change mitigation.

Authors	Application Level	Objectives		
		Economic	**Environmental**	**Other**
Adedeji et al. (2020)	National: Brunei	total generation cost	life cycle GHG emissions	renewable energy ratio
Dorotić et al. (2019)	City: Velika Gorica	total system cost	CO_2 emissions	-
Fazlollahi et al. (2012)	-	investment/operational costs	CO_2 emissions	-
Fesanghary et al. (2012)	Building: US (southern)	life cycle cost	CO_2e emissions	-
Flores et al. (2015)	National: Argentina	net present value	GHG emissions	-
Forouli et al. (2019a)	Regional: EU	-	GHG emissions	energy security
Forouli et al. (2019b)	National: Greece	budget	energy savings	risk
Gharavi et al. (2015)	National: Iran	economics	environmental emissions	-
Jing et al. (2018)	Buildings: Beijing, Shanghai, Xiamen	annual total cost	annual carbon emissions	-
Katsigiannis et al. (2010)	City: Chania	system’s cost of energy	life cycle GHG emissions	-
Murray et al. (2020)	suburb Switzerland	total cost	life cycle emissions	-
Santibanez-Borda et al. (2021)	National: UK	total costs	GHG emissions	-
Schwartz et al. (2016)	Building: Sheffield	life cycle cost	life cycle carbon footprint	-
Sweetapple et al. (2014)	-	operational costs	GHG emissions/effluent pollutant concentrations	-
Xiong et al. (2018)	City: Beijing	total cost	GHG emissions/water ecosystem impact	-
Jeong et al. (2019)	Building: South Korea	investment/net present value/saving to investment	CO_2 emissions	-

		ratio/marginal abatement cost		
He et al. (2021)	National: China	economic output	energy consumption/carbon emissions	-
Rosso et al. (2020)	Building: Rome	investment/energy cost	energy demand/CO_2 emissions	-

Authors	Application Field	Time Scale		
		Short-term	Medium-term	Long-term
Adedeji et al. (2020)	Energy sector planning		• (2035)	
Dorotić et al. (2019)	District heating and cooling operation	• (year period)		
Fazlollahi et al. (2012)	Energy system design and operation	• (year period)		
Fesanghary et al. (2012)	Single-family house building envelope design		• (lifetime 25 years)	
Flores et al. (2015)	Energy resources investment planning		• (2010-2030)	
Forouli et al. (2019a)	Technological portfolios for power generation			• (2050)
Forouli et al. (2019b)	Budget allocation for energy efficiency measures	• (2020)		
Gharavi et al. (2015)	Hybrid green power systems design		• (lifetime 20 years)	
Jing et al. (2018)	Distributed energy systems planning		• (10 years)	
Katsigiannis et al. (2010)	Small autonomous hybrid power systems design		• (Lifetime 20 years)	
Murray et al. (2020)	Decentralised multi-energy systems design			• (2050)
Santibanez-Borda et al. (2021)	Offshore natural gas production networks design		• (10 years)	
Schwartz et al. (2016)	Existing buildings refurbishment design			• (lifetime 60 years)
Sweetapple et al. (2014)	Wastewater treatment plant operation & control strategies	•		
Xiong et al. (2018)	Urban water supply systems design	• (2020)	• (2030)	
Jeong et al. (2019)	Energy efficiency improvement for deteriorated multi-family housing complexes		• (2030)	
He et al. (2021)	Energy efficiency improvement in industrial sectors		• (2035)	
Rosso et al. (2020)	Energy retrofit on existing building stock	• (year period)		

5.2 Conflicting criteria and Multi-Objective Mathematical Programming

An optimisation problem is defined as the search for a minimum or a maximum (the optimum) of a function (Pardalos and Resende, 2002). A variety of computational optimisation methods have focused on optimizing one objective function (the name we give to the function that the optimisation algorithm will try to optimise) considering all the parameters of the problem, so-called single-objective optimisation, over a feasible set determined by constraint functions. However, a considerable number of applications require the simultaneous optimisation of several objectives (Chiandussi et al., 2012), which may be conflicting; a decrease in one objective's value leads to an increase in the other objective's value. Multi-objective optimisation programming is concerned with this type of decision-making problems.

Depending on the method used to find an optimum for a problem, the result is different. The MOMP method, which has become an important tool for decision-making, allows a degree of freedom compared to the single-objective method (Collette and Siarry, 2003). MOMP does not offer a unique optimal solution that simultaneously optimises all the objective functions. Whenever second or more objectives are introduced in a problem, the concept of optimality no longer exists. In MOMP, the optimality is replaced by Pareto optimality (Pareto, 1906) or efficiency, a concept well known to economists that is named after the Italian economist Vilfredo Pareto.

A general multi-objective optimisation problem (minimisation) can be described in mathematical terms as follows (Collette and Siarry, 2003):

$$\min \vec{f}(\vec{x}) \;\; s.to.$$

$$\vec{g}(\vec{x}) \leq 0 \;\; and$$

$$\vec{h}(\vec{x}) = 0$$

where $\vec{x} \in \mathbb{R}^n, \vec{f}(\vec{x}) \in \mathbb{R}^k, \vec{g}(\vec{x}) \in \mathbb{R}^m$ and $\vec{h}(\vec{x}) \in \mathbb{R}^p$. The vectors $\vec{g}(\vec{x})$ and $\vec{h}(\vec{x})$ represent m inequality constraints and p equality constraints, respectively. Comparing that with the description of a general optimisation problem included in Chapter 3.2, there is no longer one objective function to be optimised, but *k* functions.

In this type of optimisation problems, there is a multitude of solutions. A relation between solution A and solution B exist in order to make solution A interesting. That domination relation is defined as follows (Collette and Siarry, 2003):

Vector $\overrightarrow{x_1}$ dominates a vector $\overrightarrow{x_2}$ if:

a) $\overrightarrow{x_1}$ is a least good as the $\overrightarrow{x_2}$ for all the objectives and,
b) $\overrightarrow{x_1}$ is strictly better than $\overrightarrow{x_2}$ for at least one objective.

In other words, $\overrightarrow{x_1}$ is Pareto dominant if there exists no feasible vector $\vec{x}$ which would improve a criterion without worsening at least one other criterion.

The Pareto optimal solutions, also referred to as non-dominated, are those which dominate the others but do not dominate themselves. Global optimality in the Pareto sense is defined as:

Vector $\vec{x}$ is Pareto optimal if there does not exist any vector $\overrightarrow{x'}$ such that $\overrightarrow{x'}$ dominates the vector $\vec{x}$.

The set of all Pareto optimal solutions is called a Pareto optimal set. The Pareto optimal front is the set consisting of objective function vectors related to the Pareto optimal set.

Summarising the above, the result of the optimisation process is expressed as a set of Pareto or non-dominated or non-inferior or efficient solutions, representing optimal trade-offs between given criteria; improvement of one criterion results in a loss in another (Branke et al., 2009; Metaxiotis and Liagkouras, 2012). The plot of the objective functions, whose non-dominated vectors are in the Pareto optimal set, is called the Pareto optimal front. The produced PF, also called the trade-off surface, takes certain shapes, depending on the type of problem we are dealing with.

5.2.1 Solution Methods of Multi-Objective Optimisation Problems

Based on the classification of Hwang and Masud (1979), there are three optimisation methods of solving MOMP problems: the priori methods, the interactive methods and the posteriori (or generation) methods. The classification is based on the stage in the process in which the decision-maker is involved. The posteriori method is applicable in our study since the involvement of the decision-maker happens at a later stage when all the information is on the table; the decision-maker chooses from a palette of solutions. It now depends on him/her which of the criteria he/she considers more important and eventually will have to specify a trade-off between those criteria. In this type of approach, amongst the most popular methods are the weighted sum and epsilon constraint (ε-constraint) method.

The goal of the weighted sum method is to convert the multi-objective problem into a single-objective one; each objective function is associated with a weight, and a weighted sum of objective functions is produced (Ehrgott, 2005; Steuer, 1989). There are methods that allow us to convert the multi-objective optimisation problem into a single-objective optimisation problem with additional constraints. The ε-constraint method falls into this approach where one of the objective functions is chosen to be optimized with high priority while transforming all other objective functions into inequality constraints (Collette and Siarry, 2003).

The vector of initial constraints is already being selected, and the problem is transformed for each objective function. Suggesting that the objective function with a high priority has index 1, and there is a constraint vector $\varepsilon_i, i \in \{2, \dots, k\}, \varepsilon_i > 0$, the general multi-objective optimisation problem (minimisation) presented above is transformed into the following:

$$\min f_1(\vec{x}) \ s.to.$$

$$f_2(\vec{x}) \leq \varepsilon_2$$

$$\vdots$$

$$f_\kappa(\vec{x}) \leq \varepsilon_\kappa$$

$$\vec{g}(\vec{x}) \leq 0 \ \ and$$

$$\vec{h}(\vec{x}) = 0$$

Summarizing the above, in the ε-constraint method, one objective function is optimized while the other objective functions are transformed into constraints (Cohon, 1978; Haimes et al., 1971). By parametrical variation on the right-hand side of the constrained objective functions, the efficient solutions of the problem are produced (Chankong and Haimes, 1983).

Difficulties and drawbacks of the weighted sum method over the ε-constraint method have been identified and discussed (Mavrotas, 2009; Steuer, 1989). Several studies are dedicated to improving the ε-constraint method (Hamacher et al., 2007; Laumanns et al., 2006). Mavrotas (2009) proposed a novel version of the conventional ε-constraint method, the augmented ε-constraint method (AUGMECON), that removes weakly Pareto solutions and incorporate some acceleration issues. The AUGMECON method tries to address three issues: the guarantee of the Pareto optimality of the solutions in the payoff table and the generation process, and the increased computational time when more than two objective functions are considered.

Innovative additions to the algorithm to deal with these aspects include: (i) the lexicographic optimisation for every objective function to construct the payoff table, (ii) the transformation of the objective function constraints to equalities by explicitly incorporating the appropriate slack or surplus variables and at the same time using these variables as a second term in the objective function, forcing the program to produce only efficient solutions, and (iii) the algorithm's acceleration with an early exit from the loops when the problem becomes infeasible (Mavrotas, 2009).

This study utilises an improved version of AUGMECON, AUGMECON2 (Mavrotas and Florios, 2013). The introduction of the bypass coefficient is being made, exploiting the information from the slack or surplus variables in every iteration while reducing the computation time as many redundant iterations are avoided. Therefore, the exact PF can be produced in a reasonable computation time.

The new problem with the use of this method becomes:

$$min\left[f_1(\vec{x}) + eps\left(\frac{s_2}{r_2} + 10^{-1} \times \frac{s_3}{r_3} + \cdots + 10^{-(k-2)} \times \frac{s_k}{r_k}\right)\right]\ s.to.$$

$$f_2(\vec{x}) - s_2 = \varepsilon_2$$

$$\vdots$$

$$f_\kappa(\vec{x}) - s_k = \varepsilon_\kappa$$

$$\vec{g}(\vec{x}) \leq 0\ \ and$$

$$\vec{h}(\vec{x}) = 0$$

where the parameters $r_2, \dots r_k$ are the ranges of the respective objective functions, $s_2, \dots s_k$ represent the surplus variables of the respective constraints and $eps \in [10^{-6}, 10^{-3}]$. The AUGMECON2 method has been coded in General Algebraic Modelling System (GAMS).

5.3 Adopted Approach

To support policymakers in light of the future changes in emission reduction targets set by the EU, this approach focuses on providing a set of optimal solutions, instead of a unique one, exploring trade-offs between economic and environmental criteria. The first step of the adopted approach was to specify the optimisation problem by defining the objective functions, the decision variables and the constraints. The next step considered the selection of a suitable programming method to perform the multi-objective optimisation problem. This study utilised an improved version of the so-called ε-constraint method, AUGMECON2, explained in the previous section and coded in the GAMS. Once the problem was formulated, Figure 5.1 displays the next steps.

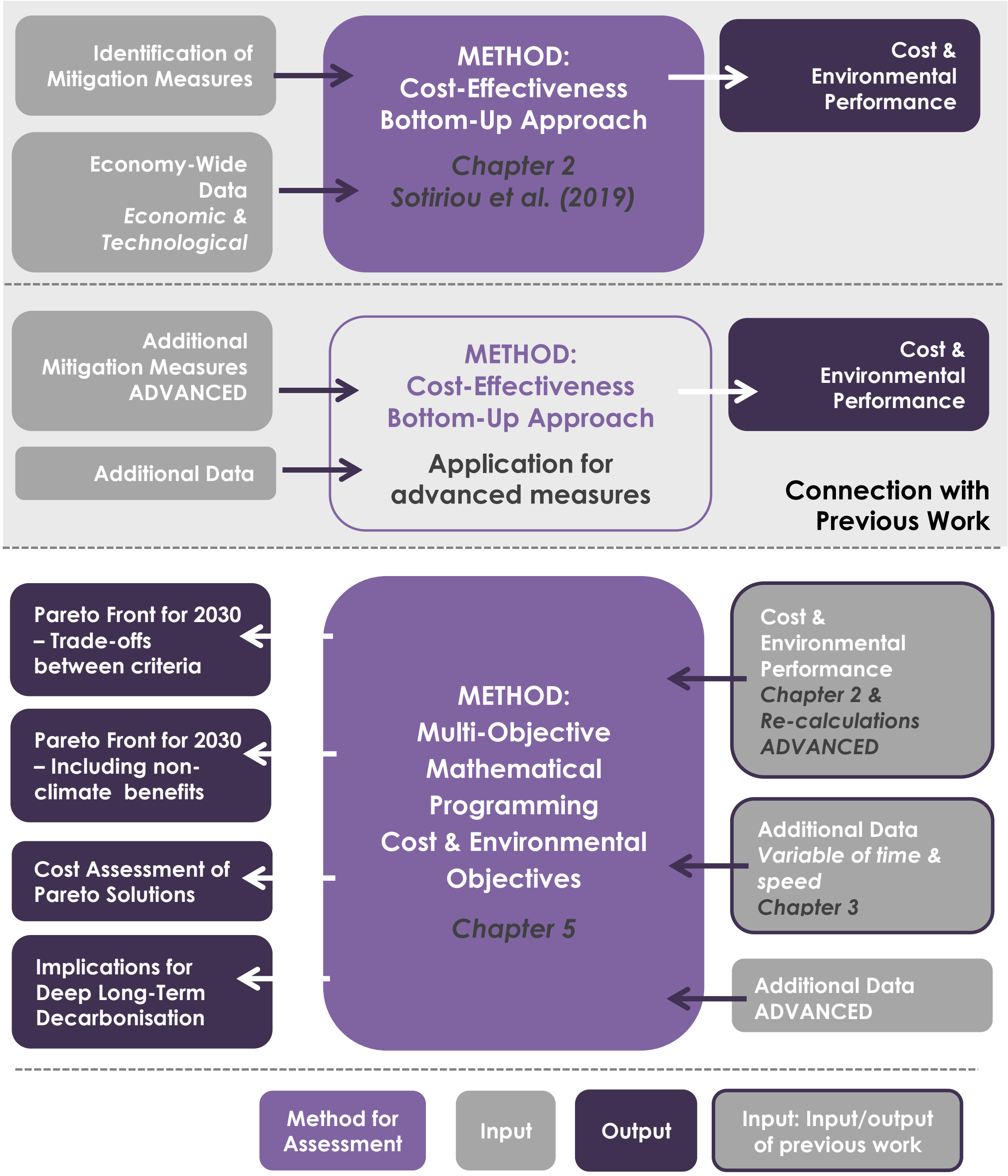


Figure 5.1|Methods and models applied, main input and output included in the exploration of the trade-offs between conflicting criteria.

The multi-objective optimisation model presented in this paper builds on previous work that involved a static cost-effectiveness model presented in Chapter 2 (Sotiriou et al., 2019) and the formulation of a dynamic optimisation model, with a single objective to minimise abatement costs, presented in Chapter 3 (Sotiriou and Zachariadis, 2019). These previous approaches furnished the MOMP model with data about the costs and the emission reduction potential of abatement measures. Then, as shown in Figure 5.2, the MOMP model is applied with the aid of previous data and calculations as well as additional data collected and assumptions made in the frame of this study. Model implementation leads to the construction of the PF, which provides decision-makers with a set of potential solutions to the overall MOMP problem and some very useful insights about trade-offs among the objective functions and implications about the possibility to attain the climate neutrality target of 2050.

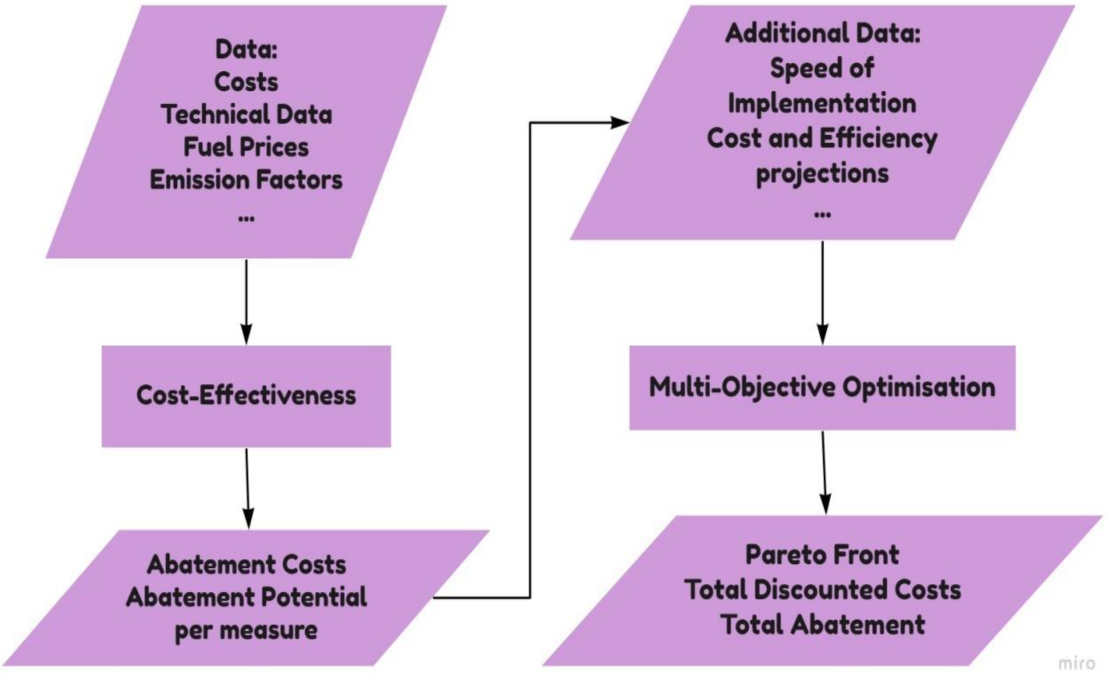


Figure 5.2|Schematic presentation of the combinations of the two methods; cost-effectiveness analysis (Chapter 2) and multi-objective optimisation.

5.3.1 Problem Formulation

The decision-makers problem, as described in Sotiriou and Zachariadis (2019), only minimizes economic costs, while a constraint holds on GHG emissions. Expanding this cost-optimal GHG reduction problem, the emission reduction constraint mentioned above is introduced as an objective function. The two criteria for optimisation now are a) the minimisation of the total discounted cost of abatement and b) the maximization of total abatement, i.e. the amount of GHG emissions reduced by 2030 through the implementation of each policy mix. In this way, we balance the costs and the achievable GHG abatement potential by constructing a PF using the AUGMECON2 method. This allows insights into the trade-offs between the two objectives but also enables decision-makers to choose a policy mix depending on the GHG abatement goal to be finally adopted by EU leaders for their country.

Following the selection of the criteria and mathematical formulation of the optimisation problem, the possible climate change mitigation measures to be considered are selected, and the parameters of the model are determined.

Here we are dealing with a Linear Programming (LP) problem, as the constraints and the objective functions are linear functions of the decision variables (Hillier and Lieberman, 2015). The consideration of both a cost objective function and an emissions abatement objective function leads to the following bi-criteria optimisation. The first objective is related to the minimisation of the total present cost of abatement:

$$minimise\ \boldsymbol{cost} = \sum_{j}\sum_{t} AC_{j,t} * a_{j,t}$$

Equation 5.1 | Cost-Objective of a bi-criteria optimisation problem.

Where $a_{j,t}$ is the GHG abatement (major GHG were considered including CO_2, CH_4 and N_2O) achieved by the j^{th} mitigation option for the year t and $AC_{j,t}$ is the discounted abatement cost associated with each measure for a specific year. Coefficients $AC_{j,t}$ are obtained from results of a different model performing cost-effectiveness calculations (Sotiriou et al., 2019). The abatement cost is expressed in Euros per tonne of CO_2 equivalent emissions avoided, and $a_{j,t}$ is expressed in avoided annual emissions in tonnes of CO_2 equivalent. Costs are assessed from the perspective of a social planner attempting to maximise social welfare; this means that fuel costs include only the cost of fuel imports to the country and are net of excise and value added taxes which are re-distributed within the country and that a relatively low discount rate is used (4% in real terms) in line with recommendations of international organisations for public policy assessments (Sotiriou et al., 2019)

The second objective function seeks to maximize the reduction of GHG emissions:

$$maximise\ \boldsymbol{GHGabatement} = \sum_{j}\sum_{t} a_{j,t}$$

Equation 5.2 | Environmental-Objective of bi-criteria optimisation problem.

The model runs for the period 2021-2030 with a time step of one year, t, for the scenarios considering only the medium-term target. When the long-term net-zero emission target is introduced in the analysis, the single-objective version of the model is used to draw the pathway from 2031-2050.

The decision variables, $a_{j,t}$ of the model, are the annual GHG abatement realised by each measure. By modifying the values of these variables, the different Pareto optimal solutions are created. Three constraints are imposed on the decision variables. First, there is an upper limit to the achievable full abatement potential (Equation 3.4) up to a year due to constraints in financial, human or natural resources. Second, as those mitigation measures cannot be realised overnight, each measure has a limit on the annual implementation speed, which develops differently for the available measures (Equation 3.5). Finally, for a subset of measures associated with strong economic and behavioural barriers, an additional constraint assumes that annual values of the speed of implementation depend on the cumulative amount of abatement that has already been deployed up to that year (Equation 3.6).

Table 5.2 | Problem definition – Multi-objective optimisation programming.

Sets	Description
j	Mitigation measures available for consideration
t	Time step of a year
Decision Variables	**Description**
$a_{j,t}$	Abatement achieved through the implementation of measure *j* for the time period *t*
Objective Functions	**Description**
$\text{minimize } \mathbf{cost}$	Minimisation of the total discounted cost of abatement, Equation 5.1
$\text{maximize } \mathbf{GHGabatement}$	Maximisation of the achievable abatement, Equation 5.2
Constraints	**Description**
Maximum emissions abatement	Achievable maximum abatement potential for each measure, Equation 3.4
Maximum implementation speed for measures with loose barriers	Maximum speed of implementation that can be achieved per year for the subset of measures *j* with loose economic and behavioural barriers, Equation 3.5
Maximum implementation speed for measures with strict barriers	Maximum speed of implementation that can be achieved per year for the subset of measures *j* with strict economic and behavioural barriers, Equation 3.5
Dependence of implementation speed and selected abatement for measures with strict barriers	Annual values of speed of implementation depend on the cumulative amount of abatement that has already been deployed up to that year for the subset of measures *j* with strict economic and behavioural barriers, Equation 3.6

This Section presented only the equations of the two objective functions, Equation 5.1 and Equation 5.2, as all the mathematical formulations of the constraints mentioned above have already been included in Chapter 3, i.e., Equation 3.4, Equation 3.5, Equation 3.6 and Equation 3.7. Table 5.2 gives an overview of the MOMP problem formulated in the context of this study.

The nomenclature of the main components of the problem – sets, subsets, variables and parameters – is presented in Table 5.3. The modelling and optimisation is performed in the GAMS platform (Rosenthal, 2016). More information regarding the source code is given in Appendix II.

Table 5.3 | Main components of the multi-objective optimisation model.

Nomenclature	
Sets	
j	Mitigation measures available for consideration, *j={Res1, Res2, Res3, Res4, Res5, Res6, Res7, Ser1, Ind1, Ind2, RTr1, RTr2, RTr3, Agr1, Res1a, Res2a, Res3a, Res4a, Res5a, Res6a, Res7a, RTr1a, RTr2a}*
t	Periods of time, a step of a year *t={2021,…,2030}*
i	Lifetime of mitigations measures, *i={1,…,30}*
Subsets	
$lbj(j)$	Mitigation measures with loose economic & behavioural barriers, *lbj(j)={Res1, Res2, Res3, Res4, Res5, Res6, Res7, Ser1, Ind1, Ind2, RTr3, Agr1,Res1a, Res2a, Res3a, Res4a, Res5a, Res6a, Res7a}*
$sbj(j)$	Mitigation measures with strict economic & behavioural barriers, *sbj(j)={RTr1,RTr2,RTr2a}*
$sbj25(j)$	Mitigation measures with strict economic & behavioural barriers introduced after 2025 *sbj25(j)={RTr1a}*
Variables	
$a_{j,t}$	Abatement achieved through the implementation of measure *j* for the time period t, [thousand tonnes of CO$_2$ equivalent]
Parameters	
r	Discount rate
fa_j	Full abatement of mitigation measure *j* [thousand tonnes of CO$_2$ equivalent]
$AC_{j,t}$	Abatement cost of mitigation measure *j* for the time period *t* [Euros per thousand tonnes of CO$_2$ equivalent]
$s_{j,t}$	Speed of implementation of mitigation measure *j* with loose economic and behavioural barriers for the time period *t*, subset $lbj(j)$ [thousand tonnes of CO$_2$ equivalent/y/y]
ssl_{sbj}	Starting level of speed of implementation of mitigation measure *j* with strict economic and behavioural barriers, subset $sbj(j)$ [thousand tonnes of CO$_2$ equivalent/y/y]
$sincr_{sbj,t}$	Speed increase of mitigation measure *j* with strict economic and behavioural barriers, subset $sbj(j)$, for the time period *t* [%]
ssl_{sbj25}	Starting level of speed of implementation of mitigation measure *j* with strict economic and behavioural barriers introduced after 2025, subset $sbj25(j)$ [thousand tonnes of CO$_2$ equivalent/y/y]
$sincr_{sbj25,t}$	Speed increase of mitigation measure *j* with strict economic and behavioural barriers introduced after 2025, subset $sbj25(j)$, for the time period *t* [%]

Note1: A full description of the mitigation measures and their corresponding notation will be given in the following tables; Table 5.4 and Table 5.5.

Note2: Source code is given in Appendix II.

5.3.2 Data and Parameters

Sotiriou et al. (2019) identified a variety of mitigation measures that can be implemented in all economic sectors of Cyprus and can yield GHG emission reductions. After consultation with policymakers and other stakeholders, fourteen mitigation actions were considered, addressing emissions in the residential sector, services, industry, road transport and agriculture, and were later expanded by Sotiriou and Zachariadis (2020). In the following text, those measures are being referred to as 'basic'. Table 5.4 presents these basic measures; a detailed description of the abatement options, along with the associated technological and economic data, is provided in the previously mentioned studies.

Table 5.4|Description of basic mitigation measures considered in the multi-objective optimisation programming approach.

Notation	Description	Sector
Res1	Full Renovation in Multi-Family building constructed 1991-2007	Residential
Res2	Roof Insulation in Multi-Family buildings constructed 1991-2007	Residential
Res3	Wall Insulation in Multi-Family buildings constructed 1991-2007	Residential
Res4	Wall Insulation in Single-Family buildings constructed 1991-2007	Residential
Res5	Pilotis Insulation in Multi-Family buildings constructed 1991-2007	Residential
Res6	Heat Pumps in Multi-Family buildings constructed 1991-2007	Residential
Res7	Heat Pumps in Single-Family buildings constructed 1991-2007	Residential
Ser1	Combined heat and power generation	Services
Ind1	Combined heat and power generation	Industry
Ind2	Burner Replacement in Industry	Industry
RTr1	Promotion of Public Transport	Road Transport
RTr2	Electric Private and Light Goods Conveyance Vehicles	Road Transport
RTr3	Low-Carbon Trucks	Road Transport
Agr1	Anaerobic Digestion for Animal Waste	Agriculture

In the residential sector, the focus has been on buildings constructed before 2008, which did not have to comply with any energy performance requirements, and after 1990, because energy renovations of older buildings are very likely to be technically difficult and much more costly. Out of the building stock of Cyprus of 431,059 residential buildings (Vougiouklakis et al., 2017), single-family buildings constructed between 1991 and 2007 represent 24% of the total stock, while multi-family buildings constructed in the same period account for 9% of the total stock (Zachariadis et al., 2018). The mitigation measures related to single-family buildings (Res4 and Res7) are assumed to be implemented on a number of houses that represent 14% of the total single-family 1991-2007 stock. The remaining measures (Res1, Res2, Res3, Res5 and Res6) are realised in 60% of the total multi-family 1991-2007 building stock. It is important to note that the energy efficiency measures for the existing residential stock of Cyprus are assumed to be implemented up to 2030. Any renovation after 2030 is considered to be too costly or even not realistic based on the age of the remaining non-renovated building stock (Vougiouklakis et al., 2017).

In the services sector, mainly hospitals and hotels, we considered the installation of 50 CHP units fuelled by LPG, which will replace gas oil fired boilers for hot water needs; 10 units will be installed up to 2030. The same measure, cogeneration, was considered in the industrial sector in addition to the replacement of old fuel oil-fired burners with modern, efficient ones burning LPG.

For the measures related to road transport, we considered the following assumptions:

- a shift of passenger-kilometres (pkm) from private cars (fuelled by gasoline/diesel) to buses (fuelled by diesel) will occur at a rate of 7% up to 2030 (RTr1);
- all newly registered private & light good conveyance vehicles will be electric up to 2040 (RTr2);
- new trucks sold up to 2040 will use CNG as fuel, and a moderate introduction of electric trucks will occur up to 2050 (RTr3).

Finally, for the agriculture and waste sector, it is assumed that an extra amount of waste, both animal (i.e. manure management) and municipal solid waste, will be directed to anaerobic digestion per year (Agr1).

As explained above, these fourteen interventions have been included in the previous modelling work. This chapter expands the list of emission abatement measures to twenty-three mitigation options; the nine new measures, so-called advanced measures, constitute an expansion of some of the basic and are presented in Table 5.5.

Table 5.5|Description of advanced mitigation measures considered in the multi-objective optimisation programming approach.

Notation	Description	Sector
Res1a	Full Renovation in Multi-Family buildings constructed 1971-1990	Residential
Res2a	Roof Insulation in Multi-Family buildings constructed 1971-1990	Residential
Res3a	Wall Insulation in Multi-Family buildings constructed 1971-1990	Residential
Res4a	Wall Insulation in Single-Family buildings constructed 1991-2007+	Residential
Res5a	Pilotis Insulation in Multi-Family buildings constructed 1971-1990	Residential
Res6a	Heat Pumps in Multi-Family buildings constructed 1971-1990	Residential
Res7a	Heat Pumps in Single-Family buildings constructed 1991-2007+	Residential
RTr1a	Promotion of Public Transport/BEV Buses	Road Transport
RTr2a	Electrical Private and Light Goods Conveyance Vehicles+	Road Transport

Table 5.6|Input of the multi-objective optimisation programming - Maximum potential of basic measures in residential buildings up to 2030 expressed in the number of buildings to be renovated and the share that those renovations hold in the total building stock.

Single-Family (SF) constructed between 1991-2007

Measure	Buildings Renovated	Share in Total Stock	Share in SF stock
Res4	7,500	1.7%	7.1%
Res7	7,500	1.7%	7.1%
Total	15,000	3.5%	14.3%

Multi-Family (MF) constructed between 1991-2007

Measure	Buildings Renovated	Share in Total Stock	Share in MF stock
Res1	1,500	0.4%	3.9%
Res2	14,000	3.3%	36.9%
Res3	1,800	0.4%	4.8%
Res5	900	0.2%	2.4%
Res6	4,500	1.0%	11.9%
Total	22,700	5.3%	59.8%

The measures for single-family buildings (Res4a and Res7a) are expanded in a way that, together with the respective basic measures, Res4 and Res7, will cover the total stock of single-family dwellings built between the years 1991 and 2007. Regarding the multi-family buildings, the basic measures suggest interventions on 60% of the total multi-family stock. Keeping in mind the difficulties of renovating this type of buildings due to their size and multiple ownership, we expand the measures to buildings of a different construction period. The advanced measures Res1a, Res2a, Res3a, Res5a and Res6a are related to multi-family buildings constructed between the years 1971 and 1990, which represent 10% of the total stock (Zachariadis et al., 2018). Table 5.6 and Table 5.7 summarise the extent of implementation for all measures of the residential sector.

Table 5.7|Input of the multi-objective optimisation programming - Maximum potential of advanced measures in residential buildings up to 2030 expressed in the number of buildings to be renovated and the share that those renovations hold in the total building stock.

Single-Family (SF) constructed between 1991-2007

Measure	Buildings Renovated	Share in Total Stock	Share in SF stock
Res4a	45,000	10.4%	42.8%
Res7a	45,000	10.4%	42.8%
Total	90,000	20.9%	85.6%

Multi-Family (MF) constructed between 1971-1990

Measure	Buildings Renovated	Share in Total Stock	Share in MF stock
Res1a	3,000	0.7%	6.8%
Res2a	28,000	6.5%	60.4%
Res3a	3,600	0.8%	8.2%
Res5a	1,800	0.4%	4.1%
Res6a	9,000	2.1%	20.5%
Total	45,400	10.5%	100%

For road transport, two measures were evaluated as expandable. One relates to the promotion of public transport, where we assume an additional 7% shift of passenger kilometres from private cars to battery-electric (BEV) buses from 2025 up to 2030 (RTr1a) and increase to 23% up to 2050. The second, advanced road transport measure (RTr2a), is a modified version of the basic measure RTr2, with a faster penetration of electric cars so that the full abatement that can be reached up to a year is greater. The two measures mentioned above, RTr2 and RTr2a, are in conflict; the difference between the two measures is the available abatement potential of RTr2a. Table 5.8 and Table 5.9 summarize all the above information. All the advanced measures, as discussed below, are associated with higher abatement costs.

Table 5.8|Input of the multi-objective optimisation programming - Maximum potential of basic measure for the road transport sector expressed in the number of kilometres shifted and the number of vehicles to be introduced.

Measure	million pkm shifted*	Share of total pkm
RTr1	434 434	7% up to 2030 7% up to 2050

Measure	Vehicles*	Share of newly registered
RTr2/Private	55,000 up to 2030 487,500 up to 2050	increasing to 100% by 2040
RTr2/Light Good Conveyance	- 46,500 up to 2050	increasing to 100% from 2030-2040

*Based on data from the Statistical Service of the Republic of Cyprus retrieved from https://www.mof.gov.cy/mof/cystat/statistics.nsf/index_en/index_en

Table 5.9|Input of the multi-objective optimisation programming - Maximum potential of the advanced measures for the road transport sector expressed in the number of kilometres shifted and the number of vehicles to be introduced.

Measure	million pkm shifted*	Share of total pkm
RTr1a	434 1,426	7% during 2025-2030 23% up to 2050

Measure	Vehicles*	Share of newly registered
RTr2a/Private	300,000 up to 2030 525,000 up to 2050	increasing to 100% by 2025
RTr2a/Light Good Conveyance	12,000 up to 2030 92,000 up to 2050	increasing to 100% by 2030

*Based on data from the Statistical Service of the Republic of Cyprus retrieved from https://www.mof.gov.cy/mof/cystat/statistics.nsf/index_en/index_en

As mentioned at the beginning of this section, after the formulation of the optimisation problem, the parameters of the model must be determined, i.e. those used in the constraints and the objective function. That requires the application of an appropriate methodology in order to calculate the values of the parameters or to retrieve them from the literature. Here the marginal abatement cost methodology found in Sotiriou et al. (2019) has been used in order to estimate most of the quantitative information of the measures. Outputs of that study like the abatement cost and the abatement potential per appropriate unit (houses renovated, passenger kilometres shifted etc.) were translated into parameters and fed into the multi-objective optimisation model that finds optimal solutions for the two conflicting criteria.

Table 5.10|Input of the multi-objective optimisation programming – Parameter: environmental performance of mitigation measure including a) maximum emissions abatement for 2030 and 2050, b) initial speed of implementation, and c) evolvement of the speed of implementation through the study period.

Measure	$A_{j,2030}$ [ktonnes of CO_2 equivalent]	$A_{j,2050}$	Initial $s_{j,t}$ [ktonnes of CO_2 equivalent/y/y]	Variation of $s_{j,t}$ during the study period
Res1	4.16	-	0.42	constant up to 2030
Res2	13.79	-	1.38	constant up to 2030
Res3	0.89	-	0.09	constant up to 2030
Res4	0.91	-	0.09	constant up to 2030
Res5	0.93	-	0.09	constant up to 2030
Res6	11.37	-	1.14	constant up to 2030
Res7	15.10	-	1.51	constant up to 2030
Ser1	5.00	32.58	0.47	slight incr. up to 2050
Ind1	5.29	33.94	0.49	slight incr.up to 2050
Ind2	0.74	0.74	0.07	constant up to 2050
RTr1	29.46	39.98	2.79	gradual incr. up to 2050
RTr2	120.16	407.82	2.08	gradual incr. up to 2040; const. up to 2050
RTr3	24.97	240.64	2.22	gradual incr. up to 2050
Agr1	10.5	43.83	1.00	gradual incr.up to 2050
Res1a	8.33	-	0.83	constant up to 2030
Res2a	27.57	-	2.76	constant up to 2030
Res3a	1.79	-	0.18	constant up to 2030
Res4a	5.43	-	0.54	constant up to 2030
Res5a	1.87	-	0.19	constant up to 2030

Measure	$A_{j,2030}$ [ktonnes of CO_2 equivalent]	$A_{j,2050}$	**Initial** $s_{j,t}$ [ktonnes of CO_2 equivalent/y/y]	**Variation of** $s_{j,t}$ **during the study period**
Res6a	22.74	-	2.27	constant up to 2030
Res7a	90.58	-	9.06	constant up to 2030
RTr1a	53.23	100.45	10.65	gradual incr. up to 2030;
RTr2a	603.58	951.69	13.55	gradual incr. up to 2030;

As already mentioned, some measures have more challenging economic and behavioural barriers than others, in which case there is a correlation between the value of implementation speed for the year t and the cumulative amount of abatement achieved up to the previous year (t-1). This is relevant for measures RTr1, RTr2, RTr1a and RTr2a, in which case the dependence of implementation speed and selected abatement constraint (Equation 3.6) is applied. This means that the speed of implementation, *s* is not necessarily fixed for each year t. Table 5.10 reports relevant assumptions.

The output of Sotiriou et al. (2019) also includes the cost performance of all the basic mitigation measures. According to their estimated abatement costs, they can be classified into three main groups as shown in Table 5.11: measures with net social benefits appearing with negative abatement costs, measures with modest abatement cost and measures with high costs (greater than 1,000 Euros per tonne of CO_2 equivalent). The same methodology was used to estimate the cost of abatement for the advanced measure RTr1a since it corresponds to an additional technological measure.

Table 5.11 | Input of the multi-objective optimisation programming – Parameter: Economic performance including a) evolution of abatement costs over time and b) abatement cost including external costs of GHG and air pollutants.

Measure	$AC_{j,2021}$ [€'2015/ tonnes of CO_2 equivalent]	$AC_{j,2021}^{Ext}$ [€'2015/ tonnes of CO_2 equivalent]		**Variation of** $AC_{j,t}$ **during the study period**
Basic mitigation measures				
Res1	>1,000	More cost-effective	>1,000	constant up to 2030
Res2	<0	More cost-effective		constant up to 2030
Res3	>1,000	More cost-effective	>1,000	constant up to 2030
Res4	>1,000	More cost-effective	>1,000	constant up to 2030

Measure	$AC_{j,2021}$ [€'2015/ tonnes of CO_2 equivalent]	$AC_{j,2021}^{Ext}$ [€'2015/ tonnes of CO_2 equivalent]		**Variation of $AC_{j,t}$ during the study period**
Res5	59.36	More cost-effective	<0	constant up to 2030
Res6	<0	Less cost-effective	<0	constant up to 2030
Res7	<0	Less cost-effective	<0	constant up to 2030
Ser1	<0	More cost-effective		10% reduction every 5 years
Ind1	<0	More cost-effective		10% reduction every 5 years
Ind2	<0	More cost-effective		10% reduction every 5 years
RTr1	68.99	More cost-effective	<0	10% reduction every 5 years
RTr2	59.09	More cost-effective	<0	15% reduction every 5 years
RTr3	95.17	More cost-effective	<0	10% reduction every 5 years
Agr1	3.85	More cost-effective	<0	10% reduction every 5 years
Advanced mitigation measures				
Res1a	>1,000	More cost-effective	>1,000	constant up to 2030
Res2a	<0	More cost-effective	<0	constant up to 2030
Res3a	>1,000	More cost-effective	>1,000	constant up to 2030
Res4a	>1,000	More cost-effective	>1,000	constant up to 2030
Res5a	71.23	More cost-effective	<0	constant up to 2030
Res6a	<0	Less cost-effective	<0	constant up to 2030
Res7a	<0	Less cost-effective	<0	constant up to 2030
RTr1a	40.85	Less cost-effective		10% reduction every 5 years
RTr2a	70.91	More cost-effective	<0	15% reduction every 5 years

The abatement costs included in Table 5.11 refer to data that are representative of the current market, i.e. around the year 2020. They are assumed to decline during the 2020-2050 period due to technological progress, learning processes and deployment of enabling infrastructure, as described in Sotiriou and Zachariadis (2020) and presented in the last column of Table 5.11. These assumptions are based on data that were made available by the European Commission to EU governments in 2018 as guidance to their energy and climate modelling; information was made available to the authors by the government of Cyprus.

With regard to the advanced abatement measures that have been defined for the purpose of this analysis (Table 5.5), they represent an expansion of the corresponding basic measures found in Table 5.4. The number of interventions allocated for the basic measures reflects the realistic potential in the household sector of Cyprus, as determined by Vougiouklakis et al. (2017). Any enhancement of this type of measures will require the removal of financial, technical and behavioural barriers, resulting in higher abatement costs. We, therefore, assume an increase of their cost in the following way: for the advanced single-family 1991-2007 measures, the cost will be doubled up to 2030, for the advanced multi-family 1971-1991 measures, an increase in the cost by half will occur up to 2030 and finally for measure RTr2a the cost will undergo the same rate of increase like the multi-family measures.

The analysis also includes an alternative optimisation by counting the external costs of the emissions of GHG, NO_x, SO_2 and PM in the abatement cost. Emissions of CO_2, NO_x, SO_2 and PM are associated with fossil fuel burning, and strong interactions between different goals, climate change mitigation and air pollution control are often recognised (Cai et al., 2018; Markandya et al., 2018). They are usually termed as co-benefits because, in most cases, a GHG abatement measure has positive effects on air pollution as well. To perform this type of assessment, one has to calculate the emissions of the above gases, which are generated from a measure as well as those avoided thanks to this measure. This is usually done by multiplying the corresponding change in emissions by their marginal damage cost. More details on the methodology can be found in Zachariadis and Hadjikyriakou (2016), which was based on established international methodologies to assess external costs. The marginal damage cost is expressed in Euros per tonne of each gas emitted in the atmosphere, whose values are included in Sotiriou and Zachariadis (2019). It is evident that most of the mitigation measures become more cost-effective under this assessment. A number of measures, especially those related to road transport, move to the group of measures with net social benefits.

5.4 Application and Results

The goal of this study is to estimate the optimal mix of technological measures by simultaneously minimising the total cost and maximising non-ETS emissions abatement. These two objectives are mutually competitive. Two types of solutions have been obtained from the multi-objective optimisation model. Both of them concern the same period, from 2021 up to 2030, but they differ on their cost-related objective functions in the following ways:

Case 1: the basic approach includes the abatement costs associated with each measure, $AC_{j,t}$

Case 2: the alternative approach uses the abatement costs, including external costs of GHG, NOx, SO_2 and PM emissions, $AC^{Ext}_{j,t}$

Then a preliminary assessment of the effect of previously calculated efficient solutions on the attainability of the 2050 emissions reduction target is performed. Sensitivity analyses are also presented for the central scenarios of Case 1 and Case 2, where direct rebound effects and the risk of delayed implementation is included in the optimisation procedure – new PFs are produced.

It is important to note that all the cases are compared with the evolution of non-ETS GHG emissions in Cyprus according to the scenario WEM that was prepared by the government of Cyprus in its National Energy and Climate Plan (Republic of Cyprus, 2020). WEM is the baseline scenario against which all policies are compared. The mandatory emission target for Cyprus for the year 2030, according to the EU Effort Sharing Regulation 2018/842, is 3,242 thousand tonnes of CO_2 equivalent and comprises a 24% reduction in non-ETS emissions compared to those of the year 2005. Considering the projected evolution of emissions up to 2030, according to WEM, the legal commitment of Cyprus amounts to 586.8 thousand tonnes of CO_2 equivalent that must be reduced by 2030 compared to WEM. If new EU climate targets may demand raising the ambition of Cyprus to 35% abatement compared to 2005, emissions in 2030 will have to decline by 1,056 thousand tonnes of CO_2 equivalent. As of this writing (March 2021), the new EU climate target for 2030 has not been formulated in specific emission reduction requirements for non-ETS sectors of individual countries. A 35% target is chosen here as a possible objective for Cyprus because stronger emission reductions seem to be unattainable, as will be shown later in this section.

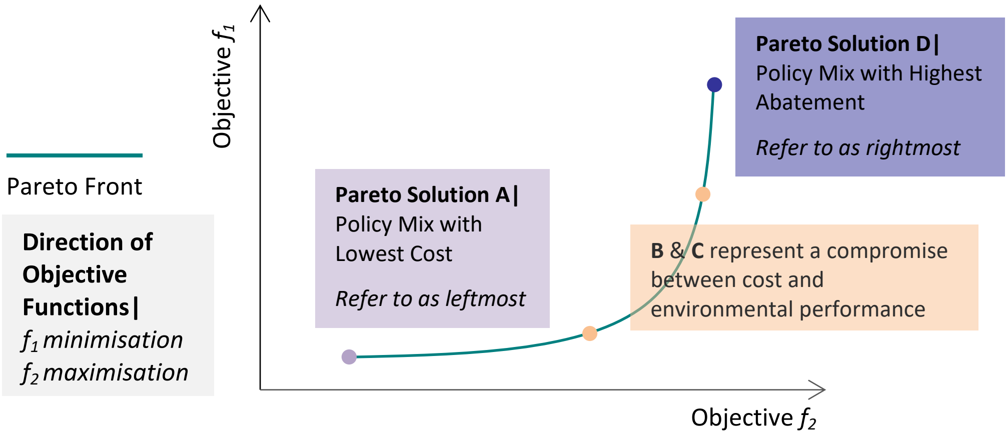


Figure 5.3 | Common shape of a Pareto Front for bi-objective optimisation.

5.4.1 Balancing Economic and Environmental Criteria

Figure 5.4 depicts the basic PF obtained by applying the AUGMECON2 method (Mavrotas and Florios, 2013). The different levels of the 2030 non-ETS emissions reduction target, current and increased, are also presented with the vertical dash and solid blue lines, respectively. For demonstration purposes, the graph also includes an earlier optimal solution of the single-objective version of the problem as presented in Sotiriou and Zachariadis (2019), where the abatement was introduced to the model as a constraint, not as an objective, included only the basic abatement measures described in Table 5.4, and therefore could not lead to the attainment of the 24% target.

The multi-objective optimisation programming solution space includes a variety of policy mixes. In twenty-four PSs out of the thirty in total, the solution results in net social benefits, i.e. negative costs on the graph. Solutions to the right of the dash blue vertical line indicate that the measures proposed in this study, if implemented together with measures included in the WEM scenario of the government of Cyprus, can meet the 24% non-ETS emission reduction commitments of Cyprus up to 2030 at a negative cost – upfront investment costs are outweighed by cost savings (mainly reduced fuel costs) throughout the lifetime of the interventions. However, if the EU goal becomes considerably more ambitious, the corresponding optimal sets appear with gradually – but smoothly – increasing costs. The right extreme solution, corresponding to over-achieving the 35% objective, is associated with a very strong rise in total cost because strong abatement requires that the policy mix includes measures with very high costs, of the order of more than 1,000 Euros per tonne of CO_2 equivalent.

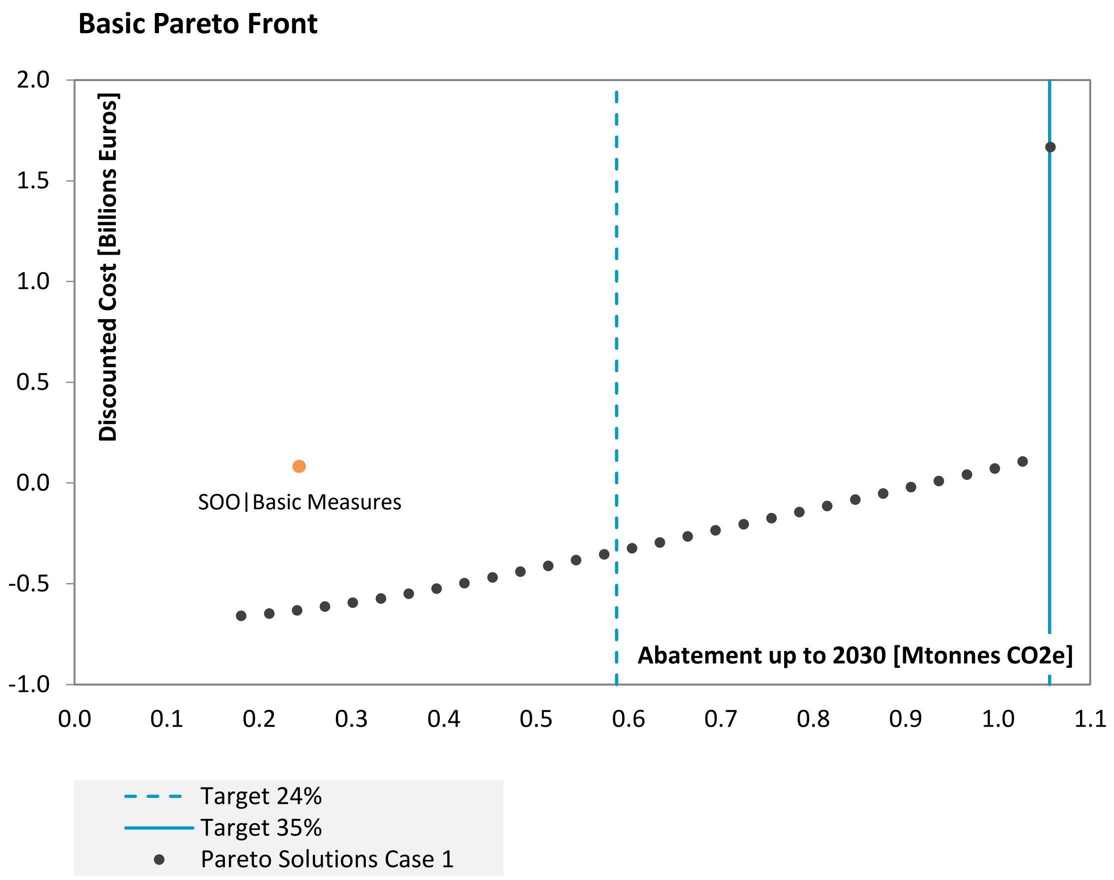


Figure 5.4|Basic Pareto front for Case 1.

Figure 5.5 focuses on the two benchmarks – the current 24% emission reduction commitment and a potential new target of 35% reduction, which may come out of the negotiation process in the frame of the European Green Deal. It compares the temporal evolution of non-ETS emissions for the selected PSs of Figure 5.4 with that of the baseline, which is the WEM scenario of the government of Cyprus. The two solutions can make a significant difference when considering the need to achieve almost zero emissions by 2050. The 24% target shows a very slow reduction path which would need to accelerate very fast in order to approach climate neutrality in the mid-21st century; the 35% target leads to a rate of emissions decline that is still not sufficient to reach net-zero by 2050 but is still closer to the desired decarbonisation pathway. This aspect will be mentioned later in Section 5.4.4.

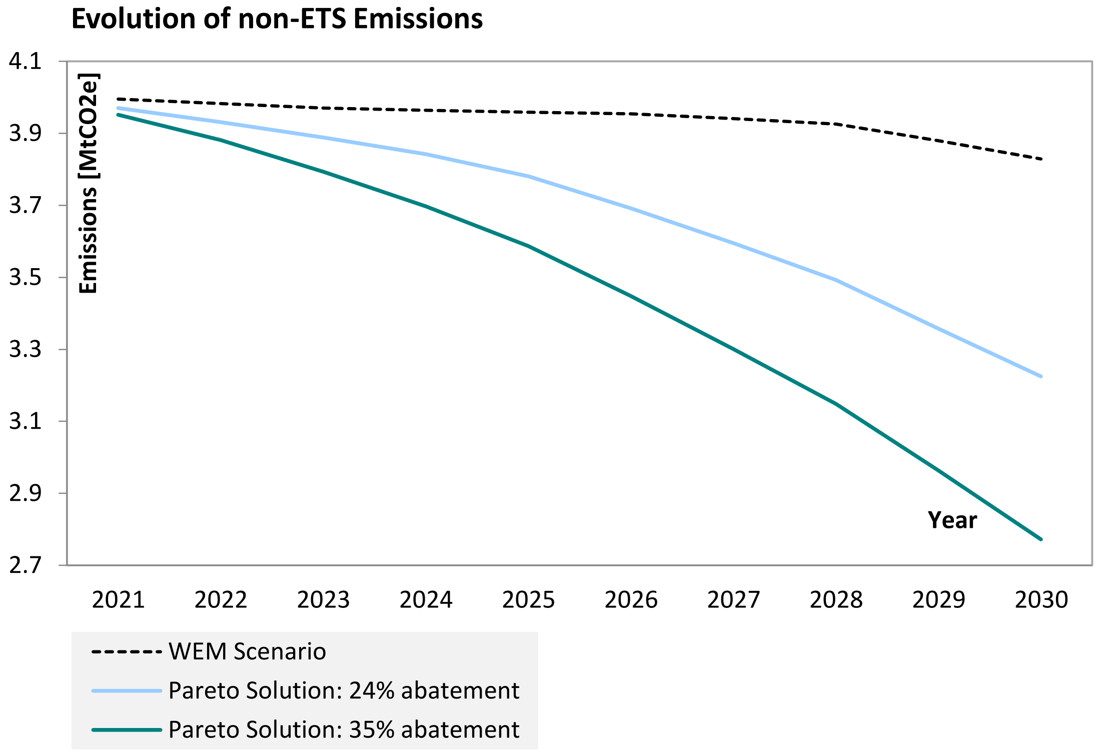


Figure 5.5|Evolution of non-ETS emissions up to 2030 for the WEM scenario and the Pareto Solutions of Case 1, which satisfy the 24% and 35% emissions reduction target.

Figure 5.6 portrays the policy mix associated with the two PSs mentioned above, i.e. achieving the already legislated 24% reduction target and moving to a more ambitious 35% target, respectively. The figure presents the percentage contribution of each measure to total available abatement up to 2030. It is evident that road transport interventions have the highest potential for emissions abatement, without a significant modal shift (measures RTr1 and RTr1a) and electrification of passenger cars and light trucks (measures RTr2 and RTr2a), no significant emission reduction in non-

ETS sectors can be achieved. With regard to the building sector, installation of modern, highly efficient heat pumps is the major abatement measure; note that due to climatic conditions, buildings in Cyprus have relatively low heating and high cooling needs, so that most of these requirements are met by electric heat pumps during both summer and winter periods. This explains why the emission abatement potential is limited as regards non-ETS emissions, i.e. direct emissions from fuel combustion.

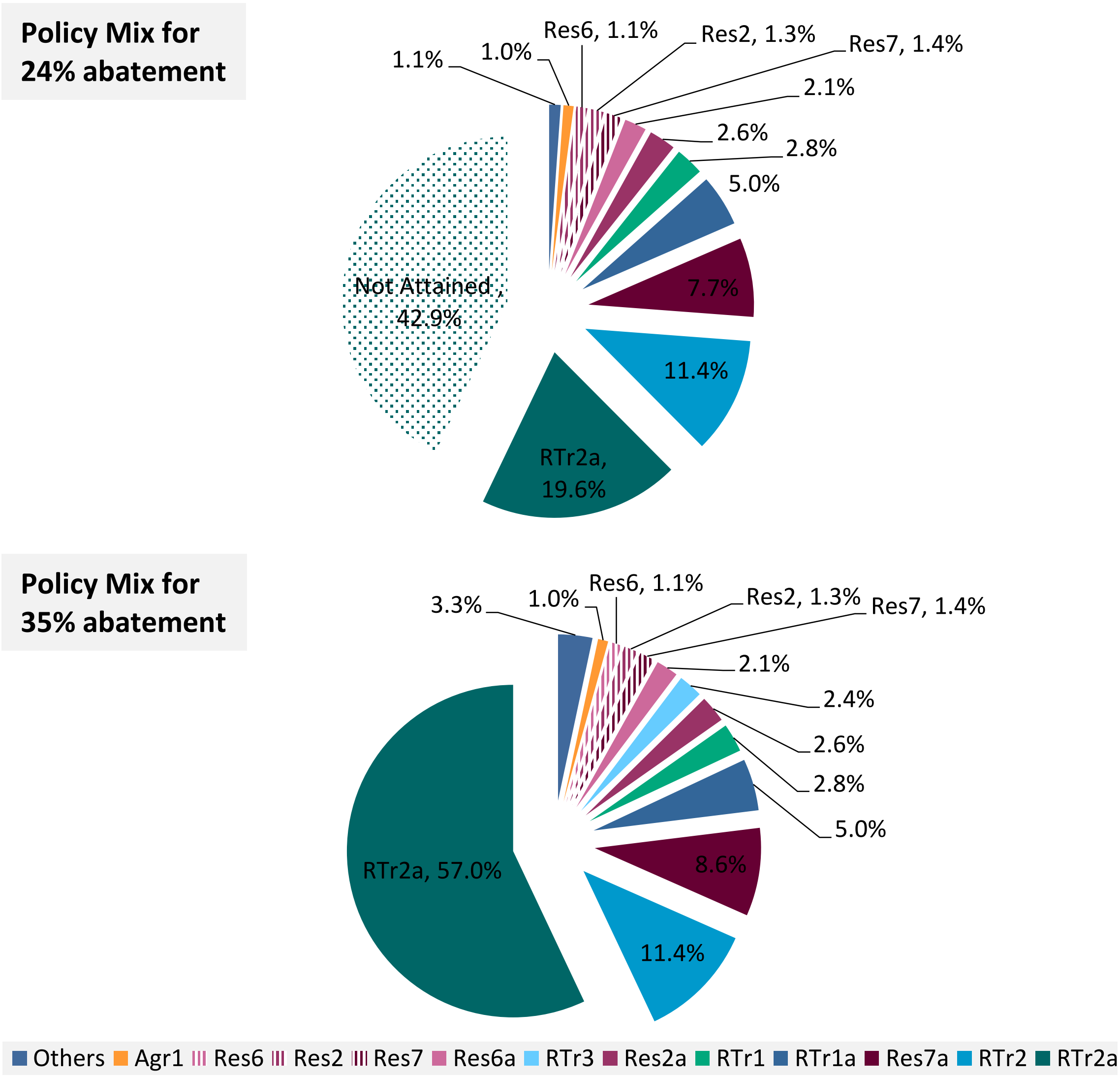


Figure 5.6 | Policy mixes for selected Pareto Solutions of Case 1, which satisfy the 24% and 35% emissions reduction target. See Table 5.4 and Table 5.5 for a description of each measure shown in the legends.

Table 5.12|Output of multi-objective optimisation programming – extent of implementation for each measure's category of the Pareto solutions that satisfy the 24% and 35% emissions reduction target.

			24% Target		35% Target	
Measure's Category	**Individual Measures**	**Extent of Implementation**	**Basic**	**Advanced**	**Basic**	**Advanced**
Full Renovation	Res1, Res1a	no. of houses	0	0	1,500	3,000
Roof Insulation	Res2, Res2a	no. of houses	14,000	28,000	14,000	28,000
Wall Insulation MF	Res3, Res3a	no. of houses	0	0	1,800	3,600
Wall Insulation SF	Res4, Res4a	no. of houses	0	0	7,500	44,725
Pilotis Insulation	Res5, Res5a	no. of houses	782	0	900	1,800
Heat Pumps MF	Res6, Res6a	no. of houses	4,500	9,000	4,500	9,000
Heat Pumps SF	Res7, Res7a	no. of houses	7,500	40,511	7,500	45,000
Cogeneration in Services	Ser1	no. of CHP units	10	-	10	-
Cogeneration in Industry	Ind1	no. of CHP units	10	-	10	-
Industrial Burner Replacement	Ind2		10	-	10	-
Public Transport	RTr1	Mpkm shifted	434	-	434	-
Electric Private & Light Goods Vehicles	RTr2, RTr2a	no. of vehicles	55,000	87,000	55,000	257,000
Low-Carbon Trucks	RTr3	no. of trucks	0	-	1,500	-
Anaerobic Digestion	Agr1	m^3 of animal and municipal waste	900,000	-	900,000	-
Public Transport/BEV Buses	RTr1a	Mpkm shifted	-	434	-	434

Another aspect that is obvious from Figure 5.4 is that only full exploitation of all available measures can achieve the 35% non-ETS emission reduction target. If the new Effort Sharing target for Cyprus exceeds 35%, this seems to be infeasible, and any gap in meeting the target will have to be filled through the use of ‘flexibility mechanisms’ that may be foreseen in the EU legislation – i.e. purchasing emission permits from other countries. Table 5.12 summarises the extent of implementation for each category of mitigation actions for the two benchmark PSs. This provides useful information to policymakers about how much the implementation of each measure has to be expanded if the binding abatement commitment moves from 24% to 35%.

Looking at the results shown in Table 5.12, it is important to point out that:

- Some measures related to the residential sector (full renovation and wall insulation) are not included in the policy mix of the 24% PS due to high costs. However, for the 35% target to be achieved, all these measures must be exploited. For the rest of the measures in residential buildings, the implementation must be extended to reach the 35% target; as outlined in Section 5.3.2, all single-family buildings built after 1990 and most multi-family buildings constructed after 1970 will need to undergo renovations, at a rate that has not been observed up to now.
- Road transport measures are absolutely necessary to achieve a considerable reduction in non-ETS emissions, and they appear in both solutions, with the exception of a measure on low-carbon trucks, which is chosen only in the higher abatement scenario.
- The ambitious solution of 35% requires tripling the number of passenger cars and light trucks that will be electric by 2030 compared to the less ambitious solution of 24%. For this purpose, all newly registered passenger cars from 2025 onwards would have to be electric. This is illustrated in Figure 5.7, which presents the annual penetration of electric vehicles throughout the period 2021-2030. In addition to the need to start this penetration earlier to meet the 35% goal, the graph also suggests possible lock-in effects: electrification of transport is associated with important implementation barriers so that if it is introduced at a later stage, it can result in lower maximum abatement, which apart from hindering achievement for the 2030 target can significantly delay

the needed pathway to meeting the 2050 objective. Moreover, the shift to public transport has to be implemented at an unprecedented rate.

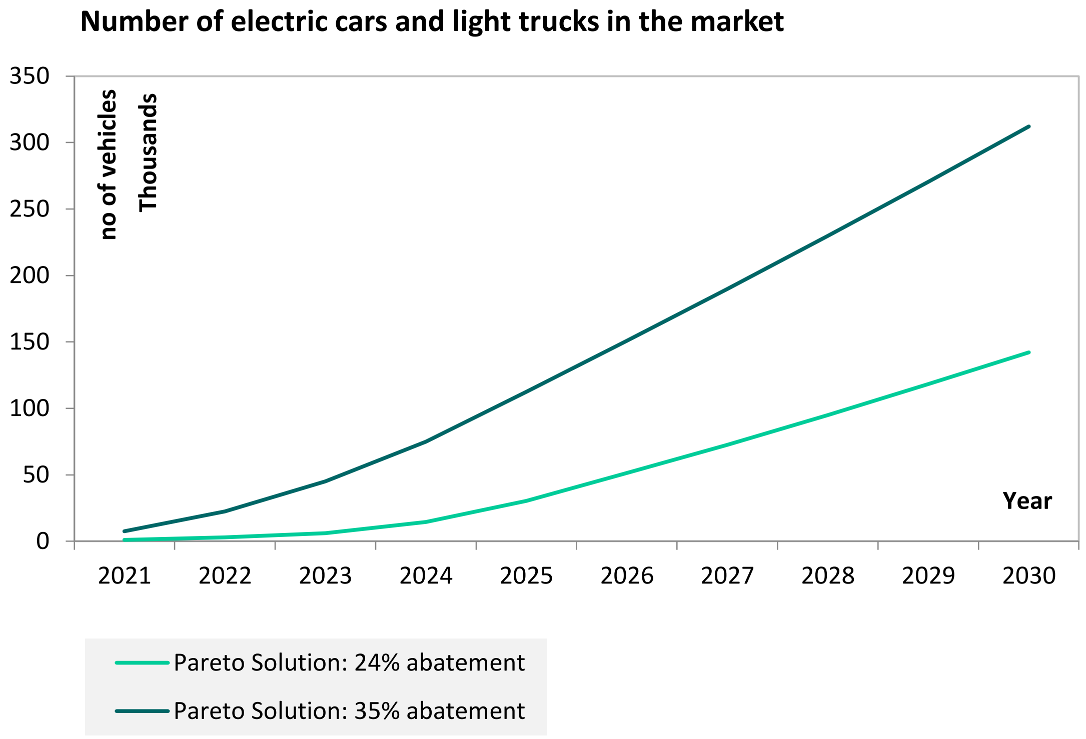


Figure 5.7 | Penetration of electric private cars and light goods vehicles in the market for the period 2021-2030 for selected Pareto Solutions of Case 1, which satisfy the 24% and 35% emissions reduction target.

5.4.2 Co-benefits for Air Pollution Control

As explained at the beginning of this section, the analysis also explored Case 2, in which the abatement costs linked to the cost-related objective function have also considered external damage costs from the emission of air pollutants and GHG. This means that the co-benefits of air pollution reduction thanks to greenhouse gas emission abatement measures is a driving factor of the produced PF.

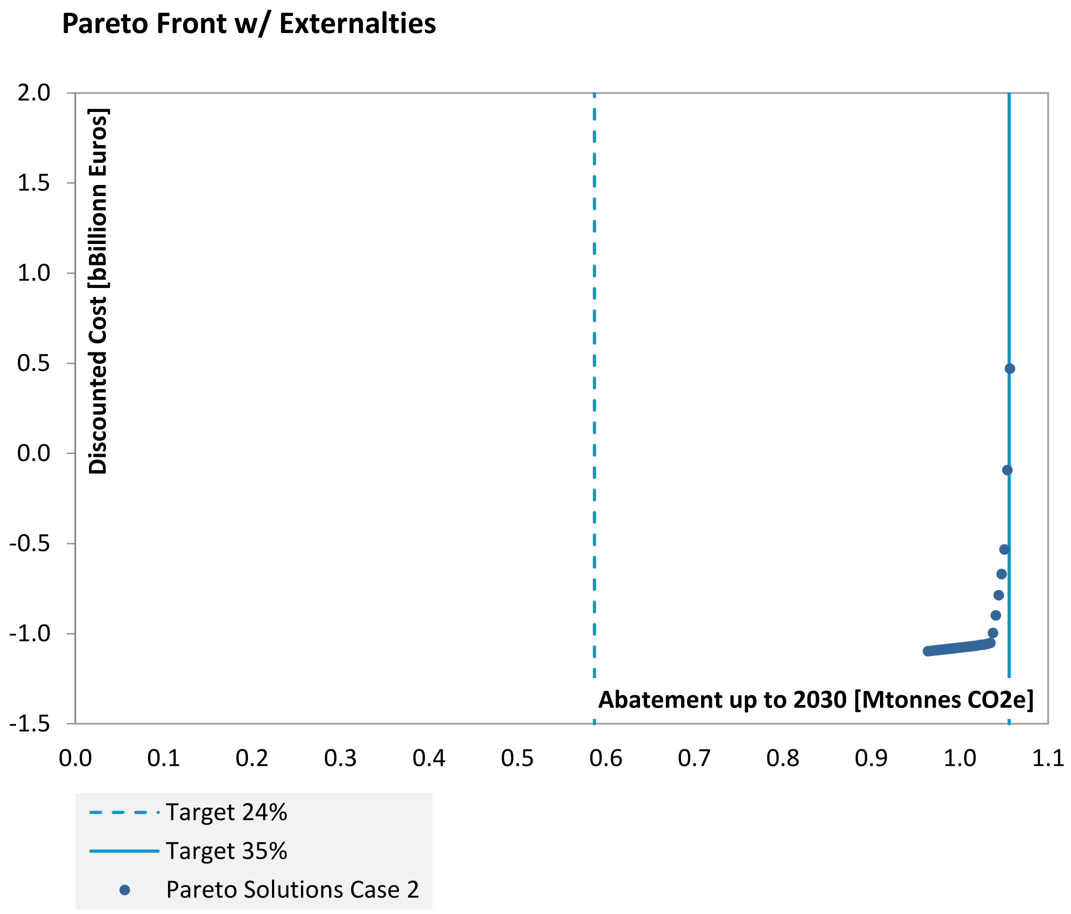


Figure 5.8 | Pareto front for Case 2, which includes co-benefits of air pollution.

Figure 5.8 shows the Pareto set of optimal solutions obtained in this case. Compared to the solutions shown in Figure 5.4, the new PF moves downwards and to the right. This indicates both a substantial reduction of total abatement costs when the avoided external costs of air pollutants are included and an increase in possible emissions abatement at a given cost. The current 24% emission reduction target for the year 2030, demonstrated with the dash blue vertical line, is easily attainable, while the target of a 35% decrease can be achieved with lower total discounted costs compared to the basic scenario. Both first and last solutions are attainable at lower total costs compared to Figure 5.4. Moreover, the leftmost optimal solution of Figure 5.8 indicates that the minimum total cost, including externalities, can result in higher mitigation than the corresponding optimal solution of the basic approach. Figure 5.9 justifies this finding by presenting the main differences in the policy mix of the leftmost

PSs of Case 1 and Case 2; measures related to road transport are prioritised in Case 2 because when the avoided external costs of these measures are accounted for, their total abatement costs decline considerably (Table 5.11). These measures are associated with a higher abatement potential and are taken up faster, thus yielding higher mitigation at a lower cost.

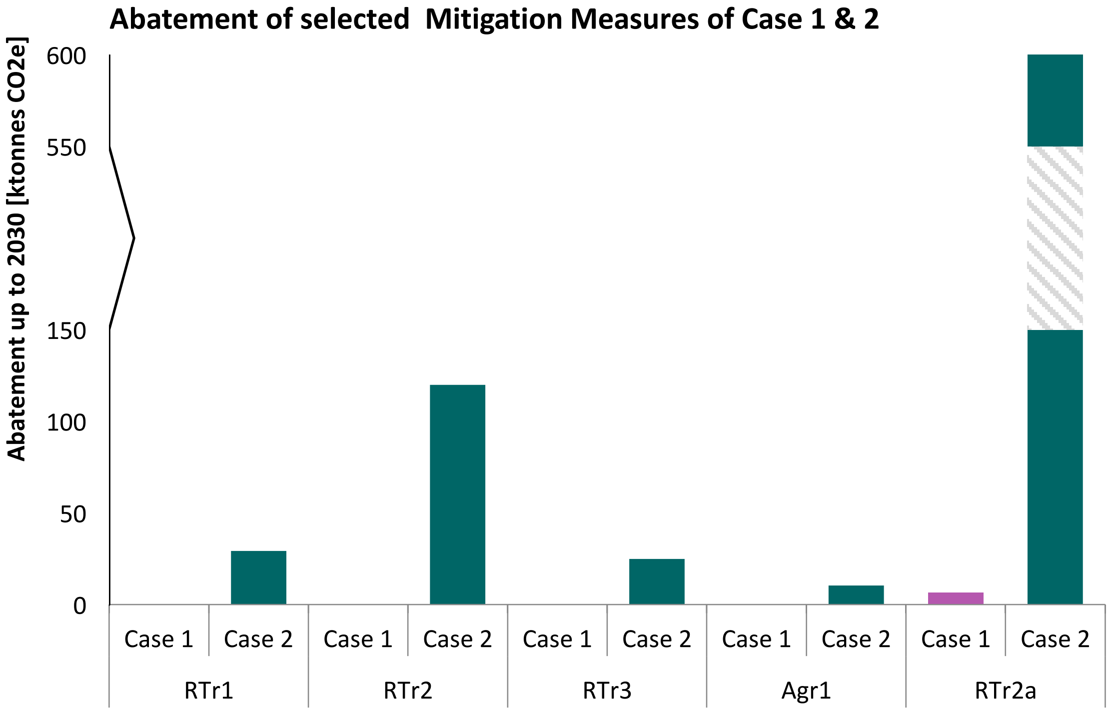


Figure 5.9|Main differences in the policy mix of the leftmost Pareto Solutions of Case 1 and Case 2.

If one matches the PS of Figure 5.4 with approximately the same total abatement as the leftmost optimal solution of Figure 5.8 (i.e., corresponds to a 33% emission reduction target), it is evident that the cost of the first set becomes positive, while the cost of the latter set is negative. This shows that the implementation of the measures included in the policy mix can yield considerable social benefits, which are particularly evident if the co-benefits on air pollution are accounted for. Most of these co-benefits result from improved air quality due to the reduction in the use of private cars (modal shift – measures Rtr1 and RTr1a) and the deployment of electric vehicles (measures RTr2 and RTr2a).

5.4.3 Total Costs, Investments and Public Expenditures

Cost calculations are conducted from a public policy viewpoint throughout this study, i.e. from the perspective of a social planner attempting to maximise social welfare. In this case, total discounted costs express the cost to society from the implementation of decarbonisation measures. This, however, is not the only cost item of interest to policymakers; abatement measures are less likely to be deployed if they are capital-intensive, especially in capital-constrained economies; and in countries with limited fiscal space, there is an increased risk of limited implementation if measures require a substantial amount of public funds.

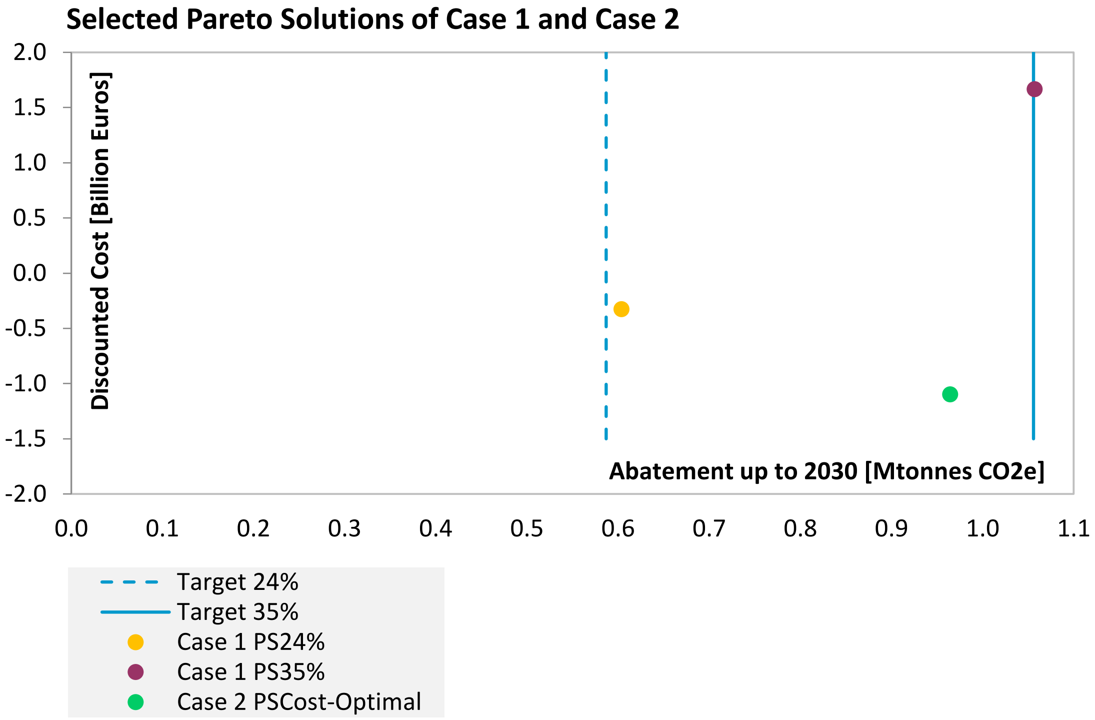


Figure 5.10| Policy mixes that the investment requirements and public financing needs are addressed.

Therefore, to make a useful contribution to public policy, an analysis has to address all these three aspects: total costs, investment requirements, and public financing needs. Table 5.13 addresses these aspects for three policy mixes the one that leads to 24% GHG emission abatement by 2030; the corresponding one yielding 35% abatement, and the policy mix that leads to least-cost emissions reduction, therefore the cost-optimal solution, if external costs are also accounted for (i.e. the policy mix that corresponds to the leftmost point of Figure 5.8). The PSs with the most interest, as mentioned above, are illustrated in Figure 5.10.

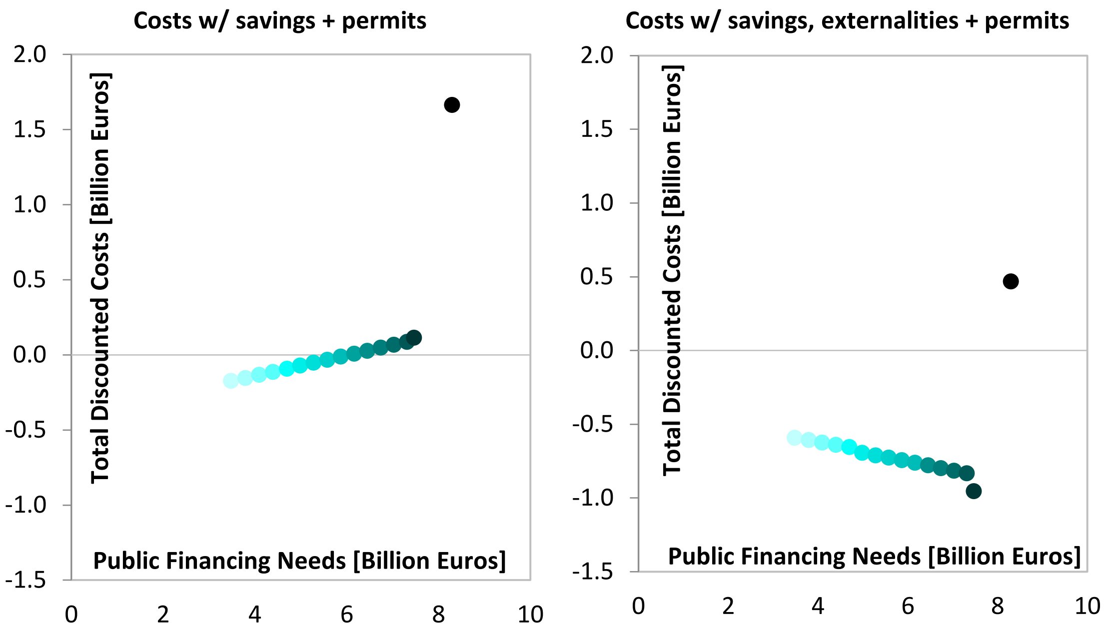
Obviously, the solution leading to higher emissions abatement is associated with higher capital costs for the adoption of stronger decarbonisation policies and measures. The same applies to total discounted costs that include the energy savings over the lifetime of each measure, although the cost difference between the two solutions is smaller in this case.

Table 5.13|Output of multi-objective optimisation programming – cost assessment for the selected Pareto solutions of Case 1 matching 24% and 35% emissions reduction target and the leftmost solution of Case 2 representing the least-cost policy mix.

	Case 1 (optimisation w/o externalities)		Case 2 (optimisation w/ externalities)
Solution **Costs [Billion €]**	**24%**	**35%**	**Least Cost**
Costs including savings over lifetime	-0.33	1.66	0.07
Costs including savings over lifetime and externalities	-0.75	0.47	-1.10
Permits to cover 2030 emission gap	0.15	-	0.02
Total Discounted Costs			
(Costs w/ savings + Permits)	-0.17	1.66	0.09
(Costs w/ savings and externalities + Permits)	-0.59	0.47	-1.08
Investment Needs	5.06	13.66	11.22
Public Expenditures	3.48	8.93	7.34

Assuming that the 35% emission reduction can achieve the new non-ETS climate objective for Cyprus for 2030, the 24% solution (second column of Table 5.13) leaves an emissions gap that has to be covered by purchasing allowances from other countries, in line with the possibility to use ‘flexibility mechanisms’ foreseen in EU legislation. The cost of using such a mechanism can be assessed by considering the official projection about the expected annual allocation of allowances for the years 2021-2030 for Cyprus (Republic of Cyprus, 2020) and a projection of the price of each allowance. As the allowance price for non-ETS sectors is highly unknown because this scheme has not been implemented so far, and in view of the inclusion of transport in non-ETS which is a sector very hard to decarbonise EU-wide, we assume a price level for such allowances that is higher than the corresponding ones of the EU Emissions Trading System. It is assumed that the price starts at 30 Euros per tonne of CO_2 equivalent in 2020 and reaches 60 Euros per tonne of CO_2 equivalent in 2030, at constant prices of the year 2020. In the case of 24% abatement, this will result in a cumulative discounted cost for purchasing permits of up to 150 Million Euros’2020. In the case of 35% abatement (third column), this cost becomes zero, while the least-cost solution of the optimisation problem accounting for externalities (last column of Table 5.13) yields an abatement of about 32% so that a small amount of allowances would have to be purchased at the cost of about 20 million Euros’2020 only.

Observing the total discounted costs, including energy savings caused by the measures over their lifetime and the permits to cover the 2030 emissions gap, it turns out that the less ambitious policy mix reaching 24% abatement is the less costly one. The more ambitious 35% policy mix is the costliest. If side-benefits of climate protection (in terms of avoided emission costs of GHGs and air pollutants) are accounted for, the least-cost policy mix of Case 2 (last column of Table 5.13) becomes the preferable option, yielding social benefits of more than one billion Euros’2020. Considering the feasibility of achieving the 2050 climate neutrality target, the 24% option is the least favourable for public policy. This underlines the importance of accounting for the external costs of climate change and air pollution when designing the optimal policy mix – it can maximise social benefits and keep the country on track to climate neutrality in 2050.



Case 1 PSs between 24% and 35% abatement

Case 1 PSs between 24% and 35% abatement

Figure 5.11|Economic indicators of Case 1 Pareto solutions between 24% and 35% abatement (i.e., Pareto solution no.15 up to no.30). The left graph indicates the costs when including savings over lifetime and permits to cover the 2030 emissions gap. The right graph includes additional the externalities of the avoided air pollution. The dots' shade presents each policy mix's abatement potential, i.e., the darker, the greater the abatement.

As regards investment needs, these are obviously lowest in the less ambitious scenario that reaches 24% emission reduction only. Our preferred solution requires cumulative investments of over 11 billion Euros, or 5% of the annual national GDP of Cyprus every year of the decade 2021-2030. Assuming that, out of these investments, decarbonisation policies for buildings, industry, and agriculture will be implemented through 50% participation of public funds, whereas clean transport policies (public transport investments and clean vehicle subsidies) will have to be covered by public funds alone, this implies public expenditures of over 7 billion Euros’2020 in the decade 2020-2030, or about 3% of the annual GDP of Cyprus each year. This indicates that the socially optimal policy mix for attaining decarbonisation of the Cypriot economy is feasible and will yield net benefits to society; however, it requires a consistent allocation of public funds to build infrastructure, overcome investment barriers and mobilise capital to enable the uptake of clean technologies across the economy. This underlines the need for a well-targeted orientation of public and private investments towards low-carbon interventions across the entire economy.

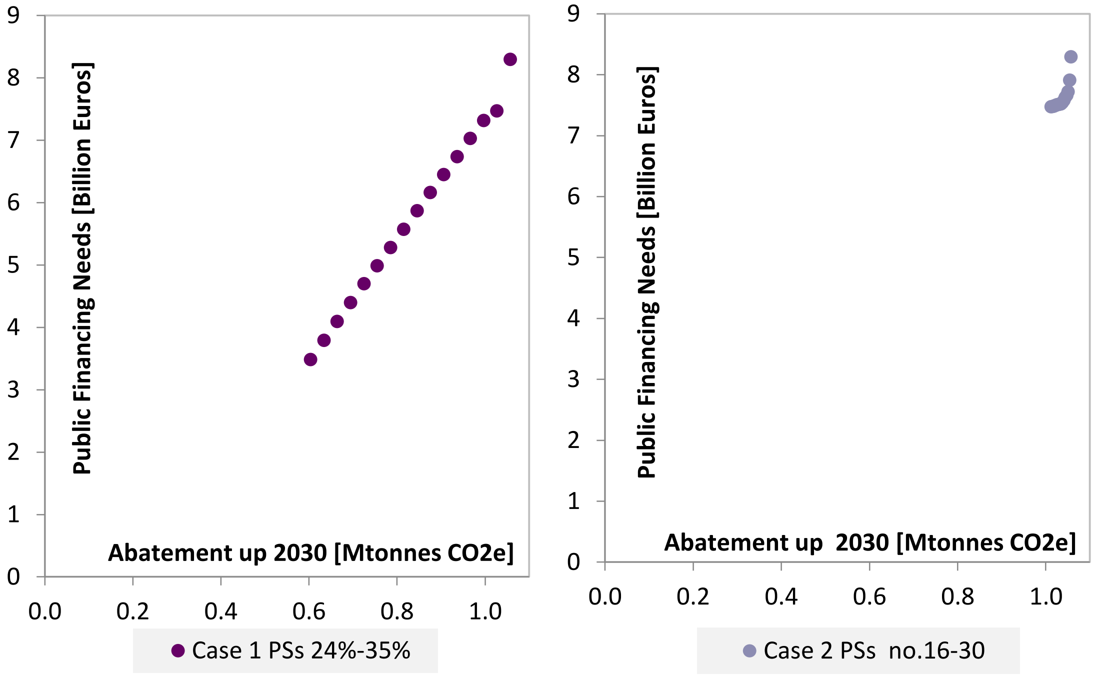


Figure 5.12|Change of the public financing needs when moving to a more ambitious mitigation scenario for selected Pareto solutions of Case 1 and Case 2, on the left and right graph, respectively. For Case 1, the Pareto solutions between 24% and 35% target are illustrated, and for Case 2, the Pareto solutions no.16 up to no.30.

5.4.4 Attainability of the Long-Term Decarbonisation Target

In light of the mid-century climate neutrality objective, it is important to explore the long-term potential of the chosen PSs. For this purpose, post-2030 simulations were carried out with a single-objective version of the model, as the long-term emissions target is fixed. To do so, the environmental objective of the MOMP model becomes an emission constraint that is set for the year 2050.

Figure 5.13 illustrates the evolution of non-ETS emissions from 2021 up to 2030 for the WEM scenario and the two benchmarks – the current 24% emission reduction commitment and a potential new target of 35% reduction which may come out of the negotiation process in the frame of the European Green Deal as presented in Section 3.1. It also demonstrates the projection of emissions for the WEM scenario and the scenario related to the PS of 35% target using a single-objective version of the model.

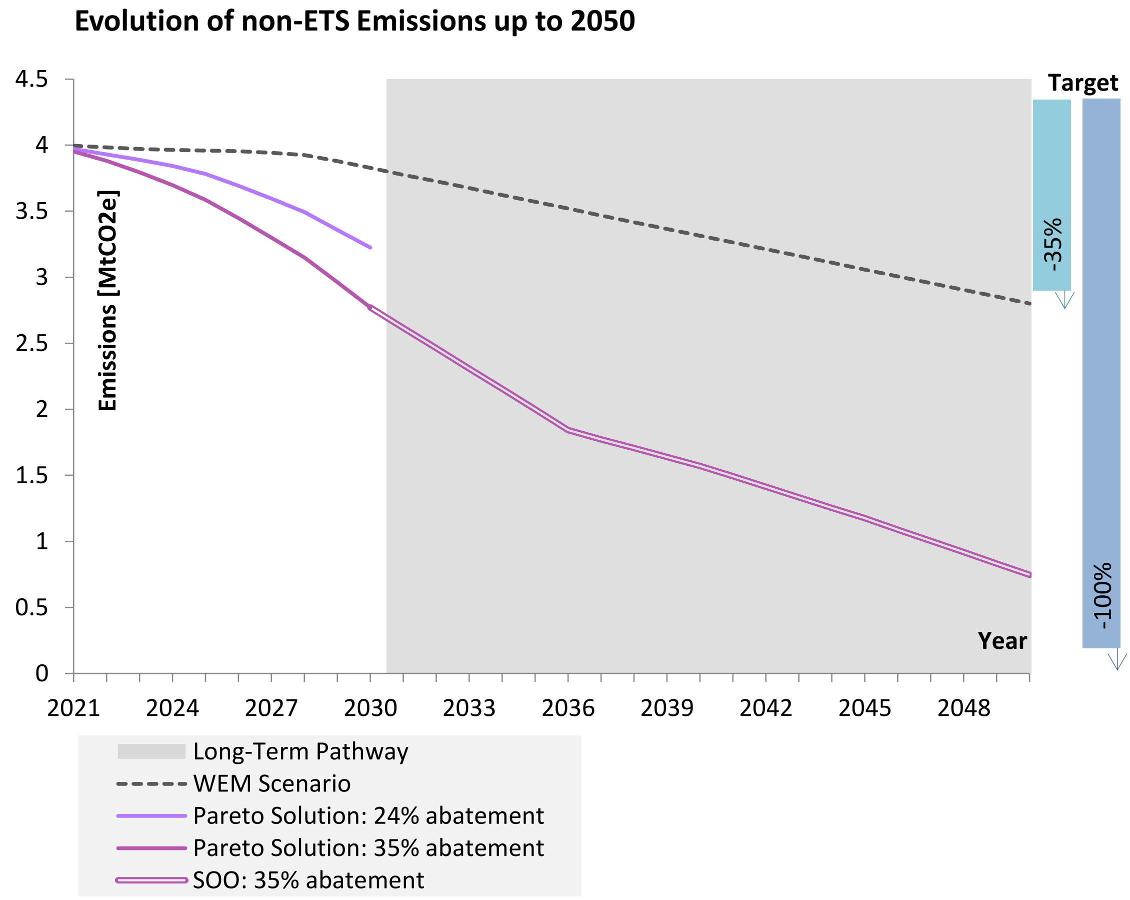


Figure 5.13 | Evolution of non-ETS emissions from 2021-2030 for specific Pareto solutions of the multi-objective optimisation approach of Case 1 and country's baseline scenario (WEM); and the projected emissions from 2030-2050 for the policy mix that leads to 35% emission reduction in 2030 following single-objective optimisation.

Although, as explained in Section 5.4.1, the higher ambition of the EU 2030 climate target can ensure a pathway that is closer to the 2050 target, the long-term climate neutrality goal appears unattainable with the set of policies and measures considered in the model; a 35% emission reduction in 2030 leads to a gap of 320 thousand tonnes of CO_2 equivalent and 747 thousand tonnes of CO_2 equivalent in 2050 if we consider a

90% and 100% emission reduction target, respectively. The available mix of mitigation measures contributes to decarbonisation up to 2036, thanks to relatively high speeds of implementation of transport-related measures. Although the aggressive penetration of electric cars can result in higher emissions abatement and avoidance of lock-in effects in order to continue the decline in non-ETS emissions, additional abatement measures need to be considered in industry, buildings and agriculture. In view of the uncertainty about post-2030 zero-carbon technologies and since the main purpose of this analysis is to inform policy about decarbonisation in 2030, finding ways to achieve climate neutrality in non-ETS sectors by 2050 is left to further research.

5.4.5 Sensitivity Analyses

5.4.5.1 Accounting for Behavioural Responses

This section investigates the rebound effect associated with energy efficiency improvements where the implementation of such measures can lead to less than proportional reductions in fuel consumption. This phenomenon found its origin in the microeconomics literature and was first proposed by Jevons (1865), who suggested that technological improvements may lead to lower energy savings than expected. Khazzoom (1980), among the first to theoretically study the rebound effect at the microeconomic level of households, explains that in cases such as the replacement of household appliances with more efficient ones or the purchase of a new car with lower average fuel consumption, the improvement in energy efficiency, which results in a lower energy price, may involve an upward pressure on energy demand. That suggests lower energy savings associated with the improved efficiency measures predicted by the engineering calculations. Summarising, the increase in demand in response to the price decreases may erode the efficiency gains.

Numerous empirical studies have focused on this topic and its presence and size (Dimitropoulos et al., 2018). Although the existence of this phenomenon is widely accepted, an argument lies in the identification and size of the effect (Gillingham et al., 2013). The significance of the phenomenon has been a long-running debate among energy economists, as documented in surveys of the literature (see, e.g., Greening et al., 2000; Sorrell, 2007). Although the premise of the rebound effect is rooted in neoclassical economic theory, there was a discussion on the need for a clear-cut definition (Berkhout et al., 2000), as that varied among researchers, while a review of various empirical studies suggested a variation in the magnitude of the effect depending on that definition (Greening et al., 2000).

Greening et al. (2000) distinguished three mechanisms for reducing energy savings achieved – direct, indirect and economy-wide rebound effect:

Direct rebound effect: improvement of the energy efficiency of service will lead to a decrease in the effective price of that service and eventually will increase the use of that service;

Indirect rebound effect: the lower effective price of an energy service will change the quantity demanded for other goods and services that also require energy (other energy services and other non-energy goods and services that require energy for manufacturing and delivering);

Economy-wide rebound effect: suggests a reduction in prices of goods and resources throughout the economy due to the lower price of the energy services, which in turn leads to increased economic output and higher energy demand.

The indirect and economy-wide rebound effects have been discussed in the literature (e.g., Barker et al., 2007; Grepperud and Rasmussen, 2004; Kok et al., 2006; Lu et al., 2017) but not to the extent of the direct effects. The majority of studies are confined to direct rebound effects (Sorrell et al., 2009), as the indirect and general equilibrium effects are difficult to quantify. For reviews of studies considering indirect and economy-wide effects, see, e.g., Dimitropoulos (2007).

The sensitivity analysis presented here focuses on the direct rebound effect only; the increase of the energy efficiency will decrease the effective price and increase the use of the corresponding service. Regarding the energy renovation measures for the building sector, the implication is that improvements in energy efficiency increase consumption often denoted as backfire (Khazzoom, 1980). The rebound effect for the building sector is expressed as a percentage of the energy savings achieved through the implementation of various energy efficiency measures. It is suggested a 30% effect in line with studies that employed econometric analysis of household survey data, such as Volland (2016) and Aydin et al. (2017). The energy efficiency improvements for the building sector proposed in this study reduce the effective price of the energy services of heating and cooling. The resulting increased consumption offsets the initially estimated energy savings (which were presented in Section 2.3.3); modified assumptions on energy savings are included in Table 5.14.

Table 5.14|Input for the multi-objective optimisation programming – Data including a) energy savings and b) energy demand for different building types and construction periods considering direct rebound effect.

Measure	**Variation in energy demand** [kWh$_{th}$] **for:**	
	Heating	Cooling
Res1/Res1a	-5,795	-13,707
Res2/Res2a	-2,055	-9,060
Res3/Res3a	-1,037	-1,211
Res4/Res4a	-252	-685
Res5/Res5a	-2,163	4,454
Energy Demand for heating [kWh]:*		
Multi-Family building constructed before 2008:		
	20,332	27,423
Single-Family building constructed before 2008:		
	16,198	59,228

*Used for Res6, Res7, Res6a and Res7a calculations

One can find different definitions on the direct rebound effect for road transport in the literature, for example, a) elasticity of travel demand with respect to fuel efficiency, and b) elasticity of travel demand with respect to fuel costs per unit of travelled distance. There is mixed evidence on the equivalence of the above definitions; some studies suggest that it cannot be assumed that the two definitions are principally different, based on both theoretical and empirical basis (e.g., Frondel et al., 2008), while others find asymmetric responses to fuel cost and fuel efficiency (e.g., De Borger et al., 2016). However, the literature showed that the former serves as the most straightforward measure of the direct rebound effect (Frondel et al., 2008; Sorrell and Dimitropoulos, 2008). In the context of this study, for the introduction of private electric cars (RTr2 and RTr2a), the rebound effect implies that the higher fuel efficiency results in a change in travel demand of personal automotive transportation by driving further and/or more by 15% in line with Dimitropoulos et al. (2018). Table 5.15 presents the new assumptions on average kilometres travelled by car per year.

Table 5.15|Input of the multi-objective optimisation model – Assumptions on the direct rebound effect related to road transport.

Measure	Savings occurring from:	New parameter value:	Change:
RTr1	Amount of passenger kilometres shifted from cars to buses	325 million pkm up to 2030 325 million pkm up to 2050	-25%
RTr1a	Amount of passenger kilometres shifted from cars to buses	325 million pkm up to 2030 1,395 million pkm up to 2050	-25%
RTr2/RTr2a	Fraction of new cars sold up using low-carbon powertrain	remains constant, new average kilometres travelled by vehicle yearly equal to 13,800 km/vehicle	+15%

For the promotion of public transportation (RTr1 and RTr1a), a different approach has been followed regarding behavioural responses. Through the successful implementation of these measures, an extended use of public modes is suggested. It is assumed that the reduction in traffic congestion, a side benefit of these mitigation measures, may encourage the use of private transportation; thus, the expected shift of passenger kilometres from private cars to buses may be lower. An effect of 25% is assumed (Table 5.15).

This optimisation run for the sensitivity analysis, with the inclusion of direct rebound effects, is performed for both cases, Case 1 and Case 2, as explained at the beginning of Section 5.4. The assumed direct rebound effect affects the abatement cost (cost-effectiveness index) and each measure's abatement potential. The methodology developed in Chapter 2 has been applied to re-calculate the new economic and environmental performance of the climate change mitigation options. Table 5.16

presents the revised full abatement potential of each mitigation measure for the years 2030 and 2050 and the relative change of the parameters compared to the initial full abatement potential when no rebound effects were included (presented in Section 5.3.2).

Table 5.16 | Input of the multi-objective optimisation model – Environmental performance of mitigation measures expressed as the maximum emissions abatement for the years 2030 and 2050 considering direct rebound effect.

Measure	$A_{j,2030}$ [ktonnes of CO_2 equivalent]	**Comparison with Baseline Cases (Table 5.10)** Relative Change
Res1	2.92	-30%
Res2	9.65	-30%
Res3	0.63	-30%
Res4	0.63	-30%
Res5	0.65	-30%
Res6	7.70	-32%
Res7	10.22	-32%
Ser1	5.00	
Ind1	5.29	
Ind2	0.74	
RTr1	22.09	-25%
RTr2	120.16	0%
RTr3	24.97	
Agr1	10.5	
Res1a	5.83	-30%
Res2a	19.30	-30%
Res3a	1.25	-30%
Res4a	3.80	-30%
Res5a	1.31	-30%
Res6a	15.40	-32%
Res7a	61.34	-32%
RTr1a	37.69	-29%
RTr2a	603.58	0%

The new economic performance with and without externalities, for Case 1 and Case 2, respectively, is included in Table 5.17. The effect on the abatement cost for measures with net social benefits and moderate abatement costs when considering the above-mentioned behavioural responses is illustrated in Figure 5.14.

Table 5.17|Input of the multi-objective optimisation model – Parameter: Economic performance including a) abatement cost considering direct rebound effect, and b) abatement cost including external costs of GHG and air pollutants considering direct rebound effect.

Measure	$AC_{j,2021}$ [€'2015/ tonnes of CO_2 equivalent]	$AC_{j,2021}^{Ext}$ [€'2015/ tonnes of CO_2 equivalent]
Basic Mitigation Measures		
Res1	>1,000	>1,000
Res2	<0	<0
Res3	>1,000	>1,000
Res4	>1,000	>1,000
Res5	263.11	166.00
Res6	<0	<0
Res7	<0	<0
Ser1	<0	<0
Ind1	<0	<0
Ind2	<0	<0
RTr1	220.15	142.97
RTr2	69.25	<0
RTr3	95.17	<0
Agr1	3.85	<0
Advanced Mitigation Measures		
Res1a	>1,000	>1,000
Res2a	<0	<0
Res3a	>1,000	>1,000
Res4a	>1,000	>1,000
Res5a	315.73	199.20
Res6a	<0	<0
Res7a	<0	<0
RTr1a	163.16	167.29
RTr2a	83.09	<0

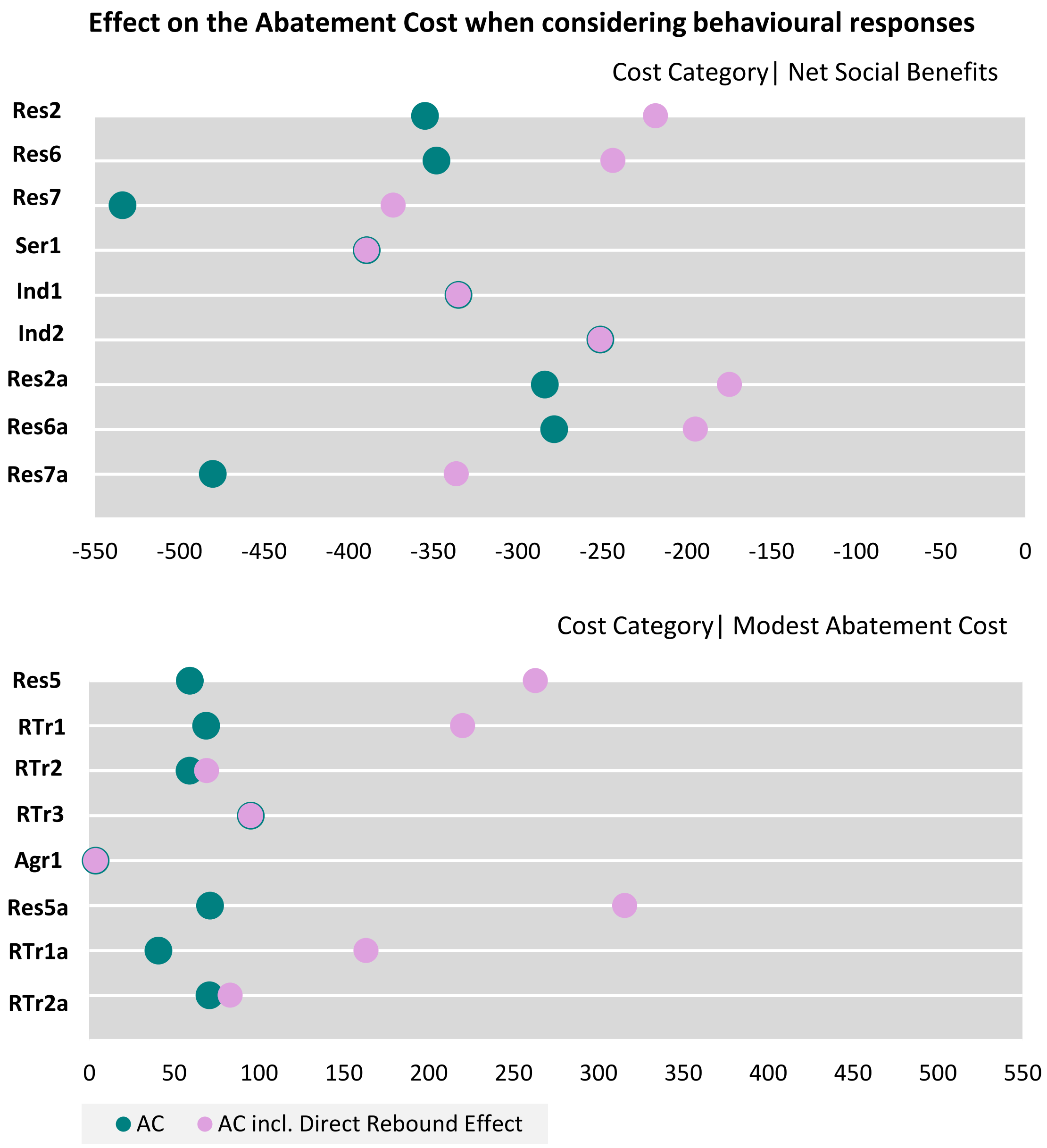


Figure 5.14|Comparison of the initial abatement costs for Case 1 (Table 5.11) and the modified abatement costs when including direct rebound effect (Table 5.17) for the measures which fall into the cost category with net social benefits and modest abatement costs.

The inclusion of direct rebound effect on energy renovations and mobility measures results, apparently, in greater total discounted costs and lower emissions reduction up to 2030 for the new PSs generated. That is evidenced by Figure 5.15, where the new PF appears to have moved upwards and to the left compared to the PF of central Case 1 produced at Section 5.4.1 (Figure 5.4).

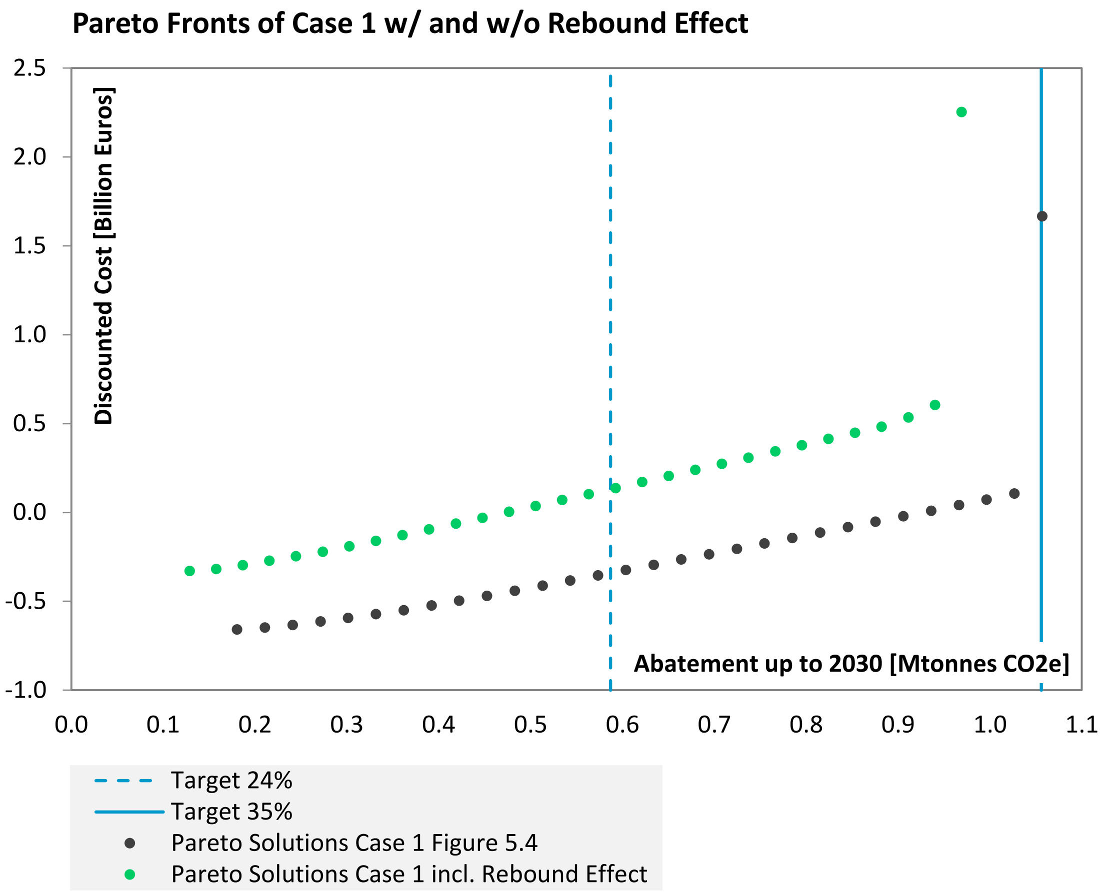


Figure 5.15 | Pareto Fronts for Case 1 with and without the direct rebound effect.

The two PSs of main interest correspond again to the current 24% emissions reduction target for 2030 and a potential new target of 35% reduction. Under this sensitivity analysis, the 24% target is achieved with a higher cost of 0.14 billion Euros, including the savings of the climate change mitigation actions over their lifetime; Cyprus cannot meet the current non-ETS emission reduction commitments up to 2030 at a negative cost as indicated in the central Case 1. It is also worth noting that by breaking down the PS of 24%, there is a preference for introducing low-carbon vehicles, i.e., electric private and light goods conveyance vehicles and CNG powered trucks, against the promotion of public transport, which is entirely left behind. That may have an effect on the need to reach carbon neutrality up to 2050, where the road transport measures, including the extended use of public transport, are necessary. This measure is associated with a correlation between the implementation speed of a year and the cumulative abatement up to the previous year; any delay in the implementation will result in lower abatement up to 2050. For the energy renovation measures, Res5 is no longer included in the policy mix as it has the greatest effect on the abatement cost, evidenced in Figure 5.14. Most of the energy efficiency measures remain cost-effective (except Res5, Res5a and the measures with cost higher than 1,000 Euros per tonne of CO_2 equivalent), even including the direct rebound effect.

The generated PF's rightmost point of Figure 5.15 represents the policy mix with the highest cost and the most significant mitigation potential. For this analysis, the available mitigation options can reach a 33% level of emissions reduction, 2% lower than the maximum abatement potential of Case 1, due to the consideration of direct rebound effects on all energy efficiency measures in buildings and the use of public transportation and low-carbon vehicles. The change on the full available potential appears moderate because the increase in the travel demand of electric vehicles, the main contributor to reducing ESR emissions, results in an increase in electricity generation emissions, which are subject to EU ETS – here we deal with ESR emissions only. The total discounted cost increases by 35% compared to the highest abatement potential point of Figure 5.4 (Case 1).

The above results are related to the inclusion of the direct rebound effect on the optimisation procedure; hence the new produced PF of Figure 5.15. However, it is also worth exploring how the PSs of central Case 1 (Figure 5.4) could overestimate the reduction of GHG emissions and underestimate the costs when neglecting possible backfire effects on the decision making process. For this purpose, the rebound effect is applied directly to the initially selected policy mix. For the PS of 24% reduction of central scenario Case 1, the results indicate an overestimation of the possible abatement by 13% (22.6% emissions reduction compared to 2005 levels) while the total cost of abatement reaches the positive value of 0.14 billion Euros (highlighted points in Figure 5.16).

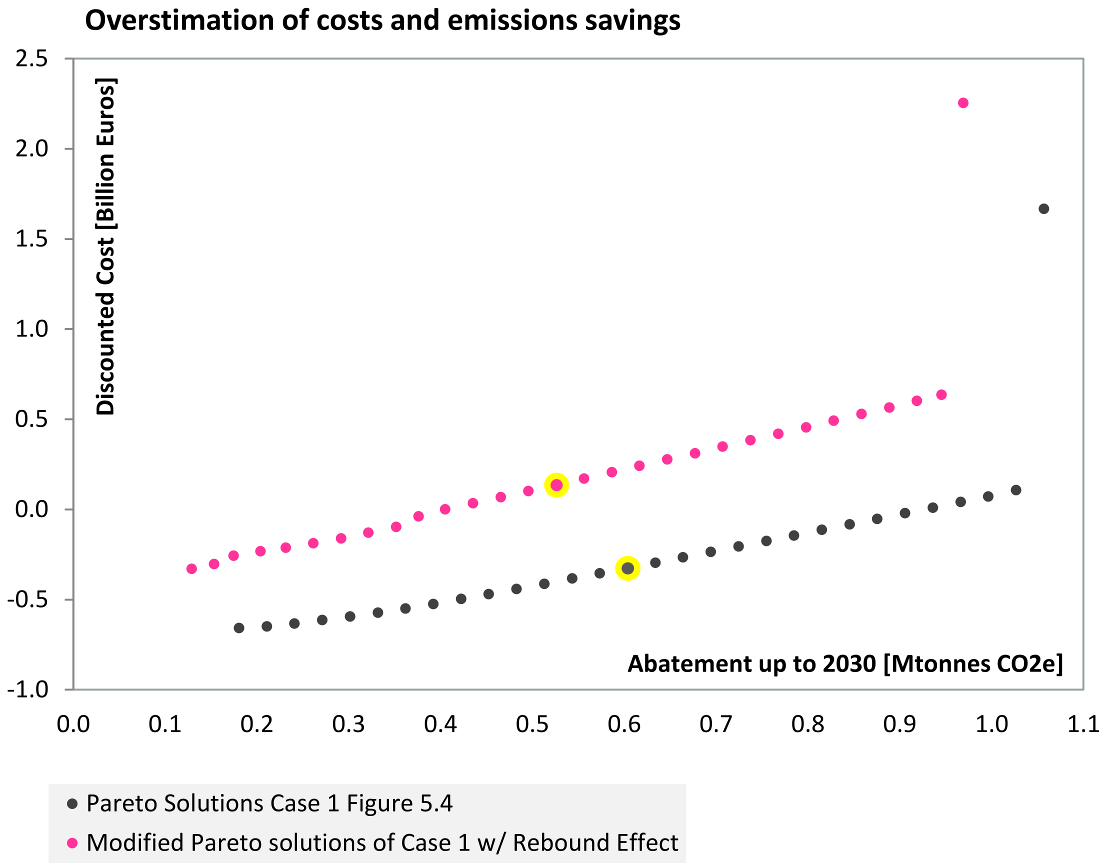


Figure 5.16 | Overestimation of the costs and abatement savings when ignoring rebound effects in the decision-making process.

The following table summarises the economic and environmental performance of the policy mix achieving 24% emissions reduction compared to 2005 level (the current non-ETS target of Cyprus) for central Case 1 and alternative Case 1 when including the direct rebound effects in the optimisation procedure. The implications of the rebound effect on the policy mix of central Case 1 is also presented to highlight, as in Figure 5.16, the risk of not including this phenomenon in the decision-making procedure. Although the policy mix of central Case 1 results eventually in lower abatement for 2030 than initially calculated, it is better balanced compared to the policy mix of alternative Case 1, leaving no measure with strong barriers behind.

Table 5.18|Economic and environmental performance of Pareto solution of 24% emissions reduction for 2030 for central Case 1 and alternative Case 1 when including direct rebound effect.

	PS24%	
	Abatement Potential [Mtonnes of CO_2 equivalent]	**Abatement Cost** [billion Euros]
Central Case 1	0.60	-0.33
Implications of Rebound Effect	0.53	0.14
Case 1 w/ Rebound Effect	0.60	0.14

Regarding the alternative scenario of Case 2, where the cost-objective function is driven by the abatement cost when accounting for the co-benefits of air pollution control and the corresponding externalities, most of the PSs are still associated with negative abatement costs as in Section 5.4.2. The point on the PF of Figure 5.17 with the lowest discounted cost (leftmost PS) matches with a policy mix with a potential of reducing the GHG emissions by 31%, reducing the environmental benefits by 2% compared with the corresponding point of Figure 5.8, and the savings by 0.4 billion Euros.

The results suggest that the energy demand increases in buildings and transport due to rebound effects in mitigation measures do not significantly affect the available policy mix's abatement potential. That is mainly because the increased demand for the use of electric cars results in an increase in ETS emissions which are not part of this assessment. Therefore, there is a relative moderate decrease, *ceteris paribus*, on the overall environmental benefits with respect to non-ETS emissions. However, it is important to eliminate this consequence on the non-ETS emissions reduction potential under the direct rebound effect, as the decarbonisation pathway of these sectors of the Cypriot economy already appears challenging. Policy pathways to reduce the rebound effect have been discussed in the literature based on market-based and non-market instruments (Maxwell et al., 2011; Vivanco et al., 2016).

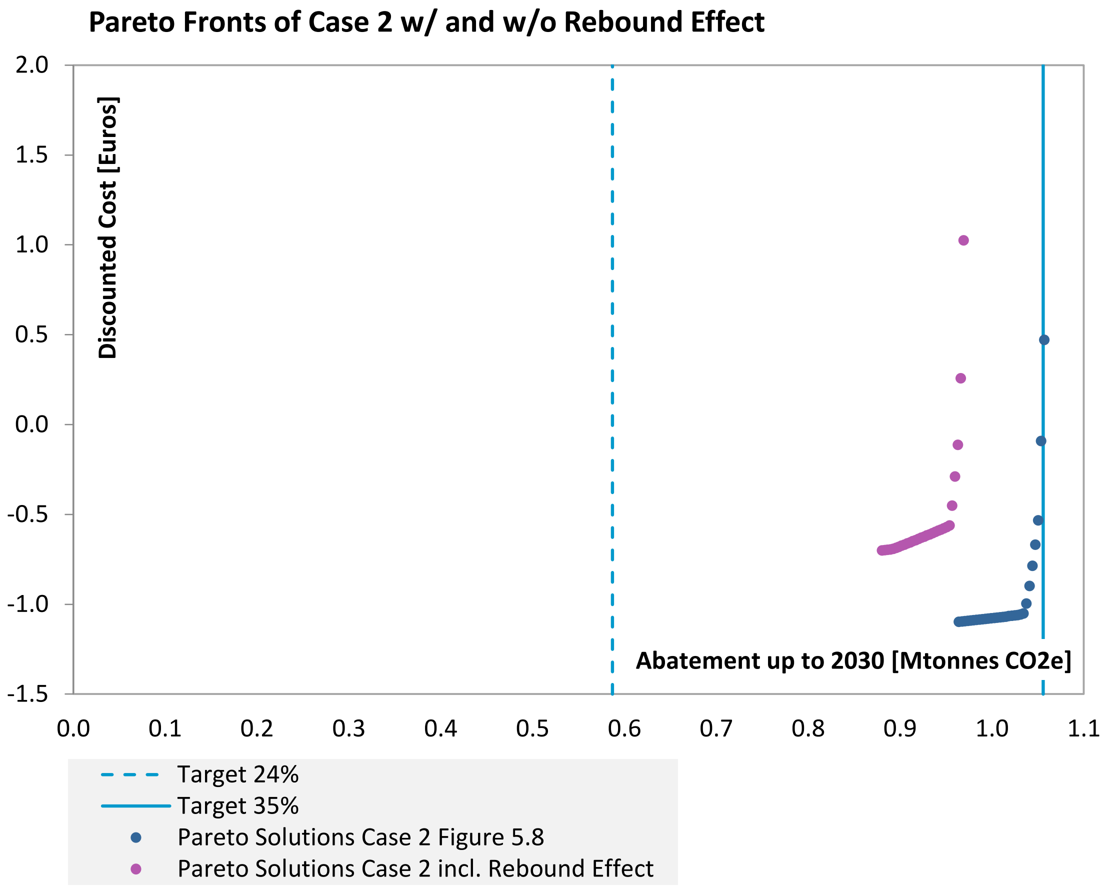


Figure 5.17 | Pareto Fronts for Case 2 with and without the direct rebound effect.

5.4.5.2 Risk of Delayed Implementation

A main feature of the model developed in Chapter 3, firstly introduced by Vogt-Schilb and Hallegatte (2014) and later expanded in this thesis to be variant over time, is the speed of implementation, which suggests that the mitigation measures cannot reach their full potential overnight but require time to be implemented and mature based on a variety of barriers. In other words, this parameter reflects the upper limit on the available abatement potential for each time step. The values given for each mitigation measure correspond to the relevant factor, e.g., a) for the energy renovations, the speed reflects the number of buildings to be renovated, or b) for public transportation, the speed matches the number of passenger kilometres shifted from private cars to buses. The two aggregated measures' categories, basic and advanced, are treated differently (justification of the speed values is presented in previous sections of Chapter 5) as they represent more realistic actions and more challenging and ambitious options, respectively.

This section presents alternative calculations of the PFs for Case 1 and Case 2, considering the risk of delayed implementation of emission abatement measures as expressed through lower values of speed. The following are assumed:

- Residential buildings: 20% fewer interventions are made for each basic measure, 30% fewer interventions are made for each advanced measure;
- Services sector: 10% less CHP units are installed;
- Industry: 10% less CHP units are installed (Ind1), 10% less Burners to be replaced (Ind2);
- Road Transport: 30% less passenger kilometres shifted from private vehicles to public buses (RTr1/RTr1a), 30% less new cars to be electric (RTr2, RTr2a) and 30% less new trucks to run on CNG (RTr3);
- Agriculture: 10% less animal and municipal waste to be directed for anaerobic digestion.

For this sensitivity analysis of Case 1, the multi-objective optimisation result suggests that the maximum abatement potential of the available climate change actions, presented by the rightmost PS of Figure 5.18, is lower by 29% compared to the central scenario of Case 1. In regards to the 2030 emissions reduction target, the corresponding policy mix can reach a 28% reduction compared to 2005 levels, 7% lower than the potential new target of 35% reduction, which may come out of the negotiation process in the frame of the European Green Deal.

The associated lower cost (1.14 billion Euros) is justified by lower abatement and thus fewer investments. However, when focusing on the current 24% non-ETS target for Cyprus, which is achievable under this assessment, as denoted by the dash blue vertical line, the cost for this policy mix appears still negative but higher than the central scenario of Case 1. That suggests lower cost savings, mainly because of the reduced abatement potential of negative cost measures in the residential sector.

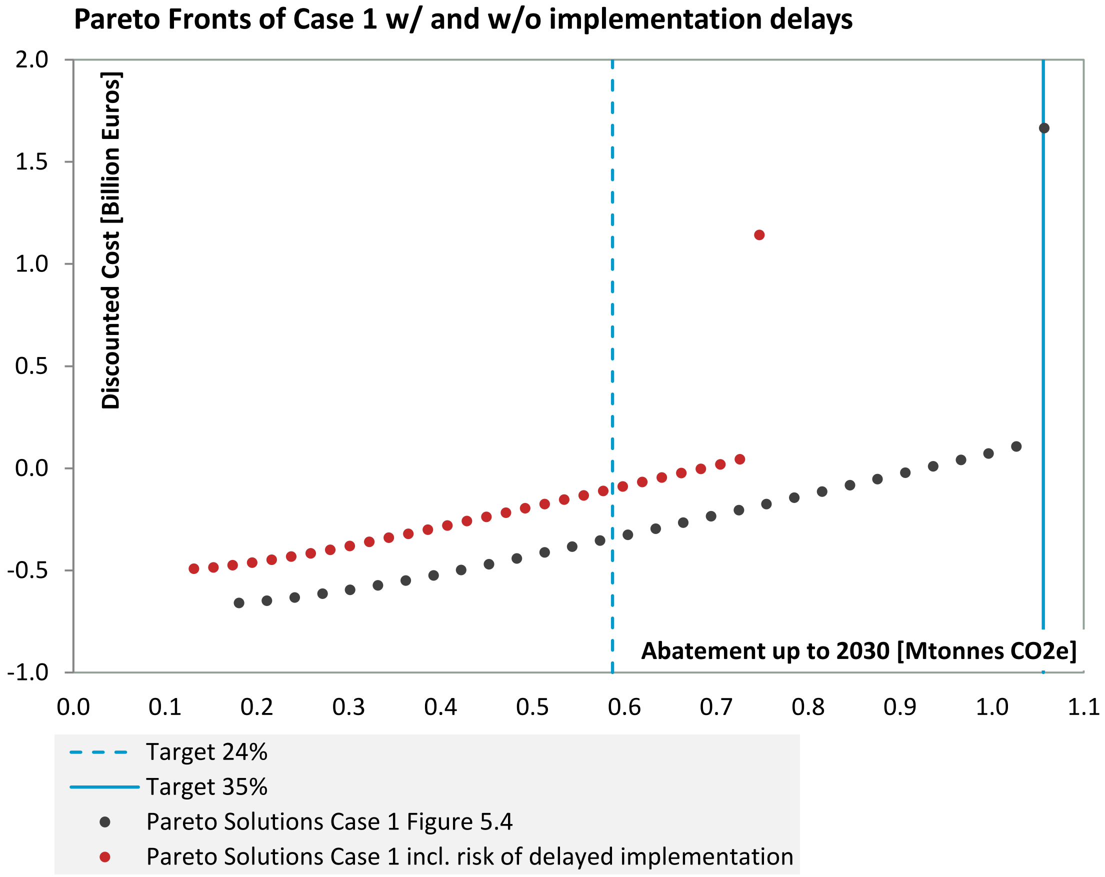


Figure 5.18 | Pareto Fronts for Case 1 with and without the implementation delay.

Similar results appear in the sensitivity analysis for Case 2, where the avoided externalities of air pollution control are included in the cost-objective function. Figure 5.19 depicts the new PF that indicates similar responses to the lower speed of implementation across the available mitigation measures, suggesting a delay in their realisation. Focusing on the cost-objective function, the policy mixes for various abatement levels are beneficial to society (negative discounted costs).

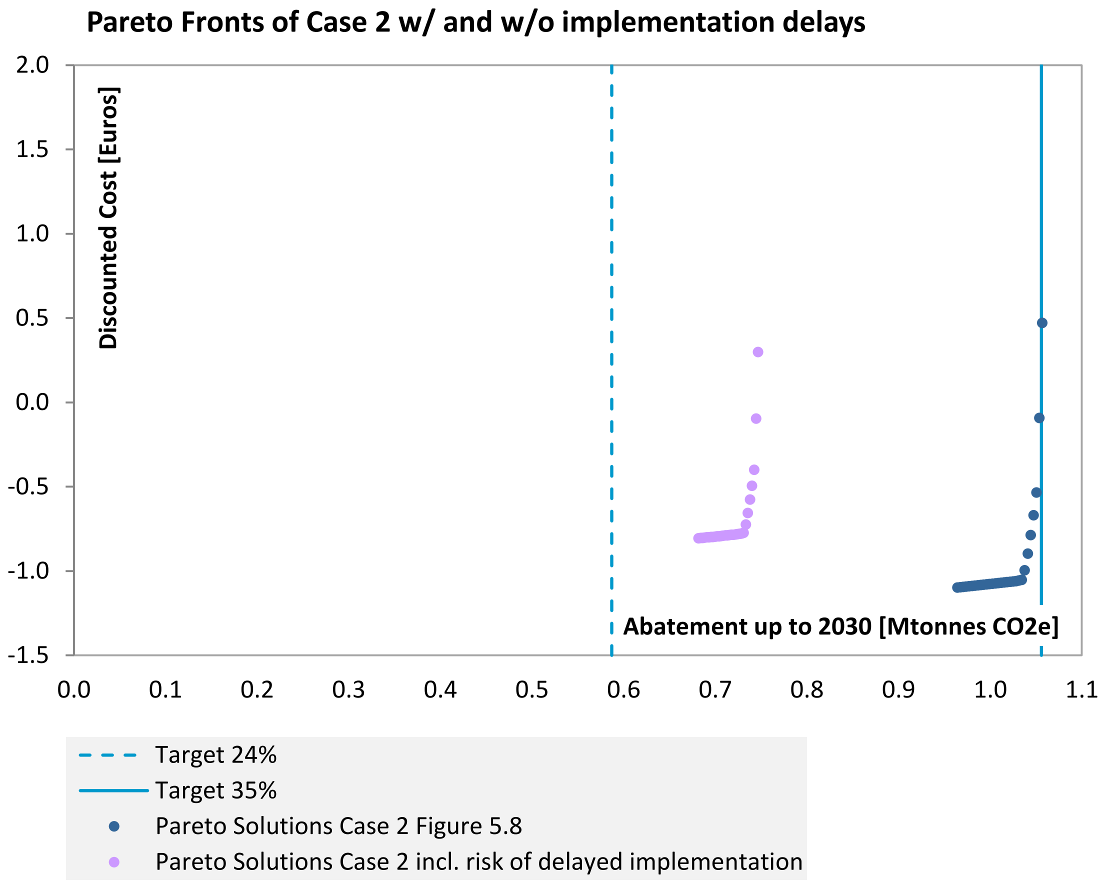


Figure 5.19 | Pareto Fronts for Case 2 with and without the implementation delay.

5.5 Conclusions and Policy Implications

The global climate policy scene is changing fast, and the EU is among the leading regions in adopting an ambitious decarbonisation strategy. In light of the decisions taken in 2020 by EU leaders to raise the bloc's ambition for the reduction of greenhouse gas emissions and the associated uncertainty about the allocation of effort between EU member states, this study presented a multi-objective optimisation approach that takes into consideration the current policy challenges. A Pareto-optimal front was developed for policies that can achieve varying levels of decarbonisation in non-ETS sectors at different costs; this allows policymakers to identify trade-offs between a more ambitious and costly decarbonisation policy and a cheaper mix of abatement measures that can achieve a less ambitious target. Then the front is re-calculated by considering additionally the change in external costs of greenhouse gas and air pollutant emissions; this enables evaluating decarbonisation strategies up to 2030 in a way that is closer to the socially optimal solution. The needs for investments and public expenditures for implementing specific policy mixes are also being assessed. Being adapted to the specific EU policy circumstances, the modelling framework was applied for the EU member state of Cyprus, building on data and policy insights from authors' previous work. However, the proposed methodology is entirely suitable for any other EU member state, as well as for other world regions with a demanding decarbonisation roadmap.

It is found that it is challenging for Cyprus, as is reportedly the case for most EU countries (European Environment Agency, 2019), to meet their non-ETS decarbonisation commitments even under the existing legislation, which will be strengthened during 2021. As shown in Table 5.12, even to reach modest emission abatement, fast deployment of measures is required for electrification of transport, shift to public transportation, and energy renovations of buildings, much beyond the speed at which such interventions had been implemented up to now. However, without more ambitious emission reduction targets for 2030, it becomes highly unlikely for the continent to attain the climate neutrality it has pledged to achieve by 2050. Interestingly, the ambitious targets for 2030 that can help Europe stay on track for 2050, although seemingly more costly than the less ambitious ones, seem to yield net benefits to society if optimisation is conducted taking into account external costs in addition to the financial ones; the avoided economic damages thanks to the more ambitious decarbonisation policies, coupled with fuel cost savings throughout the lifetime of the interventions, demonstrate that there is no dilemma between climate ambition and economic costs. Still, the optimal decarbonisation path is capital-intensive and fiscally challenging - it requires investments of the order of 5% of Cyprus's annual national GDP every year of the decade 2021-2030, out of which more than half will have to come from public funds. Although this level of spending is feasible, it requires a well-targeted orientation of public and private investments towards low-carbon interventions across the entire economy.

The developed multi-objective framework allows decision-makers to draw conclusions in an uncertain and fast-changing policy environment. It is demonstrated, for example, that following a conventional policy mix as coming out of the simulations shown in Figure 5.4, small changes in abatement objectives do not entail large changes in costs – with the exception of ambitious policy reaching 35% emission reductions, where marginal costs increase very fast in view of the need to deploy costly measures to attain this target. The picture is somewhat different when decisions are made through factoring in external costs in the optimisation procedure, as shown in Figure 5.8: The costs to comply with a specific target rise faster the more ambitious the target becomes, but in almost all cases, they remain at negative levels. This means that, even if the decarbonisation objective becomes more stringent, the costs associated with it will be beneficial to – or at least affordable by – the national economy. In any case, the issues concerning the feasibility of ambitious decarbonisation given the needed levels of investment and public spending, as outlined above, continue to be relevant.

EU leaders, along with international organisations, have outlined the importance of such a green transition in the aftermath of the COVID-19 pandemic; it has been well documented that a "return-to-normal" economic stimulus is not only environmentally unsustainable but also economically inferior to a green economic recovery plan comprising measures like those included in this paper (European Commission, 2020; IMF, 2020). Political will and societal engagement can overcome economic, financial, and behavioural barriers to build infrastructure, mobilise capital, and change production and consumption patterns on the way to stabilise the global climate. The sensitivity analysis described in Section 5.4.5 reinforces the above: Incomplete implementation of abatement measures, which may be due to different reasons – rebound effects, less responsive shift to public transport, or less successful implementation of building renovations – can adversely affect the decarbonisation effort.

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6 Conclusions and Outlook

6.1 Concluding Remarks

In the demanding international and EU climate policy context, the objective of this doctoral thesis was to expand existing and develop new approaches for assessing policies and measures in order to identify cost-effective climate change mitigation strategies that are beneficial to society and in line with the goal to achieve climate neutrality by 2050.

This thesis addressed the general research question, *how can the decarbonisation of non-ETS sectors of an EU Member State be analysed in a computationally tractable manner that can be useful to policymakers?,* by looking into more focused research questions such as the importance of the planning horizon, the interaction between short- and long-term optimal strategies, and the decarbonisation pathway of Cyprus. Selected decision-making aids on which policy is based have been used, i.e., marginal abatement cost curve, cost-optimisation and multi-objective mathematical programming.

To support the policy formulation for complying with the reduction targets for Cyprus' non-ETS emissions, the research began with identifying realistic country-specific mitigation measures that are additional to the existing national and EU legislation in order to provide meaningful support to national policymakers. A list of different types of mitigation actions across all economic sectors – improving energy efficiency, switching to low- or zero-carbon fuels, and inducing behavioural change towards public transport modes – has been selected (Chapter 2, pp. 38-45). A comprehensive data collection effort has been made to identify all the necessary economic and technical data of the various emissions reduction options (Chapter 2, pp. 58-77). Each measure's costs have been assessed after consultation with local experts and with the aid of data from the national market. Relying on real-world information about the availability, technical deployment potential, and energy efficiency under local operating conditions, each measure's environmental performance has been appraised.

Answering the question, *can Cyprus reach the allocated medium-term target and how?,* the calculated achievable abatement potential of those realistic climate change actions highlights the country’s difficulty to meet the non-ETS decarbonisation commitments under the existing legislation (results in Chapter 2, p. 81). The need to move into a ‘full’ potential approach is highlighted in Chapter 3, 4 and 5, where the initial measures are expanded, and additional technological solutions are introduced. Results found in Section 4.3 and Section 5.4 suggest that even to reach modest emission abatement, fast deployment of measures is required for electrification of transport, shift to public transportation, and energy renovations of buildings, much beyond the speed at which such interventions had been implemented up to now. That appears necessary as the 2030 target will become more ambitious under the European Green Deal to facilitate the net-zero emissions target up to 2050 (Chapter 5, pp. 179-185) – the relationship between the medium- and the long-term target has been explored in Chapter 3, and the assessment of the way that Cyprus can reach the new demanding 2030 target has been dealt in Chapter 5.

So, *is the level of ambition for the medium-term a condition to achieve the long-term goal? Are there consequences of neglecting the long-term climate target when formulating the near or medium-term policy?* The simulations in Chapter 3, pp. 117-124, offer evidence that if the 2030 objective is unambitious, the decarbonisation target of 2050 can only be met if a policymaker – already in 2020 – decides jointly the optimal pathway for meeting both 2030 and 2050 objectives. This is profound for Cyprus's case where road and freight transport, and to some extent waste management, are the sectors that are particularly vulnerable to unambitious 2030 objectives because deployment of new vehicle technologies and anaerobic digestion/biogas plants takes time to materialize. Road transport holds the greatest responsibility in non-ETS emissions; thus, the alignment of medium- and long-term climate change policy is necessary (conclusions also highlighted in Chapter 5, pp. 192-194).

Is the long-term climate neutrality target attainable? Even when avoiding lock-in effects, delayed implementations and prioritising costly and challenging to decarbonise sectors. Moving forward to a 'full' abatement approach is essential to attain the current or future, more ambitious, medium-term objective negotiable under the European Green Deal and to ensure the best possible trajectory for the long-term climate neutrality goal. However, the identified actions are insufficient (see results in Chapter 5, pp. 192-194); finding ways to achieve climate neutrality in non-ETS sectors by 2050 for Cyprus is left to further research.

Although ambitious policy mixes have excessive up-front capital requirements, many measures are expected to yield net benefits to society from an economic viewpoint. These benefits become even more pronounced if side-benefits are taken into account (an aspect that was highlighted in Figure 5.11). In order to reap these environmental and economic benefits, governments have to remove financial, economic and regulatory barriers that hinder progress towards decarbonisation.

Therefore, *what might be the key actions and sectors to achieve the desirable mitigation for the medium-term for Cyprus and facilitate the long-term goal?* It is clear that the shift to lower-carbon transport modes, including the shift from private to public transportation, holds the most significant potential regarding the non-ETS abatement in Cyprus. Nevertheless, even if with lower potential, the rest of the climate change actions are also essential for achieving the targets. It is noted throughout the dissertation that immediate emphasis should be given to measures with lower penetration but high overall potential. Still, no action should be left behind in this challenging and highly ambitious effort.

Table 6.1 presents the major categories of mitigation measures and their applicability across Cyprus's main sectors of economic activity. This approach attempts to translate the horizontal policies into vertical ones and identify the sectors that could benefit from the proposed actions and, thus, be targeted for non-ETS emissions reduction. As the dots indicate, tourism, households, and the manufacturing industries are important sectors as they can accommodate many abatement measures. Six out of seven abatement categories can be implemented for reducing emissions related to

Tourism activities, with the Household sectors following with four out of seven being compatible actions. From the abatement quantity perspective, the two sectors mentioned above hold the lead mainly due to the inclusion of energy efficiency improvements and road transport related measures (electric cars and public transport). It is also evident that future attention must be given to Agriculture and Construction sectors to identify and assess supplementary mitigation actions.

Table 6.1 | Applicability of individual mitigation measures across main economic sectors of Cyprus.

	Main economic sectors					
Abatement actions	**Agriculture**	**Manufacturing Industries**	**Construction**	**Tourism**	**Households**	**Tertiary sector**
Energy renovations in buildings				●	●	
Energy efficient equipment (heat pumps, industrial machinery)		●	●	●	●	
Cogeneration (CHP)		●		●		●
Electric cars				●	●	●
Low-emission trucks		●				
Promotion of public transport				●	●	
Anaerobic digestion of waste for power & heat generation	●			●		

6.2 Impact of the Research Work on Policy

As explained above, the major challenge that guided this thesis's work was developing and applying innovative methods to provide realistic recommendations to decision-makers for addressing current energy and climate policy issues. In fact, research questions were in some cases formulated on the basis of policy needs, while in other cases, the work of this thesis attempted to provide early signals to policymakers for upcoming challenges in view of global and EU pledges on climate stabilisation.

It is safe to conclude that several analyses that were conducted in the frame of this doctoral research have been indeed useful to national decision-makers in Cyprus for the formulation of their energy and climate policy. Moreover, the work has proved useful for advising policy professionals in a broader group of countries.

At a national level, apart from informal recommendations provided during numerous discussions with stakeholders from public authorities and private organisations of Cyprus, the work of this thesis has been used for official policy formulation as shown in the following examples:

- Results of the MAC analysis of Chapter 2 were used in 2018-2019 at internal policy deliberations of the Cypriot government on the most cost-effective use of revenues from ETS auctions in order to finance non-ETS decarbonisation measures.
- The outcome of both the MAC calculations of Chapter 2 and the optimal timing analysis of Chapter 3 was included in the Impact Assessment (Chapter 5) of the National Energy and Climate Plan of Cyprus that was submitted to the European Commission in January 2020 (Republic of Cyprus, 2020).
- Simulations of carbon tax scenarios of Chapter 4 were included in a proposal for an environmental fiscal reform that was adopted by the Finance Minister of Cyprus in 2019 and formed the basis for the inclusion of a concrete “Green Tax Reform” in the National Recovery and Resilience Plan submitted by the government of Cyprus to the European Commission in early 2021 (not yet published by the time of this writing).
- The challenges associated with the stronger EU-wide decarbonisation pledge for 2030 in the frame of the European Green Deal, and the relationship between stronger abatement and higher costs, as resulting from Chapter 5, were presented by senior staff of the Environment Ministry of Cyprus to four Ministers in late 2020, to highlight the urgent need for the Cypriot government to adopt a more ambitious climate policy.

In the international policy scene:

- Results of the modelling analyses shown in Chapters 2, 3 and 4 were presented and discussed with several officers of the European Commission (Directorate General for Economic and Financial Affairs, Directorate General for Climate Action, and Directorate General for Structural Reform Support) with a view to providing policy insights for the broader EU-wide decarbonisation strategy and its implications at a national level.
- The MAC methodology and its real-world application were presented at two training courses organised by the International Atomic Energy Agency in late 2020 and early 2021, in the frame of capacity-building activities to design national energy and climate strategies that are in line with the Paris agreement. These courses were attended by about 70 professionals from public authorities and research institutions in Eastern Europe and Central Asia.

6.3 Limitations and Future Outlook

A number of limitations are worth mentioning that can be the cornerstones for future research regarding the design of climate change mitigation strategies. The MAC calculations are currently a separate, stand-alone module and are performed outside the optimisation model. Expanding the model in GAMS to perform the cost-effectiveness analysis will result in a more comprehensive tool for exploring medium- and long-term mitigation pathways with a large number of economic and technical parameters. That links with another direction for future research, a detailed analysis regarding uncertainty. Having a plethora of parameters, a number of which can be identified as uncertain factors, robustness analysis featuring stochastic uncertainty could be performed. Using Monte Carlo simulation, various probability distributions for uncertain parameters can be contemplated. For the case of the MOMP approach, different Pareto fronts of optimal policy mixes are produced based on the sampling of the model's parameters.

Regarding the multi-objective optimisation framework, two objective functions, i.e., total discounted cost and abatement over the lifetime of measures, have been used to address a specific research question. The insertion of further sustainability criteria into the optimisation framework can produce sustainable solutions apart from reducing GHG emissions. An aspect of that has been addressed in the context of this thesis when considering the co-benefits of air pollution control resulting from GHG abatement measures – from the view of external costs avoided. Collection of real-world data on the costs and potential of actions to abate air pollutants such as NOx, $SO_{2,}$ and PM can create a model that can simultaneously advise policymakers for a policy mix to mitigate GHG and air pollutant emissions simultaneously. Apart from the example of air pollution, other goals (e.g. related to climate change adaptation, circular economy or nature protection) can be added to create a model useful in the context of sustainable development.

Focusing on the mitigation measures, there is a shortcoming worth exploring regarding the interaction between them. A main critique of the MAC approach is that the cost-effectiveness of measures depends on the order in which they are implemented; the reference scenario changes for the second in line mitigation action. However, this can be a serious problem when mitigation measures in end-use sectors and energy supply are considered simultaneously. Based on the need to support the very demanding and challenging mitigation target of the non-ETS sector, this thesis studied only measures in end-use sectors like buildings, transport and light industry; hence, this problem is much less critical. The measures are also introduced in a way to remain independent. Overcoming, however, this drawback may enable a more dynamic approach.

Finally, it is evident that additional effort has to be made in the future, as new decarbonisation technologies enter the market, to identify new solutions for Cyprus' case with regard to non-ETS emissions reduction. That will enable the enrichment of the cost-effectiveness methodology and identify a pathway to the ultimate goal, the 2050 climate neutrality target.

Appendix I

Online Data File

An online file includes the data and material used throughout the PhD Thesis. Access can be given through personal invitation.

Link: Online Data File

Appendix II

Source Code

Long-Term Mitigation Planning (LTMP) Model

Version: *Multi-Objective*

Application: *Section 5.4.1.* Balancing Economic and Environmental Criteria *&*

Section 5.4.2. Co-benefits for Air Pollution Control

```
Set
j  "mitigation measures"/
Res1        "Full Renovation/MF pre-2008"
Res2        "Roof Insulation/MF pre-2008"
Res3        "Wall Insulation/MF pre-2008"
Res4        "Wall Insulation/SF pre-2008"
Res5        "Pilotis Insulation/MF pre-2008"
Res6        "Heat Pumps/MF pre-2008"
Res7        "Heat Pumps/SF pre-2008"
Ser1        "CHP-Services"
Ind1        "CHP-Industry"
Ind2        "Burner Replacement"
RTr1        "Promotion of Public Transport"
RTr2        "El. Private & Light Good Conveyance Vehicles"
RTr3        "Low-Carbon Trucks"
Agr1        "Anaerobic Digestion for Animal Waste"
Res1a       "Full Renovation/MF pre-1990"
Res2a       "Roof Insulation/MF pre-1990"
Res3a       "Wall Insulation/MF pre-1990"
Res4a       "+Wall Insulation/SF pre-2008"
Res5a       "Pilotis Insulation/MF pre-1990"
Res6a       "Heat Pumps/MF pre-1990"
Res7a       "+Heat Pumps/SF pre-2008"
RTr1a       "Promotion of Public Transport/BEV Buses"
RTr2a       "+El. Private & Light Good Conveyance Vehicles"/

lbj(j)  "measures with loose economic & behavioural barriers"
/Res1, Res2, Res3, Res4, Res5,Res6,Res7, Ser1, Ind1, Ind2, RTr3,
Agr1, Res1a, Res2a, Res3a, Res4a, Res5a, Res6a, Res7a/

sbj(j)  "measures with strict economic & behavioural barriers"
/RTr1,RTr2,RTr2a/

sbj25(j) "measures with strict economic & behavioural barriers
introduced after 2025" /RTr1a/
```

```
t  "time step of one year"  /2021*2030/

i  "lifetime of mitigation measures"  /1*30/

k  "objective functions"  /cost, CO2eabatement/;
$set min -1
$set max +1
Parameter dir(k) "direction of the objective functions"
/cost %min%, CO2eabatement %max%/;

Scalar  r  "discount rate"  /0.04/;
*economic assessment: public discount rate

Parameter  n(t)  "number of periods";
           n(t)=ord(t);

Parameter  df(t)  "1/discount factor";
           df(t)=1/(1+r)**n(t);

Parameter  ldf(i)  "1/lifetime discount factor";
           ldf(i)=1/(1+r)**ord(i);

Parameter  fa(j)  "full abatement of each measure [ktCO2e]"/
$ondelim
$include C:\...
$offdelim
/;

Table  ac(t,j)  "annual abatement cost of each measure
[Euros/tCO2e]"
$ondelim
$include C:\...
$offdelim
;

Parameter  acdisc(t,j)  "discounted an. abatement cost
[Euros/tCO2e]";
acdisc(t,j) = ac(t,j)*df(t);

Table  s(t,lbj)  "annual speed of implemenation for measures
with loose economic & behavioural barriers [ktCO2e/y/y]"
$ondelim
$include C:\...
$offdelim
;
```

```
Parameter ssl(sbj)  "speed of implementation starting level for
measures with strict economic & behavioural barriers
[ktCO2e/y/y]"
$ondelim
$include C:\...
$offdelim
/;

Table sincr(t,sbj)  "annual speed increase for measures with
strict economic & behavioural barriers [%]"
$ondelim
$include C:\...
$offdelim
display sincr;

Parameter ss(t,sbj)  "annual speed of implementation for
measures with strict economic & behavioural barriers
[ktCO2e/y/y]";
ss(t,sbj)$(n(t)=1)= ssl(sbj);
ss(t,sbj)$(n(t)>1)=ssl(sbj)+ssl(sbj)*sincr(t,sbj);

Parameter ssl25(sbj25)  "speed of implementation starting level
for measures with strict economic & behavioural barriers
[ktCO2e/y/y]"/
$ondelim
$include C:\...
$offdelim
/;

Table sincr25(t,sbj25)  "annual speed increase for measures with
strict economic & behavioural barriers [%]"
$ondelim
$include C:\...
$offdelim
;
*this quantity represents the % increase for each year compared
to the speed starting level(ssl)

Parameter ss25(t,sbj25)  "annual speed of implementation for
measures with strict economic & behavioural barriers
[ktCO2e/y/y]";
ss25(t,sbj25)$(n(t)<5)=0;
ss25(t,sbj25)$(n(t)=6)= ssl25(sbj25);
ss25(t,sbj25)$(n(t)>6)=ssl25(sbj25)+ssl25(sbj25)*sincr25(t,sbj25
);

Variables
```

```
    z(k)    "objective function variables"
    A(t,j)  "annual abatement by measure [ktCO2e]"

Positive Variable a;

Equation
objcost               "objective for min total discounted
abatement cost [1000Euros]"
objabatement          "objective for max emissions abatement for
medium-term"
maxpotential(j) "full abatement upper band for all measures"
speedlimit1(t,lbj)   "annual speed of implementation limits for
lb measures"
speedlimit2(t,sbj)    "starting annual speed of implementation
limits for sb measures"
speedlimit3(t,sbj)   "annual speed of implementation limits for
sb measures"
speedlimit4(t,sbj25) "annual speed of implementation limits for
sb measures after 2025";

objcost..
sum((t,j),df(t)*ac(t,j)*sum(i,ldf(i)*A(t,j))) =e= z('cost');
objabatement..                  sum((t,j),A(t,j)) =e=
z('CO2eabatement');
maxpotential(j)..               sum(t,A(t,j)) =l= fa(j);
speedlimit1(t,lbj)..            A(t,lbj) =l= s(t,lbj);
speedlimit2(t,sbj)$(n(t)=1)..   A(t,sbj) =l= ssl(sbj);
speedlimit3(t,sbj)$(n(t)>1)..   A(t,sbj) =l= ss(t,sbj)-(ss(t-
1,sbj)-A(t-1,sbj));
speedlimit4(t,sbj25)..          A(t,sbj25) =l= ss25(t,sbj25);

Model  ltmp  "long-term non-ETS emissions mitigation"
Model"/all/;

$STitle eps-constraint method

Set k1(k)  the first element of k,
    km1(k) all but the first elements of k
    kk(k)  active objective function in constraint allobj;
k1(k)$(ord(k)=1) = yes; km1(k)=yes; km1(k1) = no;

Parameter
    rhs(k)     right hand side of the constrained obj functions
in eps-constraint
    maxobj(k)  maximum value from the payoff table
    minobj(k)  minimum value from the payoff table
    numk(k)    ordinal value of k starting with 1
```

```
Scalar
    iter         total number of iterations
    infeas       total number of infeasibilities
    elapsed_time elapsed time for payoff and e-constraint
    start        start time
    finish       finish time

Variables
   a_objval   auxiliary variable for the objective function
   obj        auxiliary variable during the construction of the
payoff table
   sl(k)      slack or surplus variables for the eps-constraints

Positive Variables sl

Equations
   con_obj(k) constrained objective functions
   augm_obj   augmented objective function to avoid weakly
efficient solutions
   allobj     all the objective functions in one expression;

con_obj(km1)..   z(km1) - dir(km1)*sl(km1) =e= rhs(km1);

* We optimize the first objective function and put the others as
constraints
* the second term is for avoiding weakly efficient points

augm_obj.. a_objval =e= sum(k1,dir(k1)*z(k1))
    + 1e-3*sum(km1,power(100,-(numk(km1)-
1))*sl(km1)/(maxobj(km1)-minobj(km1)));

allobj..  sum(kk, dir(kk)*z(kk)) =e= obj;

Model mod_payoff    / ltmp, allobj / ;
Model mod_epsmethod / ltmp, con_obj, augm_obj / ;

Parameter
   payoff(k,k)  payoff tables entries;
Alias(k,kp);


option optcr=0, limrow=0, limcol=0, solprint=off,
solvelink=%Solvelink.LoadLibrary%;

* Generate payoff table applying lexicographic optimization
loop(kp,
  kk(kp)=yes;
```

```
  repeat
    solve mod_payoff using lp maximizing obj;
    payoff(kp,kk) = z.l(kk);
    z.fx(kk) = z.l(kk);
    kk(k++1) = kk(k);
  until kk(kp); kk(kp) = no;
* release the fixed values of the objective functions for the
new iteration
  z.up(k) = inf; z.lo(k) =-inf;
);
if (mod_payoff.modelstat<>%ModelStat.Optimal% and
    mod_payoff.modelstat<>%ModelStat.Integer Solution%,
   abort 'no optimal solution for mod_payoff');

file fx / C:\... /;
file fxa / C:\.../;
file fxaa / C:\.../;

put fx ' PAYOFF TABLE'/   ;
loop (kp,
   loop(k, put fx payoff(kp,k):12:2);
   put fx /;
      );
put fx/;

minobj(k)=smin(kp,payoff(kp,k));
maxobj(k)=smax(kp,payoff(kp,k));

* gridpoints are calculated as the range (difference between max
and min) of
* the 2nd objective function from the payoff table
$if not set gridpoints $set gridpoints 29

Set g              grid points /g0*g%gridpoints%/
    grid(k,g)      grid

Parameter
    gridrhs(k,g)  rhs of eps-constraint at grid point
    maxg(k)       maximum point in grid for objective
    posg(k)       grid position of objective
    firstOffMax, lastZero some counters
*    numk(k) ordinal value of k starting with 1
    numg(g)       ordinal value of g starting with 0
    step(k)       step of grid points in objective functions
    jump(k)       jumps in the grid points traversing;
```

```
lastZero=1; loop(km1, numk(km1)=lastZero; lastZero=lastZero+1);
numg(g) = ord(g)-1;

grid(km1,g) = yes;
maxg(km1)   = smax(grid(km1,g), numg(g));
step(km1)   = (maxobj(km1)- minobj(km1))/maxg(km1);
gridrhs(grid(km1,g))$(dir(km1)=-1) = maxobj(km1) -
numg(g)/maxg(km1)*(maxobj(km1)- minobj(km1));
gridrhs(grid(km1,g))$(dir(km1)= 1) = minobj(km1) +
numg(g)/maxg(km1)*(maxobj(km1)- minobj(km1));

put fx / ' Grid points' /;
loop (g,
   loop(km1, put gridrhs(km1,g):12:2);
   put /);
put / 'Efficient solutions' /;

* Walk the grid points and take shortcuts if the model becomes
infeasible or
* if the calculated slack variables are greater than the step
size
posg(km1) = 0; iter=0; infeas=0; start=jnow;

repeat
  rhs(km1) = sum(grid(km1,g)$(numg(g)=posg(km1)),
gridrhs(km1,g));
  solve mod_epsmethod maximizing a_objval using lp;
  iter=iter+1;
  if (mod_epsmethod.modelstat<>%ModelStat.Optimal% and
      mod_epsmethod.modelstat<>%ModelStat.Integer Solution%,
    infeas=infeas+1;
    put iter:5:0, '  infeasible' /;
    lastZero = 0; loop(km1$(posg(km1)>0 and lastZero=0),
lastZero=numk(km1));
    posg(km1)$(numk(km1)<=lastZero) = maxg(km1);
  else
    put iter:5:0;
    loop(k, put z.l(k):12:2);

put fxa /'Abatement per measure (Res1-7,Ser1,Ind1-2,Rtr1-3,Agr1)
[ktCO2e]'/;
loop(t,
     loop (j$(ord(j)<=14), put a.l(t,j));
put /;
     );

put fxaa/'Abatement per measure (Res1-7a,Rtr1-2a)[ktCO2e]'/;
```

```
loop(t,
     loop (j$(ord(j)>14), put a.l(t,j));
put );
jump(km1)=1;
*   find the first off max (obj function that hasn't reach the
final grid point).
*   If this obj.fun is k then assign jump for the 1..k-th
objective functions
*   The jump is calculated for the innermost objective function
(km=1)
    jump(km1)$(numk(km1)=1)=1+floor(sl.L(km1)/step(km1));
    loop(km1$(jump(km1)>1), put '   jump');
     put fx/;
      );
* Proceed forward in the grid

firstOffMax = 0;
  loop(km1$(posg(km1)<maxg(km1) and firstOffMax=0),
     posg(km1)=min((posg(km1)+jump(km1)),maxg(km1));
firstOffMax=numk(km1));
  posg(km1)$(numk(km1)<firstOffMax) = 0;
  abort$(iter>1000) 'more than 1000 iterations, something seems
to go wrong'
until sum(km1$(posg(km1)=maxg(km1)),1)= card(km1) and
firstOffMax=0;

finish=jnow; elapsed_time=(finish-start)*60*60*24;

put fx /;
put fx 'Infeasibilities = ', infeas:5:0 /;
put fx 'Elapsed time: ',elapsed_time:10:2, ' seconds' /;
```

Source Code

LTMP model

Version: *Single-Objective*

Application: *Section 5.4.4.* Attainability of the Long-Term Decarbonisation Target

```
Set
j  "mitigation measures"/
Ser1         "CHP-Services"
Ind1         "CHP-Industry"
RTr1         "Promotion of Public Transport"
RTr2         "El. Private & Light Good Conveyance Vehicles"
```

```
RTr3       "Low-Carbon Trucks"
Agr1       "Anaerobic Digestion for Animal Waste"
RTr1a      "Promotion of Public Transport/BEV Buses"
RTr2a      "+El. Private & Light Good Conveyance Vehicles"/

lbj(j)  "measures with loose economic & behavioural barriers" /
Ser1, Ind1, RTr3, Agr1/
sbj(j)  "measures with strict economic & behavioural barriers"
/RTr1,RTr2, RTr1a, RTr2a/

t  "time step of one year"  /2031*2050/

i  "lifetime of mitigation measures"  /1*30/

Scalar  r  "discount rate"  /0.04/;
*economic assessment: public discount rate

Parameter  n(t)  "number of periods";
           n(t)=ord(t);

Parameter  df(t)  "1/discount factor";
           df(t)=1/(1+r)**n(t);

Parameter  ldf(i)  "1/lifetime discount factor";
           ldf(i)=1/(1+r)**ord(i);


Scalar     aobj50;
Table  ac(t,j)  "annual abatement cost of each measure
[Euros/tCO2e]"
$ondelim
$include C:\...
$offdelim
;

Parameter  acdisc(t,j)  "discounted an. abatement cost
[Euros/tCO2e]";
acdisc(t,j) = ac(t,j)*df(t);

Parameter  fa(j)  "full abatement of each measure [ktCO2e]"/
$ondelim
$include C:\...
$offdelim
/;

Table  s(t,lbj)  "annual speed of implemenation for measures
with loose economic & behavioural barriers [ktCO2e/y/y]"
```

```
$ondelim
$include C:\...
$offdelim
;
Parameter ssl(sbj)  "speed of implementation starting level for
measures with strict economic & behavioural barriers
[ktCO2e/y/y]"
$ondelim
$include C:\...
$offdelim
/;

Table sincr(t,sbj)  "annual speed increase for measures with
strict economic & behavioural barriers [%]"
$ondelim
$include C:\...
$offdelim
display sincr;

Parameter ss(t,sbj)  "annual speed of implementation for
measures with strict economic & behavioural barriers
[ktCO2e/y/y]";
ss(t,sbj)$(n(t)=1)= ssl(sbj);
ss(t,sbj)$(n(t)>1)=ssl(sbj)+ssl(sbj)*sincr(t,sbj);

Variables
tc      " total discounted adjusted abatement cost [1000Euros]"
A(t,j)  "annual abatement by measure [ktCO2e]"

Positive Variable a;

Equation
objcost                " total discounted abatement cost
[1000Euros]"
target50               "satisfy target for long-term"
maxpotential(j)  "full abatement upper band for all measures"
speedlimit1(t,lbj)    "annual speed of implementation limits for
lb measures"
speedlimit2(t,sbj)     "annual speed of implementation limits for
sb measures";

objcost.. tc =e= sum((t,j),df(t)*ac(t,j)*sum(i,ldf(i)*A(t,j)));
target50..                       sum((t,j),A(t,j)) =g= aobj50;
maxpotential(j)..                sum(t,A(t,j)) =l= fa(j);
speedlimit1(t,lbj)..             A(t,lbj) =l= s(t,lbj);
speedlimit2(t,sbj)..             A(t,sbj) =l= ss(t,sbj)-(ss(t-
1,sbj)-A(t-1,sbj));
```

```
Model  ltmp  "long-term non-ETS emissions mitigation"
Model"/all/;

Parameter report(*,*,*) "process level report" ;

aobj50 = 997;
solve  ltmp using lp minimizing tc;
report(t,j,'Case1') = A.l(t,j);

Execute_Unload 'LTMP_sop_C1_PS.gdx',A,tc;
Execute 'GDXXRW.EXE LTMP_sop_C1_PS.gdx var=a
rng=C1_P%!a2';
Execute 'GDXXRW.EXE LTMP_sop_C1_PS.gdx var=tc
rng=C1_PS!a24';

Display report;
```