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A multi-objective optimisation approach to explore decarbonisation pathways in a dynamic policy context

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Πολυκριτηριακή Βελτιστοποίηση για τη Διερεύνηση Σεναρίων Μείωσης των Εκπομπών Αερίων του Θερμοκηπίου

Χρύσω Σωτηρίου και Θεόδωρος Ζαχαριάδης

ΠΕΡΙΛΗΨΗ

Η Ευρωπαϊκή πολιτική για το κλίμα αλλάζει με ραγδαίους ρυθμούς, θέτοντας μέσω της Ευρωπαϊκής Πράσινης Συμφωνίας αυστηρότερους στόχους για μείωση των εκπομπών των αερίων του θερμοκηπίου μέχρι το 2030, με τελικό σκοπό τη μετάβαση σε μηδενικές εκπομπές μέχρι το 2050. Η Κυπριακή Δημοκρατία θα κληθεί να ανταποκριθεί στις νέες φιλόδοξες δεσμεύσεις. Επιπρόσθετα, υπάρχει αβεβαιότητα σχετικά με την προσπάθεια μείωσης των εκπομπών που θα απαιτηθεί από κάθε κράτος-μέλος της ΕΕ – άρα και από την Κύπρο.

Σε αυτό το δυναμικό πλαίσιο, η παρούσα μελέτη παρέχει πληροφόρηση στους υπεύθυνους λήψης αποφάσεων της χώρας, μέσω Πολυκριτηριακής Βελτιστοποίησης, για τις δυνατότητες επίτευξης υψηλότερης μείωσης εκπομπών για την περίοδο 2021-2030 σε σχέση με τις υφιστάμενες δεσμεύσεις της Κύπρου, διερευνώντας την αλληλεπίδραση μεταξύ μεγαλύτερης περιβαλλοντικής φιλοδοξίας και υψηλότερου κόστους. Η ανάλυση εφαρμόζεται σε μέτρα που επηρεάζουν τους οικονομικούς τομείς οι οποίοι δεν εμπίπτουν στο Ευρωπαϊκό Σύστημα Εμπορίας Δικαιωμάτων Εκπομπών. Το κάθε μέτρο χαρακτηρίζεται από τρία μεγέθη: το προεξοφλημένο κόστος εφαρμογής, την αποτελεσματικότητα ως προς τη μείωση εκπομπών και την ταχύτητα υλοποίησης.

Από την ανάλυση προκύπτει ότι η μέγιστη εφικτή μείωση εκπομπών έως το 2030 είναι 35% σε σχέση με το 2005. Η τρέχουσα φιλοδοξία του 24% μπορεί να επιτευχθεί και να αποφέρει ταυτόχρονα καθαρά κοινωνικά οφέλη, αλλά καθώς μετακινούμαστε σε αυστηρότερους περιβαλλοντικούς στόχους, παρατηρείται και αύξηση του κόστους. Στην περίπτωση όπου λαμβάνεται επιπλέον υπόψη το εξωτερικό κόστος εκπομπών αερίων θερμοκηπίου και ατμοσφαιρικών ρύπων, η λύση με το χαμηλότερο κόστος προσφέρει μείωση εκπομπών περίπου 32% και μπορεί να επιφέρει κοινωνικά οφέλη άνω του ενός δισεκατομμυρίου ευρώ. Για την υλοποίηση αυτού του στόχου, απαιτούνται δημόσιες δαπάνες ίσες με περίπου 3% του ετήσιου ΑΕΠ της Κύπρου για την περίοδο μελέτης 2021-2030.

CONTENTS

A multi-objective optimisation approach to explore decarbonisation pathways in a dynamic policy context

Chryso Sotiriou, Theodoros Zachariadis*

Abstract

Climate policy is changing fast in the EU, 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 EU member states. This paper develops a multi-objective optimisation framework to provide insights to decision-makers in this policy context by exploring trade-offs between stronger decarbonisation goals and higher costs. Applying this approach for Cyprus, we find that the maximum achievable abatement for the EU Effort Sharing sectors corresponds to a 35% target. The current 24% ambition can be achieved with net social benefits, but the transition to higher abatement results in positive costs with a gradual rate of increase. 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 least-cost solution delivers an abatement of about 32% and can yield social benefits of more than one billion Euros'2020. Regarding public expenditures, it requires 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 but 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. Although the modelling framework has been developed for a specific country and is tailored to the specific EU policy circumstances, the proposed methodology is entirely suitable for other world regions with a demanding decarbonisation roadmap.

Keywords: Climate change mitigation; Emissions abatement; Pareto set; Policy formulation

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1. Introduction

Compared to most other parts of the world, the European Union (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 (UNFCC, 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 greenhouse gases (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[1].

An earlier decision, adopted by EU leaders in 2014 under the 2030 Energy and Climate Framework, was to reduce GHG emissions by 40% in the year 2030 compared to those of 1990. Three pieces of climate legislation implement this target; the EU Emissions Trading System (ETS), the Effort-Sharing Regulation (ESR) and the Land Use, Land-Use Change and Forestry Regulation. Additionally, this framework of policy objectives of the years 2021-2030 includes key targets regarding the increase in the share of renewable energy and energy efficiency improvement by at least 32% and 32.5%, respectively. In view of the European Green Deal, however, the GHG emission reduction target is considered inadequate. With the 2030 Climate Target Plan initiative of the European Green Deal, the 2030 objective is currently under revision, with the declared aim to increase the target to a 50-55% 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. An additional initiative under the Green Deal includes the European Climate Pact for all parts of society in climate action. Alongside reducing greenhouse gas emissions, the EU Adaptation Strategy aims to make Europe climate resilient by 2050.

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. Measures taken at the EU level are putting

[1] 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

constraints on these 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 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.

Decarbonisation seems to be particularly challenging for these ESR (or 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 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 highly unlikely to comply with the 2050 goal.

Expanding on our previous work, this paper presents a Multi-Objective Mathematical Programming (MOMP) approach that considers the current policy challenges. We develop a Pareto-optimal front (PF) 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

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

[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

strategies up to 2030 in a way that is closer to the socially optimal solution. Finally, we explore the investment needs and public expenditures required for implementing specific policy mixes and assess these mixes' feasibility 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 paper goes beyond existing work in several ways. A main feature is that it adopts a tailor-made modelling framework that explicitly addresses the EU policy context, focusing on emissions outside the EU ETS that pose specific challenges, as explained above. This enables the assessment of several different mitigation measures across all non-ETS economic sectors, such as transport, buildings, light industry, and agriculture. Conversely, as TABLE 1 indicates, previous studies applying multi-objective optimization for emissions reduction and climate change mitigation appear to focus mainly on a specific sector only.

Furthermore, in contrast to previous work, our approach explores the interactions between decarbonisation in the medium and longer term. It does so by addressing the new challenging EU-wide climate targets for 2030 as part of a broader European Green Deal programme with a view to the ultimate carbon neutrality goal of 2050. Besides costs and abatement potential, it considers the implications for public finances and the level of economy-wide investments and includes an alternative assessment where policy optimisation is driven by a combination of abatement costs and the avoided external costs of air pollution. Finally, this is the first study that explores decarbonisation pathways for Cyprus' non-ETS sectors with a MOMP approach.

TABLE 1

Overview of published applications of multi-objective optimization for emissions reduction and climate change mitigation

Authors	Application Level	Application Field	Time Scale
Adedeji et al., 2020	National: Brunei	Energy sector planning	2011-2035
Dorotić et al., 2019	Local: City in Croatia	District heating and cooling operation	one year
Fesanghary et al., 2012	Building: US (southern)	Single-family house building envelope design	lifetime 25 years
Flores et al., 2015	National: Argentina	Energy resources investment planning	2010-2030
Forouli et al., 2019a	Regional: EU	Technological portfolios for power generation	2020-2050
Forouli et al., 2019b	National: Greece	Budget allocation for energy efficiency measures	2018-2020
Gharavi et al., 2015	Area: Northern region of Iran	Hybrid green power systems design	lifetime 20 years
Jing et al., 2018	Buildings: Cities in China	Distributed energy systems planning	10 years
Katsigiannis et al., 2010	City: Chania	Small autonomous hybrid power systems design	lifetime 20 years
Murray et al., 2020	Buildings: Suburb town in Switzerland	Decentralised multi-energy systems design	2018, 2035, 2050
Santibanez-Borda et al., 2021	National: UK Southern North Sea	Offshore natural gas production networks design	investment horizon 10 years
Schwartz et al., 2016	Listed Building: Sheffield	Existing buildings refurbishment design	lifetime 60 years
Xiong et al., 2018	Area: Central Beijing	Urban water supply systems design	2020,2030
Jeong et al., 2019	Building: South Korea	Energy efficiency improvement for deteriorated multi-family housing complexes	24 years
He et al., 2021	National: China	Energy efficiency improvement in industrial sectors	2016-2035
Rosso et al., 2020	Building: Rome	Energy retrofit on existing building stock	one year

The modelling framework is applied for Cyprus, 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 paper come from an in-depth exploration of the country's emissions abatement potential. 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 article is structured as follows: Section 2 comprises a description of the models and the methodological frameworks applied. The application and the results of the proposed approach in a real-world case study are illustrated in Section 0. Concluding remarks and implications for policy are given in Section 4. Finally, Appendix A provides a detailed description of the model.

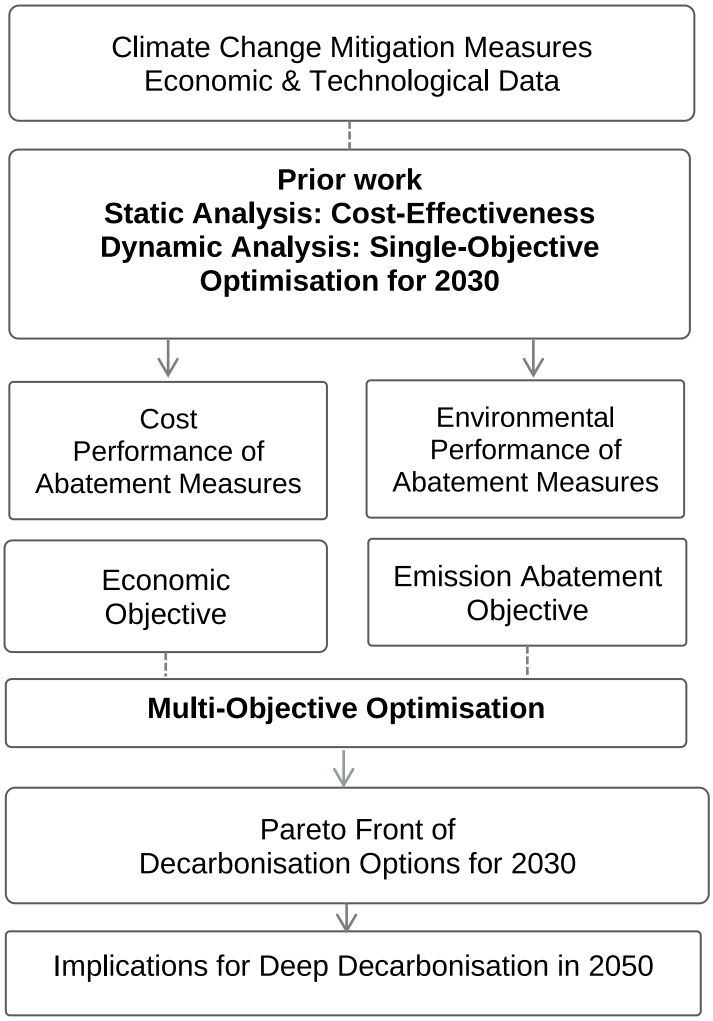
2. Adopted approach

To support policymakers in light of the future changes in emission reduction targets set by the EU, our 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 method to solve the MOMP problem. We applied an improved version of the epsilon constraint (ε-constraint) method to be explained below, and coded it in the General Algebraic Modelling System (GAMS).

Once the problem was formulated, FIGURE 1 displays the next steps. The MOMP model presented in this paper builds on previous work that involved a static cost-effectiveness assessment (Sotiriou et al., 2019) and the formulation of a dynamic optimisation model with a single objective to minimise the total abatement cost (Sotiriou and Zachariadis, 2019). These previous approaches furnished the MOMP model with data about each measure's abatement cost and potential. We then applied the MOMP model with the aid of previous data and calculations as well as additional data collected and assumptions made in the frame of this study.

FIGURE 1

Methods applied



2.1. Multi-objective optimisation

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 optimising one objective function considering all the problem's parameters, so-called Single-Objective Optimisation (SOO), subject to constraints. However, many real-world applications require the simultaneous optimisation of several objectives (Chiandussi et al., 2012), which may be conflicting ; a decrease of one objective functions' value leads to an increase of the other objective function's value. MOMP is concerned with this type of decision-making problem.

In MOMP, the optimality is replaced by Pareto optimality (Pareto, 1906) or efficiency. The result of the optimisation process is expressed as a set of Pareto solutions, representing optimal trade-offs between given criteria. The plot of the objective functions, whose non-dominated vectors are in the Pareto optimal set, is called the PF.

Based on the classification of Hwang and Masud (1979), our study falls into posteriori or generation methods where the involvement of the decision-maker happens at a later stage when all the information is on the table. Among the most popular methods for generating representations of the PF are the weighted sum and 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). On the other hand, in the ε-constraint method, one objective function is optimised, while the other objective functions are transformed into constraints (Haimes et al., 1971). By parametric variation on the right-hand side of the constrained objective functions, the efficient solutions of the problem are produced. 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 optimization 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/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 AUGMECON2, an improved version of AUGMECON (Mavrotas and Florios, 2013). The introduction of the bypass coefficient is being made, exploiting the information from the slack/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.

2.2 Formulation of the optimisation problem

The decision-maker's problem, as described in Sotiriou and Zachariadis (2019), only minimises economic costs, while a constraint holds on GHG emissions. Expanding this cost-optimal GHG reduction problem, we introduce the emission reduction constraint mentioned above as an objective function. The two criteria for optimisation are a) the minimisation of the total discounted cost of abatement and b) the maximisation of total GHG emissions abatement achieved through the implementation of each policy mix. In this way, we balance the costs and the achievable abatement potential by constructing a PF. This allows insights into the trade-offs between the two objectives and, since the analysis is carried out in the EU policy context, it enables decision-makers to choose a policy mix depending on the GHG abatement goal to be finally adopted by EU leaders.

The consideration of both a cost objective function and an emissions abatement objective function leads to the bi-criteria optimisation presented in Appendix A. The abatement cost coefficients found in Equation A 1 are expressed in Euros per tonne of carbon dioxide equivalent (CO_2e) and include the annual investment, maintenance, and fuel costs associated with each measure. 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 decision variables of the model are the annual GHG abatement realised by each measure[4]. Three constraints are imposed on the decision variables. First, there is an upper limit to the achievable full abatement potential (Equation A 3) up to a year due to financial, human, or natural resources constraints. 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 A 4). Finally, for a subset of measures associated with strong economic and behavioural barriers, an additional constraint assumes that annual values of implementation speed depend on the cumulative amount of abatement that has already been deployed up to that year (Equation A 5).

TABLE 2 summarises the optimisation problem formulated in the context of this study. All mathematical formulations are presented in Appendix A.

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[4] We consider the three major GHG, i.e. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

TABLE 2

Overview of the optimisation problem

Sets	
j	Mitigation measures available for consideration
t	Time step of a year
Decision Variables	
$a_{j,t}$	Abatement achieved through the implementation of measure j for the time period t
Objective Functions	
$minimize\ Z_1$	Minimisation of the total discounted cost of abatement, Equation A 1
$maximize\ Z_2$	Maximisation of the achievable abatement, Equation A 2
Constraints	
Maximum abatement	Achievable maximum abatement potential for each measure, Equation A 3
Speed limit 1	Maximum speed of implementation that can be achieved per year for the subset of measures j with loose economic and behavioural barriers, Equation A 4
Speed limit 2	Maximum speed of implementation that can be achieved per year for the subset of measures j with strict economic and behavioural barriers, Equation A 4
Speed limit 3	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 A 5

2.3 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, we refer to those measures as ‘basic’, presented in the upper part of TABLE 3.

In the residential sector, the focus has been on energy renovations of 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 431,059 residential buildings, single-family (SF) buildings constructed between 1991 and 2007 represent 24% of the total stock, while multi-family (MF) 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.

TABLE 3

Description of the Basic and Advanced Mitigation Measures

Notation	Description	Sector
Basic Measures		
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 & Light Goods Conveyance Vehicles	Road Transport
RTr3	Low-Carbon Trucks	Road Transport
Agr1	Anaerobic Digestion for Animal Waste	Agriculture
Advanced Measures		
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 & Light Goods Conveyance Vehicles+	Road Transport

TABLE 4

Maximum potential of the basic and advanced measures in residential buildings up to 2030 expressed in number of buildings to be renovated and the share that those renovations hold in the total building stock

Notation	Buildings Renovated	Share in Total Stock	Share in SF/MF stock
Basic Measures			
SF constructed between 1991-2007			
Res4	7,500	1.7%	7.1%
Res7	7,500	1.7%	7.1%
Total	15,000	3.5%	14.3%
MF constructed between 1991-2007			
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%
Advanced Measures			
SF constructed between 1991-2007			
Res4a	45,000	10.4%	42.8%
Res7a	45,000	10.4%	42.8%
Total	90,000	20.9%	85.6%
MF constructed between 1971-1990			
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%

It is important to highlight that the implementation of those actions is assumed on the basis of independent interventions and do not consider several measures to be realised for the same building. Any interactions are avoided, which is necessary to prevent double-counting and thus to overestimate emissions reduction potential. TABLE 4 summarises the extent of implementation. The number of interventions foreseen for residential buildings up to 2030 is based on Vougiouklakis et al. (2017). The latter study empirically assessed the Cypriot building sector's economically viable energy efficiency potential, given real-world financial, technical and behavioural aspects, as justified in detail by Zachariadis et al. (2018). It is important to note that the energy efficiency measures for existing buildings 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 combined heat and power (CHP or cogeneration) units fuelled by liquefied petroleum gas (LPG), which will replace oil-fired boilers for hot water needs. The same measure was also 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 interventions: (a) 7% shift of passenger-kilometres (pkm) from private cars (fuelled by gasoline/diesel) to buses (fuelled by diesel) will occur up to 2030 (RTr1) – an assumption based on European Commission (2017), (b) all newly registered private & light goods vehicles will be electric up to 2040 (RTr2), and (c) new trucks sold up to 2040 will use Compressed Natural Gas (CNG) as a fuel, and a moderate introduction of electric trucks will occur up to 2050 (RTr3).

Finally, for the agriculture and waste sector, we assume that an extra amount of waste, both from animal farms (i.e., manure management) and municipal solid waste will be directed to anaerobic digestion per year to be converted to biogas and used for cogeneration (Agr1).

As explained above, these interventions have been included in our previous modelling work. Sotiriou et al. (2019) concluded that if they are counted together with the already adopted policies and measures of Cyprus's government, they are insufficient for meeting the current 24% non-ETS emission reduction commitments of Cyprus up to 2030. In light of an even more stringent mitigation target, this paper expands the list of emission abatement measures to twenty-three mitigation options; the additional measures, so-called advanced, capture an expansion of the basic ones and are presented in the lower part of TABLE 3. The Promotion of Public Transport using BEV buses (RTr1a) constitutes an exception as it is a new technological solution where we introduce battery-electric buses, instead of diesel-powered (RTr1) to satisfy the shift from private to public transportation.

The measures Res4a and Res7a are defined in a way that, together with the respective basic measures Res4 and Res7 will cover renovations in the total stock of single-family dwellings built between 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 building 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 4 summarises the above information.

For road transport, two advanced measures were considered. One relates to the promotion of public transport, where we assume an additional 7% shift of passenger kilometres from private cars to battery electric buses from 2025 up to 2030, reaching a 23% modal shift in 2050 (RTr1a). The second intervention (RTr2a) is a modified version of basic measure RTr2, with a faster penetration of electric cars to raise the amount of abatement that can be attained. TABLE 5 presents the potential for all road transport measures. The advanced measures, as discussed below, are associated with higher abatement costs.

TABLE 5

Maximum potential for basic and advanced road transport measures

Measure		**mio pkm***	**Share of total pkm**
RTr1	*by 2030*	434	7%
	by 2050	434	7%
RTr1a	*by 2030*	434	7% from 2025-2030
	by 2050	1,426	23%
Measure		**Vehicles***	**Share of newly registered**
RTr2/Private	*by 2030*	55,000	100% by 2040
	by 2050	487,500	
RTr2/Light Good Conveyance	*by 2030*	-	100% from 2030-2040
	by 2050	46,500	
RTr2a/Private	*by 2030*	300,000	100% by 2025
	by 2050	525,000	
RTr2a/Light Good Conveyance	*by 2030*	12,000	100% by 2030
	by 2050	92,000	

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

To implement the optimisation problem, parameters for all the above measures have to be defined. For this purpose, we use the marginal abatement cost methodology of Sotiriou et al. (2019) 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 MOMP model.

TABLE 6

Parameters of the model related to the environmental performance of the measures – Full abatement up to 2030 and 2050, initial speed of implementation and assumptions regarding the change of the speed during the study period

Measure	$A_{j,2030}$ [$ktCO_{2e}$]	$A_{j,2050}$ [$ktCO_{2e}$]	Initial $s_{j,t}$ [$ktCO_{2e}$/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 increase up to 2050
Ind1	5.29	33.94	0.49	slight increase up to 2050
Ind2	0.74	0.74	0.07	constant up to 2050
RTr1	29.46	70.09	2.79	gradual increase 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 increase up to 2050
Agr1	10.5	43.83	1.00	gradual increase 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
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 increase up to 2030;
RTr2a	603.58	951.69	13.55	gradual increase 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 Equation A 5 is applied. This means that the implementation speed is not necessarily fixed for each year; TABLE 6 reports the relevant assumptions.

TABLE 7

Evolution of abatement costs over time for the mitigation measures assumed in the models. The abatement cost, including external costs of GHG and pollutants, is also presented

Measure	$AC_{j,2021}$ [€/tCO_{2e}]	$AC^{Ext}_{j,2021}$ [€/tCO_{2e}]		Variation of $AC_{j,t}$ during the study period
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
Res5	59.4	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	69.0	More cost-effective	<0	10% reduction every 5 years
RTr2	59.1	More cost-effective	<0	15% reduction every 5 years
RTr3	95.2	More cost-effective	<0	10% reduction every 5 years
Agr1	3.9	More cost-effective	<0	10% reduction every 5 years
Res1a	>1,000	More cost-effective	>1,000	constant up to 2030
Res2a	283.8	More cost-effective		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	71.2	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

Considering the costs of the basic mitigation measures, shown in TABLE 7, they can be classified into three main groups: measures with net social benefits appearing with negative abatement costs, measures with modest abatement costs, and measures with high costs (greater than 1,000 Euros per tonne of CO_2e). These refer to data that is 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 7.

With regard to the advanced abatement measures that have been defined for the purpose of this analysis, since they represent an expansion of the corresponding basic measures, we assume that they have higher costs than the basic ones. The number of building interventions allocated for the basic measures reflects Cyprus' household sector's realistic potential, as determined by Vougiouklakis et al. (2017). Any enhancement of this type of measure will require the removal of financial, technical, and behavioural barriers, resulting in higher abatement costs. We, therefore, assume a cost increase in the following way: for the advanced measures of single-family buildings of the 1991-2007 period, the costs gradually double up to 2030, while for the advanced multi-family buildings of 1971-1991 and electric vehicles (RTr2a) a gradual cost increase of 50% occurs by 2030.

We also perform an alternative optimisation by including in the abatement cost the external costs of the emissions of GHG as well as of air pollutants nitrogen oxide (NOx), sulphur dioxide (SO_2), and particulate matter (PM). Air quality improvement is usually a co-benefit of climate policy because, in most cases, a GHG abatement measure reduces air pollutant emissions as well. To perform this type of assessment, one has to calculate the emissions of the above gases generated from a measure and those avoided thanks to this measure and multiply the corresponding change by the marginal damage cost, expressed in Euros per tonne of each gas. Emission calculations for air pollutants were based on the internationally accepted methodology recommended in the EMEP/EEA Emissions Inventory Guidebook (EEA, 2013) with the aid of national data on fuel quality. As far as external costs are concerned, for GHG emissions, we used the assessment of marginal damage costs made by the U.S. Environmental Protection Agency (IWG, 2013). 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. Marginal damage costs for the case of Cyprus have been adapted from those relevant international studies by Zachariadis and Hadjikyriakou (2016); values expressed in Euros per tonne of pollutant are presented in TABLE 8. 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 (third column of TABLE 7).

TABLE 8

External costs of GHGs and the three pollutants considered – NOx, PM, and SO_2. See main text for explanation of data sources

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

3. Application and Results

Implementation of the model involves computing the optimal mix of measures by simultaneously considering the mutually competitive objectives to minimise total cost and maximise non-ETS emissions abatement. Two types of solutions have been obtained from the MOMP 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, $AC_{j,t}^{Ext}$

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 “With Existing Measures” (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_2e and comprises a 24% reduction in non-ETS emissions compared to those of the year 2005. According to the WEM projected evolution of emissions up to 2030, Cyprus’s legal commitment amounts to 587 thousand tonnes of CO2e that must be reduced by 2030 compared to WEM. If new EU climate targets may demand raising Cyprus’s ambition to 35% abatement compared to 2005, emissions in 2030 will have to decline by 1,056 thousand tonnes of CO_2e.[5]

Based on our objective functions, the leftmost optimal solution of the produced PF has the lowest cost and mitigation impact. That point can be seen as an optimum for the case in which

[5] As 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 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.

only the cost objective is considered. The equivalent applies for the rightmost optimal solution, where only the maximisation of abatement is accounted for, and this point corresponds to the highest mitigation impact and the higher level of cost. Summarising, the minimum cost solution leads to the worst environmental performance, while the maximum abatement potential shows the largest cost. Any optimal solution found between the two sets mentioned above represents intermediate values for both criteria.

3.1. Balancing economic and environmental criteria

FIGURE 2 illustrates the basic PF obtained by applying the AUGMECON2 method. The different levels of the 2030 non-ETS emissions reduction target, current and increased, are also presented with the vertical dash and solid grey 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 3, and therefore could not lead to the attainment of the 24% target.

The MOMP solution space includes a variety of policy mixes. In twenty-four Pareto solutions 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 grey 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 the cost savings (mainly reduced fuel costs) throughout the lifetime of the interventions. However, if the EU goal becomes considerably more ambitious, the corresponding optimal solutions appear with gradually – but smoothly – increasing costs. An exception is the extreme right solution, corresponding to over-achieving the 35% objective, which 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_2e.

FIGURE 2

Basic Pareto Front

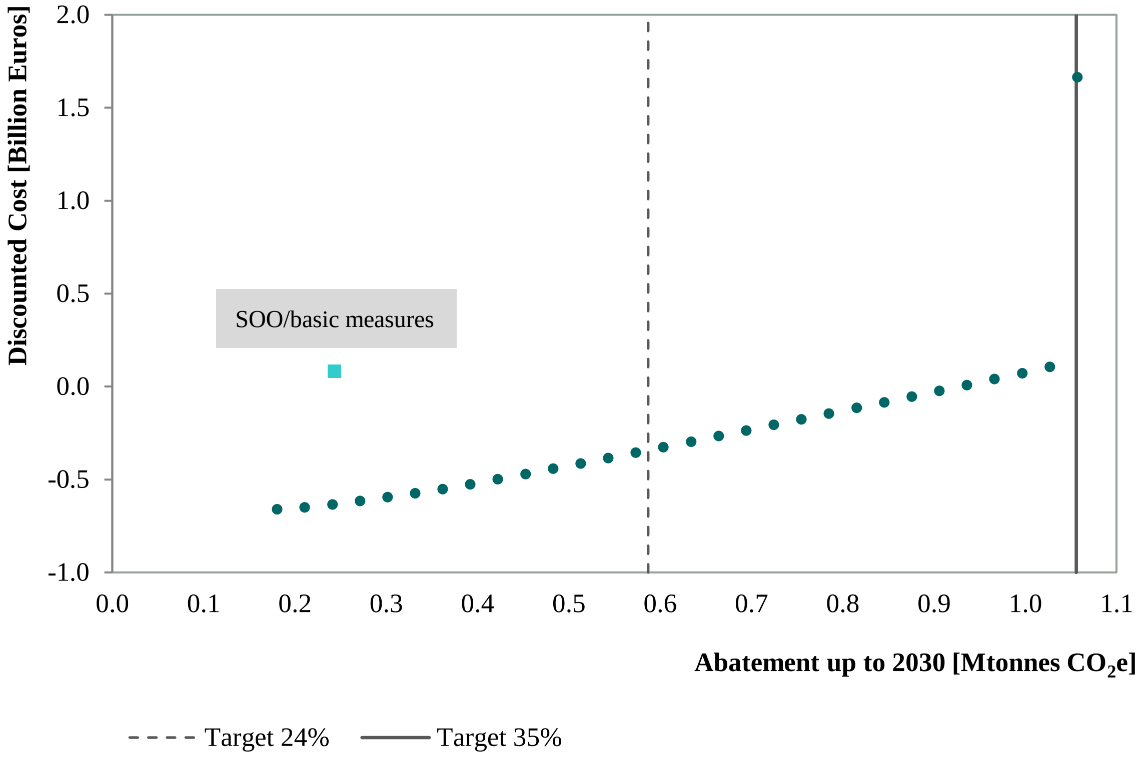
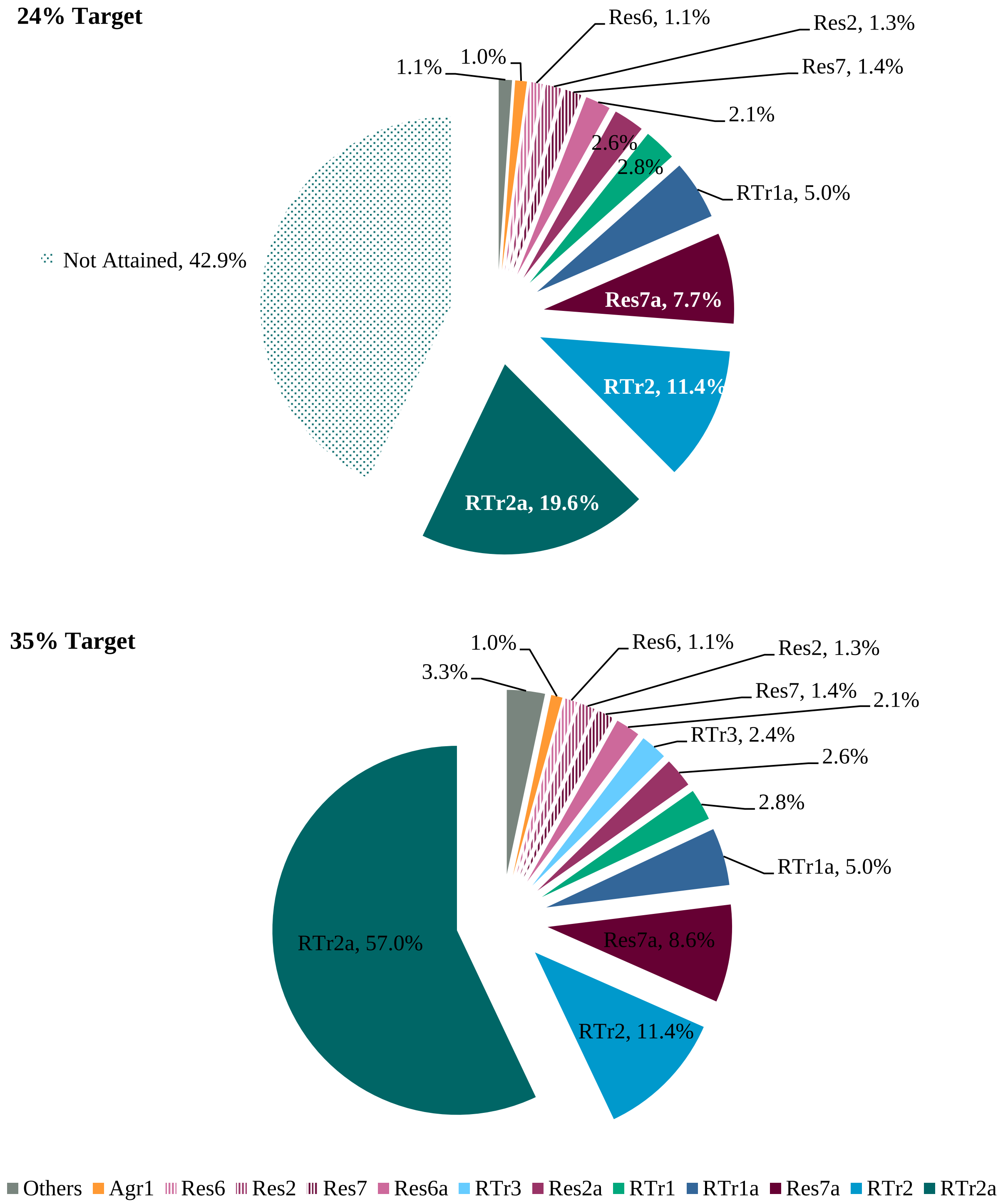


FIGURE 3 illustrates the policy mix associated with the two benchmark Pareto solutions mentioned above, i.e., achieving the already legislated 24% reduction target and moving to a more ambitious 35% target, respectively. The figure presents the percentage contribution of each measure to total abatement 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 considerable emission reduction in non-ETS sectors can be achieved. Concerning 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 regarding non-ETS emissions, i.e., direct emissions from fuel combustion.

FIGURE 3

Policy mix for two selected Pareto solutions, 24% and 35% emissions reduction – each measure's percentage share of the total available mitigation potential up to 2030



Note: See TABLE 3 for a description of the measures shown in the legend.

Another obvious aspect from both FIGURE 2 and FIGURE 3 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, to be decided by EU leaders during 2021, exceeds 35%, this seems to be infeasible. Any gap in meeting the target will have to be filled through the use of 'flexibility mechanisms' that may be foreseen in EU legislation – i.e., purchasing emission permits from other countries.

TABLE 9

Extent of implementation for each measure category of the Pareto solutions, which satisfy the 24% and 35% emissions reduction target

			24% Target		35% Target	
Measure's Category	**Individual Measures**	**no. of**	**Basic**	**Advanced**	**Basic**	**Advanced**
Full Renovation	Res1, Res1a	houses	0	0	1,500	3,000
Roof Insulation	Res2, Res2a	houses	14,000	28,000	14,000	28,000
Wall Insulation MF	Res3, Res3a	houses	0	0	1,800	3,600
Wall Insulation SF	Res4, Res4a	houses	0	0	7,500	44,725
Pilotis Insulation	Res5, Res5a	houses	782	0	900	1,800
Heat Pumps MF	Res6, Res6a	houses	4,500	9,000	4,500	9,000
Heat Pumps SF	Res7, Res7a	houses	7,500	40,511	7,500	45,000
Cogeneration in Services	Ser1	CHP units	10	-	10	-
Cogeneration in Industry	Ind1	CHP units	10	-	10	-
Industrial Burner	Ind2		10	-	10	-
Public Transport	RTr1	Mpkm	434	-	434	-
Electric Vehicles	RTr2, RTr2a	vehicles	55,000	87,000	55,000	249,000
Low-Carbon Trucks	RTr3, RTr3a	trucks	0	-	1,500	-
Anaerobic Digestion	Agr1	m^3 of waste	1.9×10^6	-	1.9×10^6	-
Public Transport /BEV Buses	RTr1a	Mpkm	-	434	-	434

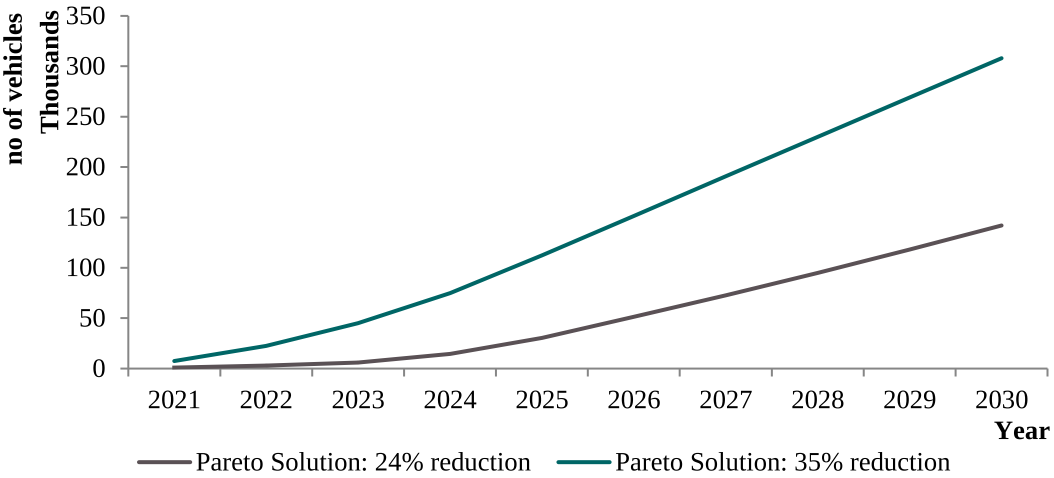
TABLE 9 summarises the extent of implementation for aggregated categories of mitigation actions for the two benchmark Pareto solutions. This provides useful information to policymakers about how much the implementation of each type of measure has to be expanded if the binding abatement commitment moves from 24% to 35%.

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% Pareto solution 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, implementation must be extended to reach the 35% target; as outlined in Section 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 essential to achieve a considerable reduction in non-ETS emissions and appear in both solutions, except for the 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 one of 24%. For this purpose, all newly registered passenger cars from 2025 onwards would have to be electric. This is illustrated in FIGURE 4, 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 related to vehicle charging infrastructure and shifting consumer preferences 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 and is also associated with behavioural change and substantial infrastructure investments.

FIGURE 4

Cumulative penetration of battery electric cars and light goods vehicles

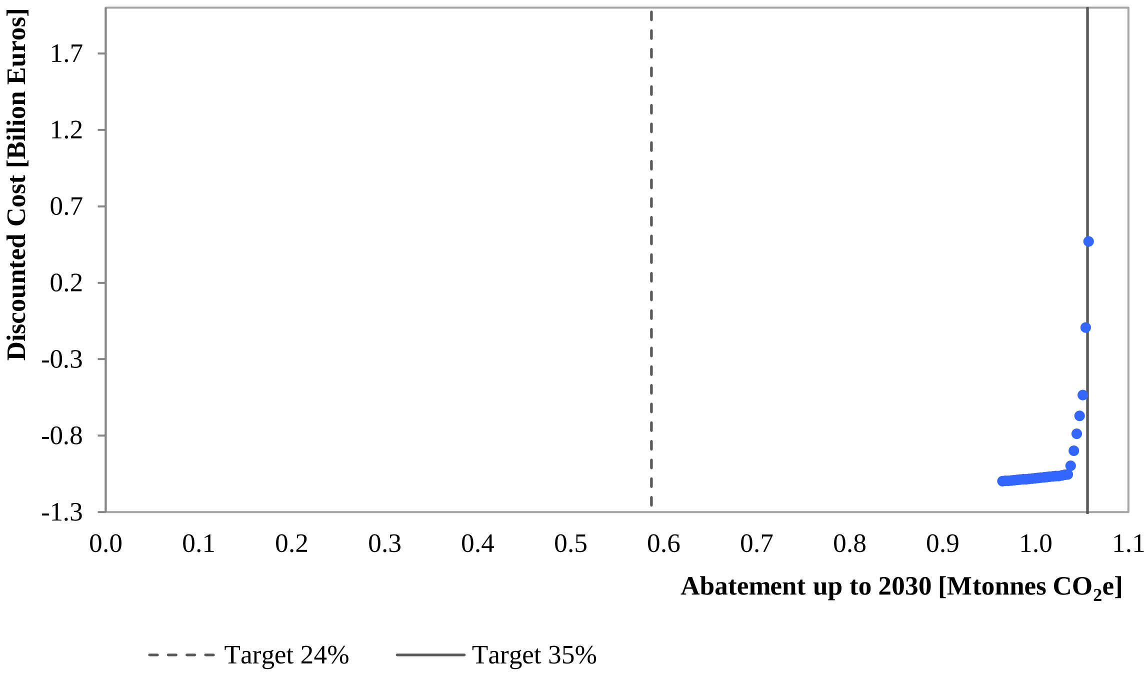


3.2. Co-benefits for air pollution control

As explained at the beginning of Section 0, we 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. In this case, the co-benefit of air pollution reduction thanks to greenhouse gas emission abatement is a driving factor of the produced PF. FIGURE 5, shows the Pareto set of optimal solutions obtained.

FIGURE 5

Pareto Front, including co-benefits of air pollution control

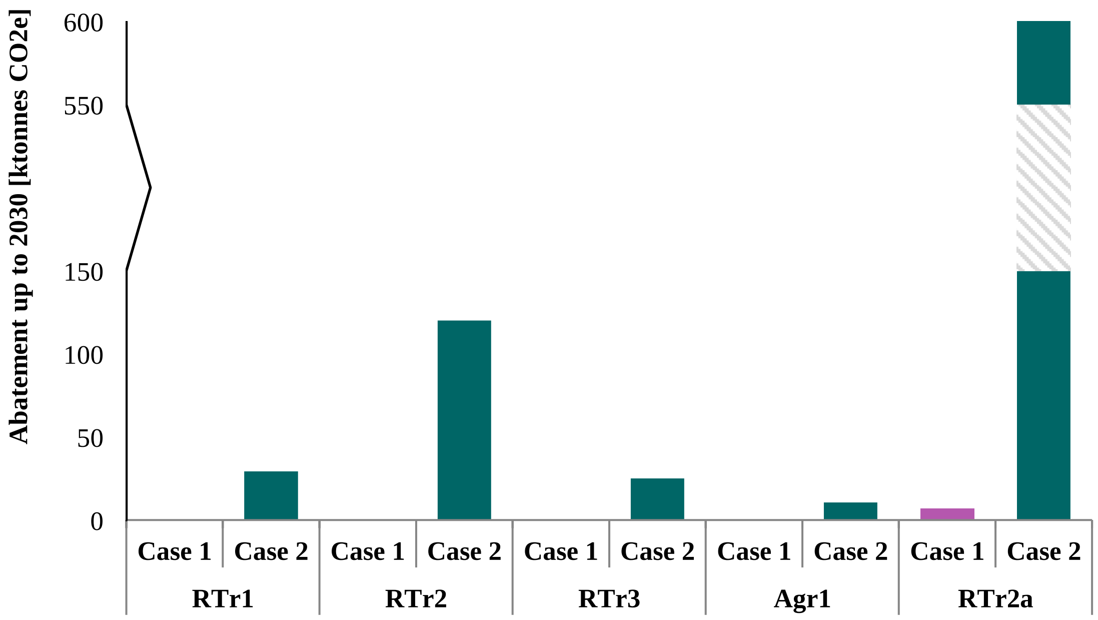


Compared to the solutions of the base case shown in FIGURE 2, the PF moves downwards and to the right. This indicates both a substantial reduction of total abatement costs when the avoided external costs of air pollutants are included and an increase in possible emissions abatement at a given cost. The current 24% emission reduction target for the year 2030, demonstrated with the yellow vertical line, is easily attainable, while the target of 35% decrease can be achieved with lower total discounted costs compared to the basic scenario. Both extreme solutions are obtainable at lower total costs compared to FIGURE 2.

Moreover, the leftmost optimal solution of FIGURE 5 indicates that the minimum total cost, including externalities, can result in higher mitigation than the corresponding leftmost solution of the basic approach. FIGURE 6 justifies this finding by presenting the main differences in the policy mix of the leftmost Pareto solutions 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 7). These measures are associated with a higher abatement potential and are taken up faster, yielding higher mitigation at a lower cost.

FIGURE 6

Main differences in the policy mix of the leftmost Pareto solutions of Case 1 and Case 2



Suppose one matches the Pareto solution of FIGURE 2 with approximately the same total abatement as the leftmost optimal solution of FIGURE 5. In that case, 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 urban 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).

3.3. Total costs, investments, and public expenditures

Cost calculations are conducted from a public policy viewpoint throughout this study, i.e., from a social planner's perspective 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.

TABLE 10

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 without externalities)		**Case 2 (optimisation accounting also for externalities)**
Costs [Billion €] \ Solution	**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 with savings + Permits)	-0.17	1.66	0.09
(Costs with 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

Therefore, to make a useful contribution to public policy, an analysis has to address all three aspects – total costs, investment requirements, and public financing needs. TABLE 10 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 if external costs are also accounted for (i.e., the policy mix that corresponds to the leftmost point of FIGURE 5).

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 more negligible in this case.

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 10) 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_2e in 2020 and reaches 60 Euros per tonne of CO_2e 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 10) 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 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 10) 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.

Regarding 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 Cyprus's annual national GDP 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, but 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.

3.4. Attainability of long-term decarbonisation target

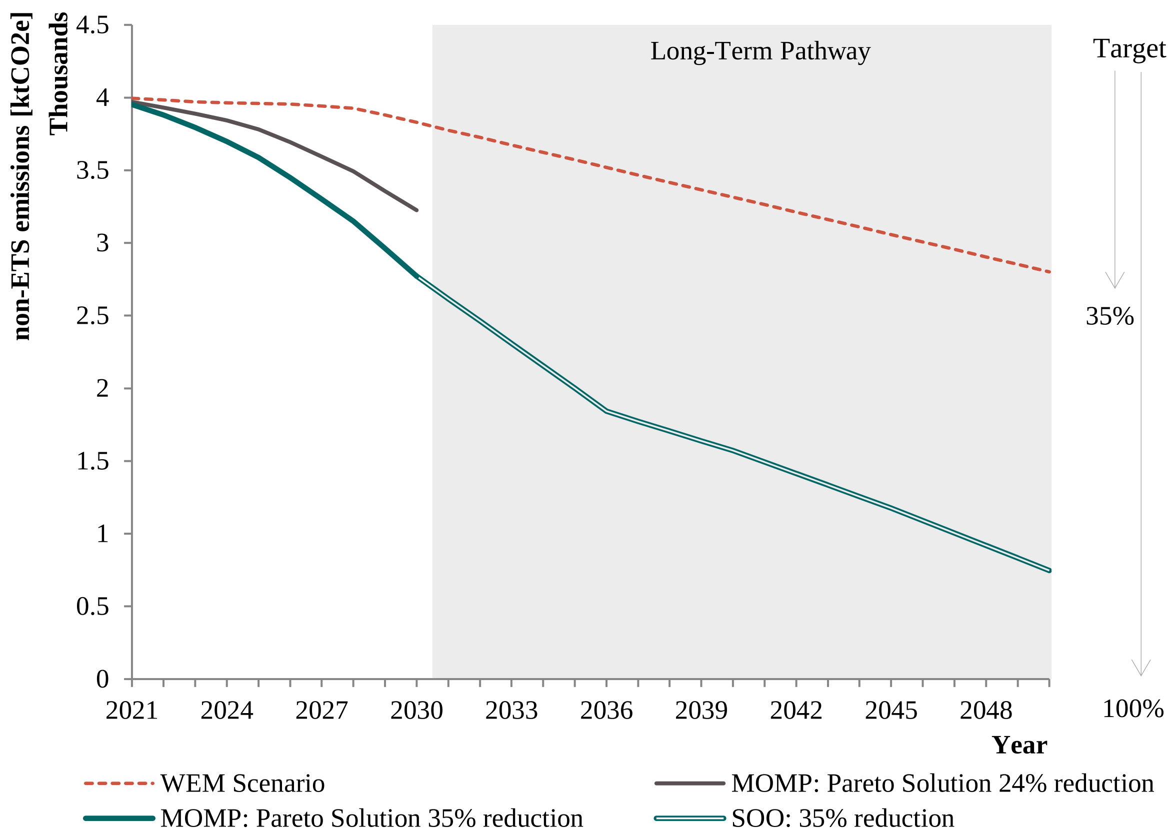
In light of the mid-century climate neutrality objective, it is important to explore the chosen Pareto solutions' long-term potential. For this purpose, post-2030 simulations were carried out with a single-objective version of the model, as the long-term emissions target is fixed. To do so, the environmental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

FIGURE 7 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 as presented in Section 3.1. It compares the temporal evolution of non-ETS emissions for the selected Pareto solutions of FIGURE 2 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 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.

Although the higher ambition of the EU 2030 climate target leads to a low-carbon pathway, 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_2e and 747 thousand tonnes of CO_2e 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 reduction and avoidance of lock-in effects 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 means to achieve climate neutrality in non-ETS sectors by 2050 is left to further research.

FIGURE 7

Evolution of non-ETS emissions from 2021-2030 for specific Pareto solutions of the MOMP of Case 1 and the country's baseline scenario (WEM)



Note: The graph also illustrates the projected emissions from 2030-2050 for the policy mix, leading to a 35% emission reduction in 2030 following a SOO approach.

4. 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 to reduce greenhouse gas emissions and the associated uncertainty about the allocation of effort between EU member states, this paper presented a

MOMP approach that considers the current policy challenges. We developed a Pareto-optimal front 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-calculated this front 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. We also assessed the needs for investments and public expenditures for implementing specific policy mixes. 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 of the authors. 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.

We 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 9, 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.

Our 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 2, 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 given the need to deploy costly measures to attain this target. The picture is somewhat different when decisions are made by factoring in external costs in the optimisation procedure, as shown in FIGURE 5: The costs to comply with a specific target rise faster the more ambitious the target becomes, but in almost all cases 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 in view of 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.

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Appendix A

Detailed description of the multi-objective optimisation model

Objective Functions

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 discounted cost of abatement:

$$minimise\ Z_1 = \sum_j \sum_t AC_{j,t} * a_{j,t}$$

Equation A 1. The first objective is related to the minimisation of the total discounted cost.

Where $a_{j,t}$ is the GHG abatement, 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 the results of a different model performing cost-effectiveness calculations (Sotiriou et al., 2019). The emissions abatement cost includes the annual investment, maintenance, and fuel costs associated with each measure; more details can be found in Appendix A of Sotiriou and Zachariadis (2019). The abatement cost is expressed in Euros per tonne of CO_2e emissions avoided and $a_{j,t}$ is expressed in avoided annual emissions in tonnes of CO_2e.

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

$$maximise\ Z_2 = \sum_j \sum_t a_{j,t}$$

Equation A 2. The second objective function is related to the maximisation of the reduction of GHG emissions.

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. The time period is expanded up to the year 2050, when we introduce the long-term net-zero emission target in the analysis.

Decision Variables and Constraints

The variables of the model are $a_{j,t}$, i.e., the emissions abated by each measure (positive variables) for each year throughout the study period. By modifying the values of the decision variables, the GHG abatement realised by each measure that the different Pareto optimal solutions are created.

Because of constraints in financial, human, or natural resources, there is a maximum cumulative abatement potential that each measure can attain up to 2030 or 2050, depending on the time period under study. An inequality expresses that the upper limit on the achievable full abatement potential per measure:

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

Equation A 3. Upper limit on the achievable full abatement potential per measure.

As those mitigation measures cannot be realised overnight (Vogt-Schilb and Hallegatte, 2014), irrespective of the full abatement potential A_j, each measure has a limit on the implementation speed, expressed in maximum annual abatement that can be achieved per year. That feature is related to the inertia in the uptake of low-carbon technologies and in consumer behaviour (Vogt-Schilb et al., 2015) and in our model is varying over time. The implementation speed is expressed in units of tonnes of CO_2e per year and develops differently for each one of the available measures. There are measures with constant speed throughout the implementation period, and others that start with low implementation speed are gradually increasing. This constraint is formulated as follows:

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

Equation A 4. Maximum speed of implementation that can be achieved per year.

Some emission abatement measures are associated with strong economic and behavioural barriers. For example, investments in public transport take time to yield large benefits because of the time required to build the relevant infrastructure and encourage car drivers to shift to public transport modes. The diffusion of such measures in the economy requires a lot of time. For this subset of measures, we assume that the annual values of the implementation speed depend on the cumulative amount of abatement that has already been deployed up to that year. Any delays in the deployment of these measures will lead to failure to realise the maximum abatement potential.

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

Equation A 5. Annual values of implementation speed depend on the cumulative amount of abatement that has already been deployed up to that year for the subset of measures with strict economic and behavioural barriers.