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“A modelling framework in support of residential energy policy: Assessing transition pathways across local, regional, and national scales”

Doctoral dissertation thesis

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Athens, June 2026

Dimitris Papantonis

*«Ο έρωτας, η εργασία και η γνώση είναι οι
αστείρευτες πηγές της ζωής, αυτές πρέπει να την
κυβερνούν.»*

Abstract (in Greek)

Ο οικιακός τομέας βρίσκεται στον πυρήνα της ευρωπαϊκής ενεργειακής μετάβασης. Αφενός, αντιπροσωπεύει σημαντικό μέρος της συνολικής τελικής κατανάλωσης ενέργειας και των εκπομπών αερίων του θερμοκηπίου· αφετέρου, αποτελεί πεδίο στο οποίο οι επιλογές κλιματικής και ενεργειακής πολιτικής συναντούν άμεσα την καθημερινότητα των πολιτών, επηρεάζοντας το κόστος διαβίωσης, τη θερμική άνεση και την έκθεση των νοικοκυριών σε ενεργειακές διακυμάνσεις. Η σημασία του αποτυπώνεται στο εξελισσόμενο πλαίσιο πολιτικής της Ευρωπαϊκής Ένωσης, όπου η ανακαίνιση του κτιριακού αποθέματος, η έμφαση στην ενεργειακή απόδοση, ο εξηλεκτρισμός, η τιμολόγηση του άνθρακα και η προστασία των ευάλωτων νοικοκυριών αντιμετωπίζονται πλέον ως αλληλένδετες πτυχές.

Παράλληλα, οι ενεργειακές παρεμβάσεις στον οικιακό τομέα εντάσσονται σε ένα περιβάλλον με μεγάλους χρονικούς ορίζοντες επενδύσεων, αργή ανανέωση του κτιριακού αποθέματος και ισχυρή εξάρτηση από υφιστάμενες τεχνολογίες και υποδομές. Επομένως, ο χρόνος, η αλληλουχία και η κατεύθυνση των σημερινών αποφάσεων αποκτούν ιδιαίτερη σημασία, καθώς μπορούν είτε να διευκολύνουν τη μετάβαση προς ένα πιο αποδοτικό και χαμηλών εκπομπών οικιακό απόθεμα είτε να παγιώσουν επιλογές που θα δυσχεράνουν την απανθρακοποίηση σε βάθος χρόνου. Η έγκαιρη και συνεκτική επιλογή διαδρομών μετάβασης είναι, συνεπώς, κρίσιμη για την ευθυγράμμιση της βραχυπρόθεσμης εφαρμογής πολιτικής με τους μακροπρόθεσμους στόχους της κλιματικής ουδετερότητας, της ενεργειακής ανθεκτικότητας και της ενεργειακής δικαιοσύνης.

Στο πλαίσιο αυτό, τα μοντέλα ενεργειακών συστημάτων αξιοποιούνται ευρέως για την υποστήριξη της χάραξης πολιτικής, ιδίως για τη διερεύνηση μακροπρόθεσμων μονοπατιών απανθρακοποίησης και την αξιολόγηση των επιπτώσεων διαφορετικών τεχνολογικών και πολιτικών επιλογών στην εξέλιξη του ενεργειακού συστήματος. Ωστόσο, πολλές υφιστάμενες προσεγγίσεις εξακολουθούν να εξετάζουν τον οικιακό τομέα με ιδιαίτερα συγκεντρωτικούς όρους, χωρίς να αποτυπώνουν επαρκώς τις διαφορές μεταξύ κτιρίων, νοικοκυριών και συνθηκών εφαρμογής της πολιτικής. Οι προσεγγίσεις αυτές μπορεί να είναι χρήσιμες για τον καθορισμό στόχων και τον έλεγχο συνοχής σε εθνικό ή ευρωπαϊκό επίπεδο, αλλά συχνά δεν επαρκούν για την κατανόηση των μονοπατιών μετάβασης στο επίπεδο της υλοποίησης. Περιορίζουν, δηλαδή, τη δυνατότητα να εξεταστεί το πώς επιτυγχάνονται οι μειώσεις εκπομπών εντός του κτιριακού αποθέματος, πώς τα μέτρα πολιτικής μεταφράζονται σε αλλαγές σε επίπεδο νοικοκυριού και πώς οι επιπτώσεις τους διαφοροποιούνται μεταξύ κοινωνικών ομάδων, περιφερειών και τοπικών περιοχών.

Με βάση τα παραπάνω, η παρούσα διατριβή συμβάλλει στη μοντελοποίηση της ζήτησης ενέργειας μέσω της ανάπτυξης πρόσθετων υπολογιστικών δυνατοτήτων στο μοντέλο “Dynamic high-Resolution dEmand-sidE Management¹” (“DREEM”). Το πλαίσιο που αναπτύσσεται υποστηρίζει την αξιολόγηση μονοπατιών ενεργειακής μετάβασης στον οικιακό τομέα σε διαφορετικούς χρονικούς ορίζοντες και χωρικά επίπεδα, διατηρώντας παράλληλα μια «από κάτω προς τα πάνω» αναπαράσταση της ενεργειακής ζήτησης των νοικοκυριών. Για τον σκοπό αυτό, η διατριβή αναπτύσσει και ενσωματώνει στο “DREEM” δύο συμπληρωματικά συστατικά στοιχεία. Το πρώτο επιτρέπει τη συγκέντρωση των προφίλ ενεργειακής ζήτησης των νοικοκυριών σε τοπικό, περιφερειακό και εθνικό επίπεδο, ενώ το δεύτερο διαμορφώνει έναν χώρο σεναρίων, μέσα στον οποίο βασικές παράμετροι της οικιακής ενεργειακής μετάβασης (π.χ., ρυθμοί ανακαίνισης και αντικατάστασης τεχνολογιών θέρμανσης, τιμές ενέργειας, κόστος τεχνολογιών, δημογραφικές μεταβολές, εξέλιξη του κτιριακού αποθέματος, συντελεστές εκπομπών και κόστη που συνδέονται με την τιμολόγηση του άνθρακα) εξελίσσονται διαχρονικά.

¹ <https://www.sciencedirect.com/science/article/abs/pii/S0196890419313469>

Το πλαίσιο μοντελοποίησης εφαρμόζεται στον ελληνικό οικιακό τομέα σε εθνικό, περιφερειακό και τοπικό επίπεδο, εξετάζοντας μονοπάτια ενεργειακής μετάβασης μέσα από τις αλληλένδετες διαστάσεις της απανθρακοποίησης, της ενεργειακής ανθεκτικότητας και της ενεργειακής δικαιοσύνης. Στις τρεις εφαρμογές, η ανάλυση διερευνά πώς διαφορετικές στρατηγικές μετάβασης, οι οποίες μπορεί να διαφοροποιούνται ως προς τη φιλοδοξία των ανακαίνισεων, την έμφαση σε διαφορετικά καύσιμα και τεχνολογίες θέρμανσης και την εξέλιξη κρίσιμων παραμέτρων, όπως οι τιμές ενέργειας, διαμορφώνουν την ενεργειακή κατανάλωση, τις εκπομπές διοξειδίου του άνθρακα και τα κόστη μετάβασης έως το 2050.

Σε εθνικό επίπεδο, η διατριβή εξετάζει πώς εναλλακτικοί ρυθμοί ανακαίνισης και διαφορετικές διαδρομές αντικατάστασης τεχνολογιών θέρμανσης επηρεάζουν τη δυνατότητα επίτευξης απανθρακοποίησης του ελληνικού οικιακού τομέα έως το 2050 ή, σε ένα πιο φιλόδοξο σενάριο, έως το 2040. Σε περιφερειακό επίπεδο, η διατριβή διερευνά πώς ο εθνικός ενεργειακός σχεδιασμός αποτυπώνεται σε περιφερειακές διαδρομές μετάβασης, εστιάζοντας στην επέκταση των υποδομών φυσικού αερίου και, κατ' επέκταση, στη διεύρυνση της χρήσης του στον οικιακό τομέα της Περιφέρειας Πελοποννήσου. Σε τοπικό επίπεδο, η ανάλυση επικεντρώνεται στον Δήμο Μεγαλόπολης, μια περιοχή με μακρά εξάρτηση από τη λιγνιτική δραστηριότητα και σήμερα σε διαδικασία μεταλιγνιτικής μετάβασης, συγκρίνοντας την αντικατάσταση της τηλεθέρμανσης που συνδεόταν με τη λειτουργία των λιγνιτικών μονάδων με επιδοτούμενους λέβητες φυσικού αερίου, έναντι εναλλακτικών διαδρομών που δίνουν προτεραιότητα στον εξηλεκτρισμό και την ενεργειακή απόδοση. Τα αποτελέσματα της ανάλυσης δείχνουν ότι τα μονοπάτια που συνδυάζουν περιορισμένη πρόοδο ανακαίνισεων με μεταβατικές λύσεις βασισμένες σε ορυκτά καύσιμα οδηγούν σε καθυστέρηση της διαδικασίας μείωσης των εκπομπών, σε αύξηση του μακροπρόθεσμου κόστους για τα νοικοκυριά, ενώ ταυτόχρονα παρατείνουν την εξάρτηση από τα ορυκτά καύσιμα. Αντίθετα, οι διαδρομές που δίνουν προτεραιότητα στον εξηλεκτρισμό και την ενεργειακή απόδοση παρουσιάζουν ευνοϊκότερα αποτελέσματα ως προς την απανθρακοποίηση και τη μείωση του μακροπρόθεσμου κόστους, ενώ περιορίζουν την έκθεση σε εισαγόμενα καύσιμα, στη μεταβλητότητα των τιμών τους και στις πρόσθετες επιβαρύνσεις που συνδέονται με την τιμολόγηση του ανθράκα στον οικιακό τομέα.

Συνολικά, η διατριβή δείχνει ότι η δυναμική, «από κάτω προς τα πάνω» μοντελοποίηση της ζήτησης μπορεί να υποστηρίξει τη χάραξη πολιτικής για την ενεργειακή μετάβαση του οικιακού τομέα, μεταφράζοντας υψηλού επιπέδου στόχους απανθρακοποίησης σε συγκεκριμένες παραμέτρους υλοποίησης, όπως οι απαιτούμενοι ρυθμοί ανακαίνισης, οι διαδρομές αντικατάστασης τεχνολογιών θέρμανσης, η εξέλιξη των εκπομπών και οι επιπτώσεις στο κόστος. Η πολυεπίπεδη εφαρμογή του πλαισίου αναδεικνύει ότι οι στρατηγικές μετάβασης στον οικιακό τομέα χρειάζεται να αξιολογούνται όχι μόνο στο επίπεδο όπου τίθενται οι στόχοι πολιτικής, αλλά και στα επίπεδα όπου οι επιπτώσεις τους εκδηλώνονται: σε περιφέρειες και δήμους με διαφορετικά χαρακτηριστικά κτιριακού αποθέματος, υφιστάμενα συστήματα θέρμανσης και γενικότερες κοινωνικοοικονομικές συνθήκες.

Τέλος, αξίζει να σημειωθεί ότι το πλαίσιο μοντελοποίησης αξιοποιήθηκε σε ερευνητικές δραστηριότητες με άμεση συνάφεια με τη χάραξη πολιτικής, στο πλαίσιο έργων χρηματοδοτούμενων από την Ευρωπαϊκή Επιτροπή. Στις δραστηριότητες αυτές, οι παραδοχές μοντελοποίησης, τα σενάρια και οι διαδρομές ενεργειακής μετάβασης συζητήθηκαν με φορείς χάραξης πολιτικής και λοιπά ενδιαφερόμενα μέρη. Παράλληλα, το πλαίσιο χρησιμοποιήθηκε για την υποστήριξη του Υπουργείου Περιβάλλοντος και Ενέργειας στην ανάπτυξη στόχων και βημάτων υλοποίησης για την επικαιροποιημένη Μακροπρόθεσμη Στρατηγική για την Ανακαίνιση του Κτιριακού Αποθέματος της Ελλάδας. Οι εφαρμογές αυτές ενισχύουν τη συνάφεια της διατριβής με την πραγματική διαδικασία σχεδιασμού ενεργειακής πολιτικής, αναδεικνύοντας πώς το αναπτυγμένο πλαίσιο μπορεί να υποστηρίξει τη μετάβαση από την αναλυτική αξιολόγηση σεναρίων στη διαμόρφωση στόχων και μέτρων προσανατολισμένων στην υλοποίηση.

Λέξεις-Κλειδιά: Απανθρακοποίηση του οικιακού τομέα· «Από κάτω προς τα πάνω» μοντελοποίηση ζήτησης ενέργειας· Εθνικό επίπεδο· Ενεργειακή ανθεκτικότητα· Ενεργειακή δικαιοσύνη· Ενεργειακή μετάβαση· Εξηλεκτρισμός· Ελλάδα· Μονοπάτια ενεργειακής μετάβασης στον οικιακό τομέα· Πολυεπίπεδη ανάλυση ενεργειακής πολιτικής· Περιφερειακό επίπεδο· Τοπικό επίπεδο· Φυσικό αέριο.

Abstract

Residential buildings occupy a central position in the European energy transition, accounting for a substantial share of final energy consumption and energy-related greenhouse gas emissions, while also constituting a primary interface between climate and energy policy and citizens' everyday lives. This importance is reflected in the European Union's evolving energy and climate policy framework, which increasingly connects renovation, energy efficiency, electrification, carbon pricing, and social protection. At the same time, decisions in the residential sector are shaped by long investment lifetimes, slow stock turnover, and strong dependence on previous technology and infrastructure choices, making the timing and sequencing of transition pathways critical for avoiding lock-in effects and aligning near-term decisions with long-term climate, resilience, and justice objectives.

In this context, energy system models have been widely used to support policymaking, particularly for exploring long-term decarbonisation pathways and assessing system-level feasibility. However, in most cases, such models are following "top-down" approaches, representing the residential sector in an aggregated manner, abstracting from building-level characteristics and household heterogeneities. While such representations are useful for ambition-setting and consistency checks at national or European scales, they often function as black boxes from a policy-delivery perspective, offering limited transparency on the mechanisms through which emissions reductions are achieved within the building stock, how policy measures translate into household-level change, and how their impacts vary across household groups and regions.

Building on these considerations, this dissertation contributes to demand-side energy system modelling by developing additional capabilities within the Dynamic high-Resolution dEmand-side Management² (DREEM) model. The resulting framework supports the assessment of residential energy transition pathways across time horizons and spatial scales, while retaining a bottom-up representation of household energy demand. To do so, the dissertation develops and integrates two complementary components within DREEM. The first enables household-level demand profiles to be aggregated to local, regional, and national levels, while the second creates a scenario space in which key residential transition parameters evolve over time (e.g., renovation and heating technology substitution rates, energy prices, technology costs, demographic change, building-stock evolution, emission factors, and carbon-pricing-related costs).

The dissertation applies this framework to the Greek residential sector across national, regional, and local levels, examining residential transition pathways through the interconnected dimensions of decarbonisation, energy resilience, and energy justice. Across the three applications, the analysis examines how different residential transition strategies, characterised by varying renovation ambition, heating technology substitution, and policy conditions, shape energy, emissions, and cost trajectories over time. These trajectories provide the basis for assessing how pathway choices affect not only the feasibility of emissions reduction, but also exposure to fossil-fuel dependence, price and carbon-pricing risks, household affordability, and territorially specific transition challenges.

At the national level, the dissertation examines how alternative renovation rates and heating technology substitution pathways affect the feasibility of achieving residential decarbonisation in Greece by 2050 or, under a more ambitious pathway, by 2040. At the regional level, it examines how nationally driven energy planning translates into region-specific transition outcomes, focusing on the expansion of natural gas infrastructure and the associated increase in natural gas use for residential heating in the Peloponnese region. At the local level, it focuses on the municipality of Megalopolis, a coal- and carbon-intensive region undergoing post-lignite transition, comparing the replacement of lignite-linked district heating with subsidised gas boilers against alternative pathways prioritising electrification and

² <https://www.sciencedirect.com/science/article/abs/pii/S0196890419313469>

energy efficiency. Across these applications, the results show that pathways relying on modest renovation progress and fossil-fuel-based transitional solutions risk delaying emissions reductions, and increasing long-term costs, while prolonging fossil-fuel dependence. By contrast, electrification- and efficiency-oriented pathways deliver more favourable outcomes in terms of decarbonisation and long-term cost reduction, while reducing exposure to fossil-fuel dependence, imported fuel volatility, and additional costs associated with carbon pricing.

Overall, the dissertation demonstrates that dynamic bottom-up demand-side modelling can support residential energy transition policymaking by translating high-level decarbonisation objectives into implementation requirements, including renovation rates, heating technology pathways, emissions trajectories, and cost implications. Its multi-level application shows that residential transition strategies need to be assessed not only where policy targets are defined, but also where their implications unfold: across regions and municipalities with distinct building-stock characteristics, heating systems and socio-economic conditions.

Finally, it should be mentioned that the framework has been applied in policy-facing research activities within European Commission-funded projects, where modelling assumptions, scenario narratives, and transition pathways were discussed with policymakers, practitioners, and stakeholders. In parallel, it was used to support the Greek Ministry of Environment and Energy in the development of targets and implementation steps for the updated Greek Long-Term Renovation Strategy. These applications strengthen the policy relevance of the dissertation by demonstrating how the modelling framework can inform real-world residential energy policy design, from analytical scenario assessment to the formulation of implementation-oriented targets and measures.

Keywords: Bottom-up demand-side modelling; Electrification; Energy justice; Energy resilience; Energy transition; Greece; Local level; Multi-level energy policy analysis; National level; Natural gas; Regional level; Residential decarbonisation; Residential energy transition pathways.

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Chapter 1 - Introduction to the PhD thesis

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Nomenclature

Acronyms & abbreviations			
CCIR/ CCIRs	Coal and Carbon Intensive Region(s)	EU	European Union
DREEM	Dynamic high-Resolution dEmand-side Management	GHG	Greenhouse Gas
EC	European Commission	NECP	National Energy and Climate Plan
EED	Energy Efficiency Directive	RQ/ RQs	Research Question(s)
EPBD	Energy Performance of Buildings Directive	TEEM	TEESlab Modelling
ETS2	Emissions Trading System 2	TEESlab	Technoeconomics of Energy Systems laboratory

1. Introduction

This Chapter introduces the background and motivation of this dissertation thesis as well as the main pillars that this thesis contributes to. It also summarises the main challenges and formulates the research questions addressing key issues in the frame of energy system modelling.

1.1. Background and problem formulation

Over the past three decades, the European Union (EU) has progressively strengthened its climate and energy policy framework, positioning itself as a global frontrunner in climate change mitigation. The objective of achieving climate neutrality by 2050, as formalised in the “European Green Deal” (European Commission 2019c) and reinforced through subsequent initiatives such as the “Fit-for-55” legislative package (European Commission 2021) and the “REPowerEU” plan (European Commission 2022c) has placed increasing emphasis on sectors characterised by both high decarbonisation potential and persistent structural inertia. Within this context, the building sector has emerged as a cornerstone of EU climate strategy, accounting for approximately 40% of final energy consumption and 36% of energy-related greenhouse gas (GHG) emissions (Urge-Vorsatz et al. 2020). Residential buildings, and in particular space and water heating, constitute the largest share of this demand, making deep energy renovations, electrification of heating, and the phase-out of fossil fuel-based technologies central to the EU’s decarbonisation agenda (García-Gutiérrez et al. 2026).

Despite the clarity of long-term objectives, the challenge of building decarbonisation has increasingly shifted from ambition-setting to policy delivery. Buildings and heating systems are long-lived assets, typically characterised by investment lifetimes spanning several decades, slow turnover rates, and strong path dependencies (Caldecott and McDaniels 2014; Seto et al. 2016). As a result, short-term policy and investment decisions can either enable or constrain future transition options. Continued investments in fossil fuel-based heating technologies, shallow renovations, or incompatible infrastructure risk locking households into emissions-intensive pathways, increasing the likelihood of stranded assets and raising the cost of future compliance with climate targets (Mercure et al. 2018; Steffen 2020). From a decarbonisation perspective, this underscores the importance of aligning near-term policy instruments with long-term climate neutrality objectives, rather than postponing structural change through incremental or “ad-hoc” solutions that risk reinforcing existing carbon-intensive pathways.

At the same time, recent energy crises have underscored that energy-system decarbonisation should be considered alongside resilience-related concerns. These concerns are particularly relevant to how technology choices, infrastructure investments, and policy design shape fossil-fuel dependence, exposure to external shocks, and the robustness of transition pathways (Guarascio, Reljic, and Zezza 2025). Volatility in fossil-fuel prices, geopolitical disruptions, and supply-chain constraints have exposed the vulnerability of energy systems that remain dependent on imported fuels (International Energy Agency (IEA) 2023). In the residential sector, continued reliance on fossil-fuel-based heating may also increase households’ exposure to energy price volatility and affordability pressures, especially in inefficient dwellings and vulnerable socio-economic contexts (Bouzarovski, Thomson, and Cornelis 2021; Farghali et al. 2023).

These dynamics also highlight the importance of considering the social and distributional dimensions of the residential energy transition. Energy poverty remains a persistent challenge across many EU Member States, reflecting the combined effects of low incomes, inefficient buildings, and high energy costs (Bouzarovski 2018). The residential energy transition interacts directly with these vulnerabilities, as households with limited financial capacity often face barriers to investing in energy efficiency improvements or low-carbon heating technologies (Sareen et al. 2020). In this context, the extension of carbon pricing to buildings and road transport under Emissions Trading System 2 (ETS2) is expected

to increase the cost exposure associated with fossil fuel-based heating, thereby amplifying the social and distributional implications of delayed transitions away from fossil fuels (Duma 2022; NOKA et al. 2025). Without targeted and well-designed policy support, decarbonisation strategies risk disproportionately burdening vulnerable households, undermining energy justice and public acceptance of climate policies (Bouzarovski, Thomson, and Cornelis 2021; Jenkins et al. 2016).

Recent EU initiatives, including strengthened social provisions under the Energy Efficiency Directive (EED) and the introduction of Social Climate Plans, explicitly recognise the need to integrate justice considerations into climate and energy policymaking (European Parliament 2023; Jüngling et al. 2025), but translating these principles into effective and well-calibrated national policies remains complex. Strategic objectives are set at the European level, while implementation relies on national policy frameworks such as National Energy and Climate Plans and National Building Renovation Plans. Differences in priorities, timing, and implementation approaches across governance levels can influence the coherence of policy mixes and their adaptation to regional and socio-economic conditions (Rogge and Reichardt 2016). In the residential sector, where investment decisions are highly decentralised and shaped by local contexts, such coordination requirements can affect the pace and effectiveness of transition dynamics (Wilson, Crane, and Chryssochoidis 2015).

Taken together, these dynamics highlight that residential energy policymaking increasingly involves complex, long-term trade-offs across decarbonisation, energy resilience, and energy justice. In this context, robust evidence-based analytical tools are essential to support policymakers in assessing transition pathways, anticipating distributional impacts, and aligning short-term measures with long-term objectives (Fell, Roelich, and Middlemiss 2022). Energy system modelling plays a critical role in this regard, with top-down and techno-economic optimisation approaches providing valuable insights into long-term decarbonisation pathways and cost-efficient end states (Pfenninger, Hawkes, and Keirstead 2014). However, these approaches often function as “black boxes”, relying on aggregated representations of energy demand that assume smooth or static transitions, and rely on assumptions that do not fully reflect the real-world dynamics of the residential sector (Pfenninger et al. 2018)..

This dissertation is situated within this critical research and policy context. It examines the Greek residential sector as a testing ground to explore how national, regional, and local strategies can be assessed and redesigned to avoid fossil fuel lock-ins, accelerate electrification, and foster resilient, just, inclusive, and cost-effective energy transitions towards climate neutrality by 2050.

1.1.1. Energy system models and their role in the European policy landscape

Energy system models constitute a central analytical tool for supporting energy and climate policymaking in Europe, particularly in the context of the transition towards low-carbon energy systems. As the EU pursues ambitious decarbonisation objectives, policymakers are required to design strategies that support the large-scale deployment of renewable energy sources, enable sector coupling across electricity, heating and transport, and balance the interests of multiple actors within the energy system. Given that real-world experimentation at system scale is neither feasible nor desirable, energy system models function as virtual laboratories in which alternative decarbonisation strategies and transition pathways can be explored, compared, and assessed in a controlled analytical environment (Gilbert et al. 2018). Through scenario analysis and policy simulations, these models help generate structured insights into the possible evolution of energy systems over time and support the development of evidence-based policy responses.

At their core, energy system models are mathematical abstractions of complex socio-technical systems. By necessity, they simplify reality, producing representations that are smaller in scale, reduced in complexity, or less detailed than the systems they aim to describe (Van Egmond and Zeiss 2010). These simplifications are not valued as neutral. Model structures, assumptions, and parameter choices reflect

not only physical and economic constraints, but also the theoretical perspectives, empirical interpretations, and mental models of the modellers themselves (Ellenbeck and Lilliestam 2019). As a result, energy system models are embedded within broader social and institutional contexts and can both shape and be shaped by the policy environments in which they are applied. In this sense, models can act as discursive or negotiation spaces, enabling interaction between different communities, such as scientists, policymakers, and stakeholders, and facilitating the co-production of knowledge and shared interpretations of energy system challenges (Evans 2000; Star and Griesemer 1989). While energy system models can therefore play an important role in informing governmental decision-making processes (Lopion et al. 2018), they are not substitutes for political judgement and cannot be treated as prescriptions to be directly implemented without deliberation (Gilbert et al. 2018).

Pfenninger *et al.* (2014) distinguish between four key groups of energy system models relevant for national and international climate policies: **(i)**. energy system optimisation models, **(ii)**. energy system simulation models, **(iii)**. power system and electricity market models, and **(iv)**. qualitative and mixed-methods scenarios (Pfenninger, Hawkes, and Keirstead 2014).

Such models have been extensively used in European policy contexts to explore possible energy futures and alternative energy transition pathways (Geels, McMeekin, and Pfluger 2018). Their influence on policymaking can be both indirect, through reference to published scenarios and modelling studies, and direct, when dedicated model runs are commissioned to support specific policy processes. Across Europe, governments have adopted diverse approaches to the use of energy modelling, with some maintaining in-house modelling capacities and others relying on externally commissioned studies (Süsser, Ceglaz, et al. 2021). In the United Kingdom, for example, the MARKAL model and its successor TIMES-UK have provided analytical support for energy and climate policy development for more than three decades, becoming deeply embedded within the national energy policy community (Taylor et al. 2014). In Greece, the Dynamic high-Resolution dEmand-sideE Management (DREEM) model has been employed to support the development of Greece's Long Term Renovation Strategy (Hellenic Republic - Ministry of the Environment and Energy 2025). In Switzerland, following the Fukushima nuclear accident, the federal government commissioned a comprehensive modelling study by Prognos AG to inform the development of the Swiss Energy Strategy 2050 (Prognos AG 2012).

Despite their widespread use, the contribution of energy system models to policymaking varies considerably. A recent survey of energy system modelling tools found that approximately two-thirds of the examined models had either a direct or indirect influence on policy processes, while more than one-third showed no identifiable policy impact, often because they were newly developed, used primarily for academic purposes, or applied within a narrowly defined analytical scope (Chang et al. 2020). This suggests that, although modelling has become a standard component of the European energy policy landscape, a significant share of existing models does not fully realise its potential to inform policy decisions (Süsser et al. 2022). Differences between the design objectives of models in academic research and the practical needs of policymakers contribute to this gap, highlighting ongoing challenges in aligning modelling frameworks with the evolving demands of policymaking related with the energy transition (Capros et al. 2016).

Within this broader modelling landscape, building sector models have become increasingly important for the development and assessment of strategies aimed at reducing energy demand and GHG emissions in buildings (Manfren, Sibilla, and Tronchin 2021; Xiong et al. 2025). While energy demand modelling at the level of individual buildings has a long history, the explicit representation of the building stock as a sector, at different levels (local, regional, national, international), has emerged more recently, reflecting the growing policy relevance of buildings in climate mitigation strategies ((IPCC) 2023).

Building sector models used in this premise are commonly classified into top-down, bottom-up, and hybrid approaches (L. Swan and Ugursal 2009). Top-down building models represent the sector in an

aggregated manner and are typically grounded in economic or technological frameworks. They are primarily used to assess economy-wide or sector-wide policy responses (Ahmad et al. 2018). Due to their aggregated structure, however, such models often lack sufficient granularity to differentiate between buildings with distinct characteristics. As a result, they may be limited in their ability to assess the differentiated impacts of technological change within the building stock, for example when evaluating the uptake of heat pumps or deep renovation measures across heterogeneous building types (Kavgic et al. 2010; Mastrucci et al. 2023).

By contrast, bottom-up building models represent individual buildings or subsystems in greater detail and subsequently aggregate results to the stock or system level. These models encompass a range of methodological approaches, including engineering-based simulations, statistical and data-driven techniques (including machine learning), as well as hybrid formulations (L. Swan and Ugursal 2009). Bottom-up models are particularly well suited to explicitly representing building heterogeneity, energy-use dynamics, and the aggregate effects of changes at the individual building level (Nageler et al. 2018). They are widely used to estimate techno-economic potentials and to assess the implications of technological and efficiency improvements across the building stock ((IPCC) 2023).

Hybrid building models combine elements of both top-down and bottom-up approaches and are typically applied to explore the interactions between resource constraints, technological choices, and building-related policies ((IPCC) 2023). These models often employ optimisation and simulation techniques and may incorporate agent-based modelling to represent heterogeneous decision-making processes and interactions among actors within the building sector (Niamir, Ivanova, and Filatova 2020).

1.1.2. Key building-sector transition challenges and modelling requirements

Despite the increasing diversity and technical sophistication of building energy models, a growing body of literature highlights persistent challenges in their ability to support contemporary energy and climate policy needs. These challenges mainly reflect a misalignment between the dominant design logics of existing modelling frameworks and the evolving requirements of energy transition implementation (Lopion et al. 2018). Recent synthesis work, most notably by (Mastrucci et al. 2023) demonstrates that many existing building-sector models remain insufficiently equipped to support this translation, especially when transitions are understood as dynamic, heterogeneous, and multi-level processes.

Temporal orientation and near-term guidance: Building-sector models used for long-term scenario analysis frequently rely on annual or multi-annual temporal resolution, particularly at national, regional, or global scales (Chatterjee et al. 2022a). While subannual and high-resolution temporal modelling has advanced in local and subnational studies, combining long-term transition horizons with sufficiently fine temporal resolution remains challenging due to data availability, computational constraints, and model complexity (Moreau et al. 2025). This limitation reduces the ability of models to capture seasonal and sub-daily variations in demand, changes in load profiles, and emerging dynamics associated with electrification, demand response, and prosumer behaviour (Chang et al. 2021). As a result, long-term projections often abstract away precisely those demand-side dynamics that become increasingly relevant during the implementation phase of the transition, particularly in the 2030-2040 timeframe (Savvidis et al. 2019).

Model granularity and the representation of heterogeneity: The building sector is characterised by substantial heterogeneity in building typologies, vintages, occupancy patterns, technologies, and socioeconomic conditions (Nageler et al. 2018; L. G. Swan and Ugursal 2009). Mastrucci et al. (2022) identify persistent gaps in the ability of existing models to represent these dimensions in a combined and consistent manner. While bottom-up engineering models often provide detailed representations of physical building characteristics and technologies, they frequently simplify socioeconomic heterogeneity. Conversely, economic and agent-based approaches may capture behavioural diversity

but struggle to integrate it with detailed representations of the building stock and its technical constraints (Niamir, Ivanova, and Filatova 2020). As a result, on the one hand, insufficient treatment of heterogeneity constrains the ability to scale up micro-level representations into an aggregated depiction of the building sector that remains analytically robust and policy relevant. On the other hand, the same simplifications limit the capacity of models to assess distributional impacts, as they struggle to extract insights into how policies and transition pathways affect different households, income groups, or building typologies in differentiated ways- particularly in the residential sector (Pavlović, Živković, and Ivezić 2023).

Representation of transition dynamics and stock evolution: While many building energy models focus on baseline and target-year outcomes, greater attention is needed to the intermediate pathways through which residential energy systems evolve over time (Mastrucci et al. 2023). Limited representation of these pathways may obscure path dependency, sequencing effects, and the long-lived nature of building assets. In the residential sector, early investment decisions, such as the adoption of transitional heating technologies or partial renovations, can create lock-ins that significantly influence feasibility, cost, and speed of deeper decarbonisation at later stages (Seto et al. 2016). Insufficient attention to stock evolution and technology replacement over time may therefore constrain the assessment of transition feasibility, timing, and potential lock-in effects (Urge-Vorsatz et al. 2020). Finally, although both forecasting and backcasting approaches are widely used, they are often applied in isolation, limiting the assessment of trade-offs between near-term feasibility and long-term ambition within a coherent modelling framework (Keppo et al. 2021).

Alignment between modelling outputs and policy implementation needs. Building energy models are often developed as analytical or exploratory tools, and their outputs may require further interpretation to inform actionable policy guidance (Ellenbeck and Lilliestam 2019). This is particularly important in the residential sector, where policy implementation depends on household adoption of energy efficiency measures and low-carbon heating technologies. Empirical studies show that such decisions are shaped not only by prices and technical performance, but also by behavioural, institutional, and social factors that are difficult to fully capture in modelling frameworks (Pavlović, Živković, and Ivezić 2023). This can create challenges in translating model-based insights into policy practice, particularly in contexts characterised by heterogeneous building stocks, uneven administrative capacity, and affordability constraints.

Table 1.1 synthesises these challenges and translates them into corresponding modelling requirements for the building sector, drawing on recent reviews of energy system and building energy modelling (Chang et al. 2021; Chatterjee et al. 2022a; Mastrucci et al. 2023; Pavlović, Živković, and Ivezić 2023; Pfenninger, Hawkes, and Keirstead 2014; Prina et al. 2020). The dissertation contributes to this direction by further developing and applying a dynamic, bottom-up demand-side modelling framework for assessing residential energy transition pathways across different governance levels (i.e., local, regional and national).

Table 1.1. Key energy planning issues and modelling requirements for the transition to climate neutrality by 2050 in Europe as synthesised from (Chang et al. 2021; Chatterjee et al. 2022a; Mastrucci et al. 2023; Pavlović, Živković, and Ivezić 2023; Pfenninger, Hawkes, and Keirstead 2014; Prina et al. 2020).

a/a	Building-sector transition challenge	What modelling frameworks need to support
1	Translation of long-term decarbonisation targets into short- and medium-term action	Link long-term targets with intermediate transition pathways, including the timing, sequencing, and pace of key interventions.
2	Increasing electrification and changing demand profiles	Capture how electrification, efficiency improvements, and behavioural assumptions may reshape energy demand patterns over time.

3	Heterogeneity of the building stock and households	Represent differences in building characteristics, technologies, energy performance, and relevant household conditions.
4	Connecting household/ building dynamics with long-term energy transition planning	Support transparent upscaling from household- or building-level dynamics to local, regional, and national building stocks.
5	Distributional impacts of building-sector policies	Assess how transition pathways and policy choices may affect households, building types, and socioeconomic groups differently.
6	Risk of technological lock-in	Account for how near-term renovation and technology choices may influence long-term feasibility, costs, and transition timing.
7	Alignment with multilevel governance	Enable analysis across local, regional, and national decision-making contexts while recognising the interaction between them.
8	Uncertainty and alternative transition pathways	Explore uncertainty in key drivers through structured scenario spaces and alternative pathway assumptions.

1.2. Scope and objective

The EU has established an ambitious and increasingly integrated policy framework aimed at transforming its energy system in line with long-term climate, security, and social objectives. Central to this framework is the commitment to achieve climate neutrality by 2050, as articulated in the European Green Deal, alongside intermediate targets for GHG emissions reduction, energy efficiency, and renewable energy deployment (European Commission 2019d). At the same time, recent policy developments have reinforced the importance of strengthening energy system resilience in the face of climate impacts, geopolitical risks, and supply disruptions, while ensuring that the costs and benefits of the transition are distributed fairly across society (European Commission 2021, 2022b). Together, these priorities define a policy landscape structured around three interrelated pillars: decarbonisation, energy resilience, and energy justice.

Within this context, the residential building sector occupies a critical position. Buildings account for a substantial share of final energy consumption and GHG emissions in Europe, while simultaneously playing a key role in energy affordability, exposure to energy poverty, and the capacity of the energy system to accommodate higher shares of variable renewable energy sources (European Commission 2020b; European Environment Agency 2025). Policy initiatives such as the Renovation Wave, the Fit for 55 package, and the revised Energy Performance of Buildings Directive (EPBD) highlight the strategic importance of accelerating building renovation, electrification, and the uptake of distributed energy technologies (European Commission 2020a, 2021, 2023b). However, the effectiveness of these policies depends not only on the ambition of their targets, but also on the ability to understand and anticipate how residential energy transitions unfold over time, across regions, and among heterogeneous households (Creutzig et al. 2022).

Despite the growing policy emphasis on buildings, as described in **Section 1.1.1** and **1.1.2**, energy planning and energy system modelling approaches face challenges in representing the dynamic and multi-dimensional nature of residential energy transitions. In many system-level and top-down modelling frameworks, residential demand is treated as an aggregated or “black-box” component, limiting the explicit representation of household-level technologies and transition processes. At the same time, bottom-up and high-resolution demand-side models, while providing detailed insights at the building or household level, often face challenges in scaling these insights consistently across temporal and spatial levels and in translating them into pathway-oriented transition assessments (Hofbauer, McDowall, and Pye 2022).

In this context, this dissertation builds on the dynamic and high-resolution demand-side modelling environment provided by the Dynamic high-Resolution demand-side Management (DREEM) model, an in-house model of the Technoeconomics of Energy Systems laboratory (TEESlab) modelling (TEEM) suite, as introduced by Stavrakas and Flamos 2020, and extends it into a modelling framework

for the assessment of residential energy transitions. While preserving a modular and computationally efficient structure, the framework enables detailed simulation of residential energy demand, end-use technologies, and flexibility options at the building level. The contribution of this dissertation lies in extending these high-resolution demand-side outputs towards the systematic and pathway-oriented evaluation of residential energy transitions. Through the introduction of a multilevel upscaling approach and a transition matrix formulation, household-level simulation results are organised and aggregated across temporal and spatial scales, allowing residential transitions to be assessed consistently at different levels (i.e., local, regional and national) (**Fig. 1.1**).

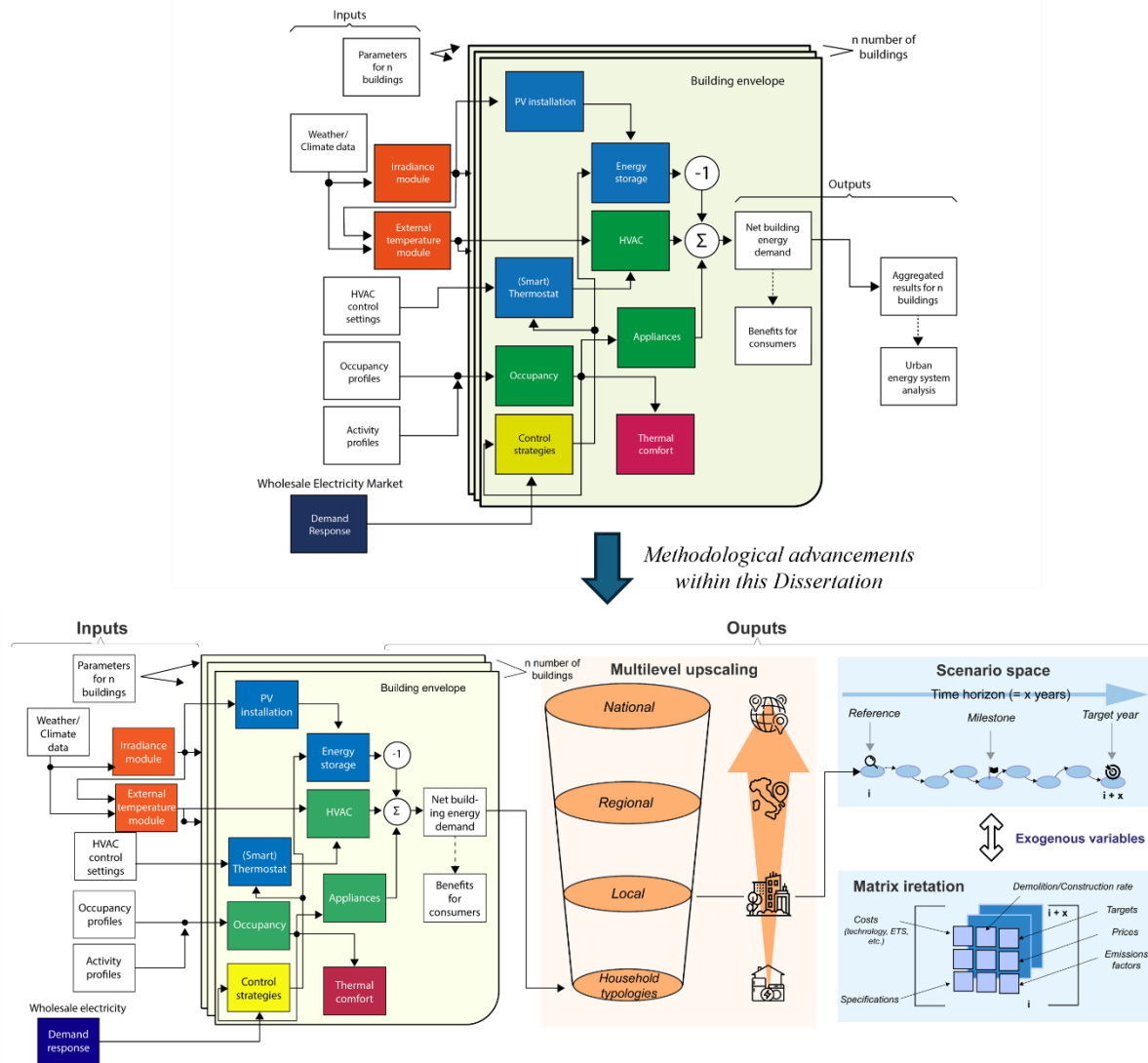


Fig. 1.1. From the original version of the DREEM model (Stavrakas and Flamos 2020) to its enhanced version: The methodological advancements in demand-side modelling within the context of this Dissertation.

The scope of the dissertation is defined by its focus on integrating detailed demand-side modelling into the analysis of residential energy transitions across multiple scales. The dissertation concentrates on how high-resolution representations of residential demand can be structured to reflect long-lived building stocks, gradual transition processes, and heterogeneous household conditions in a manner that supports transparent and policy-relevant assessment.

The overarching objective of the dissertation is **to enable the assessment of residential energy transition pathways using high-resolution demand-side modelling, supporting** the analysis of decarbonisation, while exploring energy resilience, and energy justice implications.

To achieve this objective, the dissertation pursues the following specific objectives:

- To extend the DREEM framework to support the aggregation of household-level demand-side simulation outputs across temporal and spatial scales.
- To improve the representation and tracking of residential energy transition dynamics over time, allowing the analysis of pathway-dependent outcomes.
- To enable the assessment of residential energy transition pathways with respect to decarbonisation, energy resilience, and energy justice.
- To demonstrate the applicability and policy relevance of the modelling framework through case studies in a European context.

By addressing these objectives, the dissertation contributes to strengthening the link between detailed residential demand-side modelling and higher-level energy transition analysis, supporting more nuanced and coherent assessments of building-sector transitions in line with European policy priorities.

In addition to their application, the modelling developments presented in this dissertation were embedded in research settings that explicitly incorporated stakeholder consultation and scenario co-creation processes. Within the Horizon 2020 and LIFE Programme projects “**SENTINEL**”³, “**TIPPINGPLUS**”⁴, “**ENCLUDE**”⁵, “**ENPOR**”⁶, and “**RENOVERTY**”⁷, transition scenarios were developed through structured engagement with policymakers, experts, and societal stakeholders at European and national levels, which informed the definition of scenario narratives, policy assumptions, and key uncertainties related to decarbonisation pathways, renovation strategies, and distributional impacts. This interaction between stakeholder-informed scenario design and detailed demand-side modelling supported the evaluation of residential energy transition pathways that are not only technically consistent, but also institutionally grounded and socially relevant, in line with European objectives for a resilient and just energy transition.

In parallel, this framework has also been used to support the Greek Ministry of Environment and Energy in the development of targets and implementation steps for the updated Greek Long-Term Renovation Strategy⁸.

1.3. Research questions (RQs)

This doctoral dissertation builds on the recognition that achieving climate neutrality in the residential sector requires more than the formulation of ambitious policy targets. It requires analytical tools capable of translating high-level objectives into transition pathways that account for the dynamic, heterogeneous, and spatially differentiated nature of the residential sector. As highlighted in **Sections**

³ [SUSTAINABLE ENERGY TRANSITIONS LABORATORY | SENTINEL](#)

⁴ [Enabling Positive Tipping Points towards clean-energy transitions in Coal and Carbon Intensive Regions | TIPPING.plus](#)

⁵ [Energy Citizens for Inclusive Decarbonization | ENCLUDE](#)

⁶ [Actions to Mitigate Energy Poverty in the Private Rented Sector | ENPOR](#)

⁷ [Home Renovation Roadmaps to Address Energy Poverty in Vulnerable Rural Districts | RENOVERTY](#)

⁸ <https://ypen.gov.gr/dimosia-ilektroniki-diavoulefsi-gia-to-schedio-ypourgikis-apofasis-tou-ypourgeiou-perivallontos-kai-energeias-ekthesi-makroprothesmis-stratigikis-anakainisis-tou-dimosiou-kai-idiotikou-ktiria/>

1.1 and **1.2**, existing energy system models often face challenges in representing the long-term evolution of residential building stocks.

In this context, this thesis focuses on advancing the use of dynamic, bottom-up demand-side modelling to support model-informed policy and strategy assessment for residential energy transitions. To do so, the dissertation examines how residential energy transition pathways can be formed to achieve decarbonisation, while exploring issues of energy resilience and energy justice across multiple governance levels.

Accordingly, the **overarching research question (RQ)** of the dissertation is formulated as follows:

How can advancements in bottom-up demand-side modelling support the design of energy transition strategies for the residential sector, addressing decarbonisation targets alongside energy resilience, and energy justice implications, while informing policymaking across multiple governance levels?

To address this overarching research question, the dissertation is structured around **three thematic research pillars (Fig. 1.2)**, each corresponding to a key dimension of the residential energy transition.

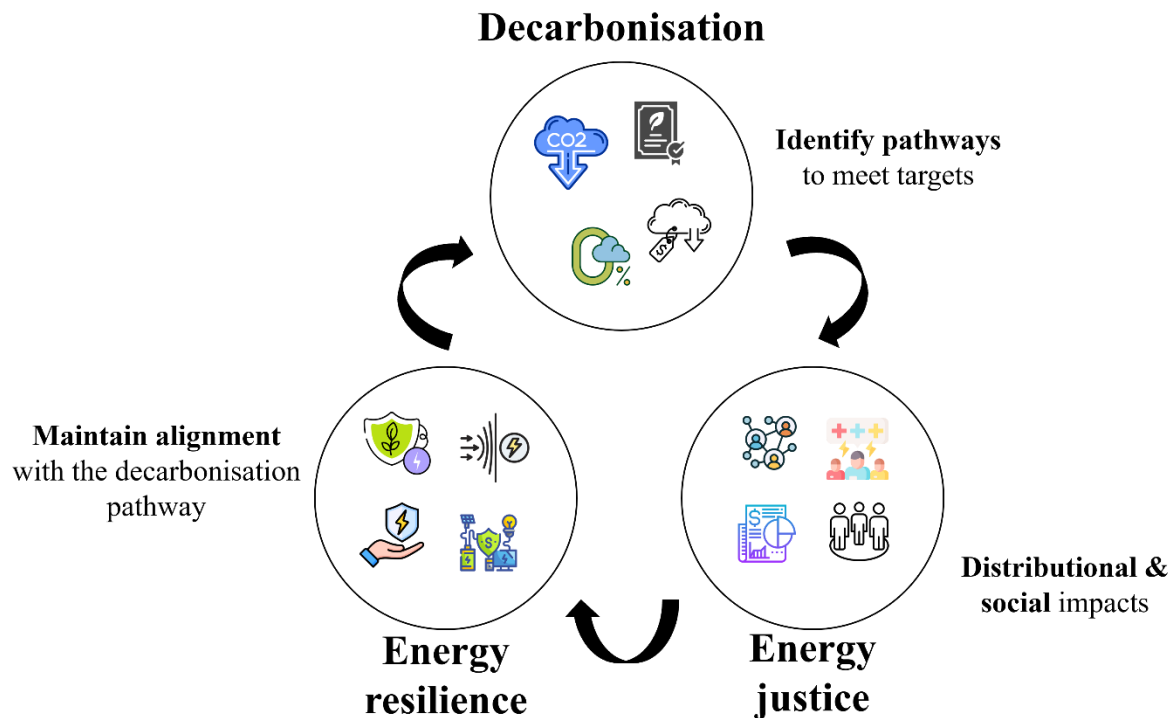


Fig. 1.2. The interaction cycle between the three main pillars on which this dissertation thesis builds.

As illustrated in **Fig. 1.3**, these pillars guide the formulation of the thematic RQs and structure the analysis presented in **Chapters 2, 3, and 4**.

The first pillar focuses on **decarbonisation**, examining how long-term EU and national climate targets can be translated into actionable transition pathways for the residential sector by identifying appropriate renovation rates, technology and policy priorities, and affordability implications.

RQ₁. *How can the residential energy transition by 2050 be shaped to meet national and EU decarbonisation targets, and what are the key considerations for achieving these goals?*

The second pillar approaches **energy resilience** as an important consideration for achieving residential decarbonisation. Energy resilience is understood here in relation to how residential decarbonisation pathways interact with fossil-fuel dependence, regional specificities, infrastructure requirements, and exposure to changing external conditions. This pillar is mainly explored by examining the interaction between national planning and regional residential energy transition pathways, as addressed in RQ2.

RQ₂. *How do nationally defined residential energy transition strategies interact with regional decarbonisation objectives, and what are the implications of this interaction for long-term energy resilience and fossil-fuel dependence?*

The third pillar brings an **energy justice** perspective into the assessment of residential energy transition pathways, focusing on how transition outcomes are experienced by households, communities, and territories. Attention is given to the distribution of transition costs and benefits, as well as to affordability concerns. Energy justice implications are considered across the three levels examined in this dissertation: national, regional, and local. However, this pillar is explored in greater depth at the local level, through RQ₃, by focusing on a coal- and carbon-intensive region facing structural vulnerabilities and transition-related challenges.

RQ₃. *Under what conditions can residential energy transitions in carbon-dependent regions evolve into green, inclusive, and just transition pathways towards 2050?*

These thematic research questions are addressed through the dissertation's modelling framework across three different levels, i.e., local, regional, and national. **Chapter 2** focuses on national-level residential decarbonisation pathways, examining the conditions under which EU and national climate targets can be met. **Chapter 3** focuses on the regional level, assessing how nationally defined energy planning interacts with regional realities. **Chapter 4** focuses on local-level transitions through participatory scenario analysis in a structurally vulnerable municipality. Together, the research questions provide a coherent structure for assessing how residential energy transition strategies can be designed at different levels, while remaining aligned with long-term decarbonisation objectives, energy resilience, and energy justice implications.

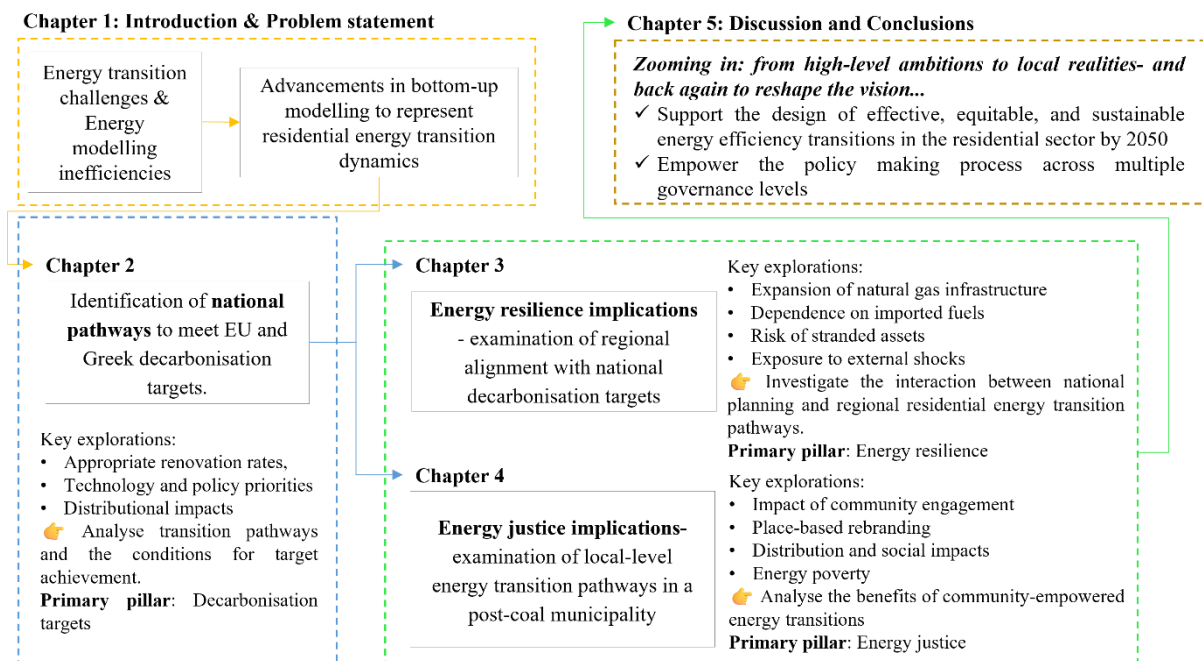


Fig. 1.3. Flowchart: Implementation steps to provide answers to the three thematic research questions that comprise the overarching research question of the dissertation thesis, in accordance with the three pillars and the interaction cycle between them.

1.3.1. RQ₁. How can the residential energy transition by 2050 be shaped to meet national and EU decarbonisation targets, and what are the key considerations for achieving these goals?

Achieving climate neutrality by 2050 constitutes a central objective of European climate and energy policy, with the residential building sector playing a critical role in its attainment. Buildings account for a substantial share of final energy consumption and carbon dioxide emissions in Europe, with space heating representing the dominant end use and a large proportion of dwellings still relying on fossil-fuel-based heating systems that have exceeded their technical lifetime (Matthias Buck et al. 2019; Ruusu et al. 2019). In this context, EU has introduced a series of policy initiatives aimed at accelerating decarbonisation in the building sector, including the “Fit-for-55” package, “REPowerEU”, and the recent revisions of the EED and the EPBD. These initiatives place strong emphasis on energy efficiency improvements, the gradual phase-out of fossil fuel boilers, and the expansion of low-carbon heating solutions (European Commission 2021, 2022b, 2023b; European Parliament 2023). At the national level, these objectives are reflected in Member States’ NECPs, which translate EU-wide targets into country-specific strategies (Economidou et al. 2020). However, despite the increasing ambition of these policy frameworks, uncertainty remains as to whether current national planning assumptions are sufficient to deliver full decarbonisation of the residential sector within the required timeframes.

A central point of debate concerns the role of natural gas as a transition fuel in residential heating. While natural gas has been incorporated into several national strategies as a bridging option, recent policy developments and scientific literature have raised questions regarding its compatibility with long-term decarbonisation objectives. Studies suggest that continued reliance on gas-based heating systems may delay the uptake of electrified solutions, increase cumulative emissions, and create new lock-in effects that constrain future transition options (Weidner and Guillén-Gosálbez 2023). At the same time, alternative pathways prioritising electrification combined with energy efficiency improvements have been shown to offer significant emissions reduction potential and greater alignment with long-term climate targets (Wu et al. 2024). Despite this ongoing debate, systematic, quantitative assessments that explicitly examine how different technology and policy priorities affect the feasibility of meeting residential decarbonisation targets remain limited.

Without quantified research outcomes, policymakers lack the insights needed to design effective strategies that align with the latest developments and evolving climate ambitions (Süsser et al. 2022). This lack of information not only hampers the ability to accurately assess the impact of current policies and identify areas for improvement, but also contributes to the persistence of significant gaps during their amendment (Michas et al. 2020). Therefore, there is a pressing need for scientific research and quantitative outcomes towards better-informed decision-making and evidence-based policymaking to amend national planning and ensure alignment with evolving EU directives and climate goals (Kleanthis et al. 2022).

Chapter 2 addresses this gap by applying a quantitative demand-side modelling framework capable of informing near- and mid-term policy decisions while remaining consistent with long-term climate neutrality objectives, in line with recent calls in the literature (Chatterjee et al. 2022a). The chapter focuses on identifying national residential energy transition pathways that align with EU and national decarbonisation targets. It examines how alternative renovation rates, heating technology choices, and policy priorities shape the feasibility and consequences of residential decarbonisation. Particular attention is given to the contrast between accelerated electrification and continued reliance on fossil-fuel-based heating systems, including natural gas, and to their implications for household energy demand, emissions, and energy-related costs.

Overall, **Chapter 2** contributes to the first thematic research question (RQ₁) by providing a structured and policy-relevant assessment of the conditions under which national and EU decarbonisation

targets in the residential sector can be achieved. By explicitly identifying key thresholds, trade-offs, and potential lock-in risks, the chapter lays the foundation for evaluating residential decarbonisation strategies that are not only ambitious, but also feasible and implementable over time.

1.3.2. RQ₂. How do nationally defined residential energy transition strategies interact with regional decarbonisation objectives, and what are the implications of this interaction for long-term energy resilience and fossil-fuel dependence?

Building on the assessment of national decarbonisation pathways addressed through RQ₁, RQ₂ shifts the focus to the regional level, by examining how nationally defined energy planning translates into region-specific outcomes and affects energy resilience. While national targets and policy frameworks provide a common direction for the residential energy transition, their effects can vary substantially across regions with heterogeneous socio-economic conditions, building characteristics, and existing infrastructure endowments (Zhou, Chen, and Chen 2022).

At the same time, although regional and local authorities are responsible for implementing national energy policies and infrastructure projects, their ability to adapt national strategies to local conditions remains limited. Recent assessments of multilevel energy governance indicate that coordination between governance levels remains insufficient, increasing the risk that national transition strategies produce misaligned regional outcomes (Defard 2023). Despite the relevance of these dynamics, quantitative analyses explicitly examining how national residential energy planning decisions affect regional energy resilience remain scarce, partly due to data limitations and the lack of suitable high-resolution modelling tools (Stavrakaki and Konstantopoulos 2023).

Chapter 3 aims to address this gap by focusing on Greece, where nationally defined planning priorities interact with regionally differentiated socio-economic, infrastructural, and climatic conditions. The analysis focuses on the Peloponnese region, where recent decisions to expand natural gas infrastructure introduce a gas-oriented transition pathway in an area where such networks were previously absent. This pathway is compared with electrification-focused alternatives, in order to examine how nationally driven infrastructure decisions interact with regional policy targets and shape residential decarbonisation outcomes, household energy costs, and fossil-fuel dependence. In doing so, the chapter provides insights into whether the expansion of natural gas infrastructure supports the region's transition or represents a missed opportunity for strengthening a long-term low-carbon and resilient residential energy pathway.

Overall, **Chapter 3** contributes to the second thematic research question (RQ₂) by examining how the interaction between national residential energy planning decisions and regional characteristics shapes region-specific transition outcomes. This interaction becomes particularly relevant where long-lived infrastructure and investment decisions influence the robustness and long-term feasibility of regionally differentiated decarbonisation pathways towards 2050.

1.3.3. RQ₃. Under what conditions can residential energy transitions in carbon-dependent regions evolve into green, inclusive, and just transition pathways towards 2050?

Beyond questions of emissions reduction and system resilience, energy transitions increasingly raise concerns related to energy justice and social inclusion, particularly in regions with a long-standing dependence on carbon-intensive activities. Coal- and carbon-intensive regions (CCIRs) across Europe have historically supported national energy systems, yet they often face disproportionate social and economic burdens during transition processes, including job losses, demographic decline, and persistent energy poverty (Oei, Brauers, and Herpich 2020; Rosenbloom 2018). In such contexts, energy transitions are not merely technical or economic transformations, but deeply socio-structural processes shaped by local identities, power relations, and institutional legacies (Markard, Rinscheid, and Widdel 2021).

Ongoing EU energy strategies, such as the European “Green Deal”, the “Clean Energy for All Europeans” package, the EU “Just Transition Mechanism” and the “Just Transition Fund”, increasingly emphasise the need to place citizens at the centre of the energy transition, recognising that social acceptance, participation, and perceived fairness are critical conditions for successful implementation (European Commission 2019d, 2019b, 2023d). To do so, there is the need to acknowledge the multiple dimensions that influence deliberate and rapid transitions, not only through investments in structural funds and technological innovations, but also through intangible cultural and perceptual factors that shape how communities construct shared meaning and collective actions (McCauley and Heffron 2018). These considerations affect local actors’ and relevant stakeholders’ capacities and willingness to collaborate in transformative governance processes (Löhr, Chlebna, and Mattes 2022).

Scientific literature increasingly highlights that just and inclusive energy transitions require more than compensatory measures or short-term subsidies. Instead, they depend on empowering local communities to actively shape transition pathways, integrate alternative development visions, and co-create solutions aligned with local needs and aspirations (Berka, MacArthur, and Gonnelli 2020; Skoczkowski et al. 2020). This includes not only technological choices, but also broader sociotechnical dimensions, including community engagement, the presence and coherence of supporting policies, and trust among citizens and public authorities, as well as place-based rebranding processes that support new economic identities beyond fossil fuel dependency (A. S. Hansen, Manniche, and Larsen 2024).

At the same time, transition pathways in CCIRs are strongly influenced by national policy decisions, particularly when these involve long-lived infrastructure investments and subsidisation schemes. When national planning prioritises fossil-based “transition” solutions, such as the expansion of natural gas infrastructure, local communities may face constrained transition options and reduced agency, even when alternative, more sustainable pathways exist. This tension is further exacerbated by shortcomings in multilevel governance, where local and regional perspectives are insufficiently integrated into strategic decision-making, despite formal requirements for inclusive climate and energy dialogue at the EU level (European Commission (EC) 2023; European Parliament and Council of the European Union 2018).

Chapter 4 addresses these challenges by examining residential energy transition pathways at the local level, focusing on the municipality of Megalopolis, a post-lignite CCIR in Greece. By integrating a participatory scenario design approach into the dissertation’s modelling framework, the chapter explores alternative residential transition pathways that differ in technology choices, household engagement, and local development orientations. This enables the assessment of how locally grounded transition scenarios affect decarbonisation outcomes, household energy costs, affordability concerns, and broader energy justice implications in a region where residential decarbonisation intersects with structural vulnerabilities and post-lignite transition challenges and opportunities.

Overall, **Chapter 4** contributes to the third thematic research question (RQ₃) by examining how local transition dynamics and degrees of citizen participation may influence energy justice implications of residential energy transition pathways.

1.4. Structure

The current dissertation thesis is structured in five chapters as depicted in Figure 1.1, namely:

Chapter 1 - Introduction: The first chapter provides the conceptual and policy background of the dissertation, situating the research within the broader context of EU climate and energy objectives and the residential energy transition. It introduces the key challenges associated with decarbonisation, energy resilience, and energy justice in the building sector, and discusses the limitations of existing energy system modelling approaches in addressing these dimensions. Based on the identified gaps, the

scope and objectives of the dissertation are defined, leading to the formulation of the overarching research question and the three thematic research questions that guide the analysis.

Chapter 2 - National decarbonisation pathways: The second chapter focuses on the assessment of long-term residential decarbonisation pathways at the national level. This chapter evaluates the conditions under which national energy planning can meet EU and national decarbonisation targets by 2050. Alternative transition pathways are explored by varying renovation rates, technology choices, and policy priorities, allowing the identification of the conditions required for achieving climate neutrality in the residential sector. The results provide quantitative insights into emissions trajectories, energy consumption, and household-level costs, with direct relevance for national policy design.

Chapter 3 – Interaction of national planning with regional transition: The third chapter examines how nationally defined residential energy transition strategies translate into regionally differentiated outcomes. Applying the modelling framework at the regional level, the analysis focuses on the Peloponnese region, where the expansion of natural gas infrastructure introduces a gas-oriented transition pathway in an area where such networks were previously absent. This pathway is compared with electrification-focused alternatives under different renovation trajectories, in order to examine how nationally driven infrastructure decisions interact with regional policy targets and shape residential decarbonisation outcomes, household energy costs, and fossil-fuel dependence. The chapter provides insights into whether new gas infrastructure supports the region’s transition or represents a missed opportunity for strengthening a long-term low-carbon and resilient residential energy pathway, including through risks related to infrastructure lock-in, stranded assets, and exposure to external fossil-fuel dependencies.

Chapter 4 – Local dimensions of a just residential energy transition: The fourth chapter shifts the analysis to the local level, focusing on the conditions under which residential energy transitions in carbon-dependent regions can evolve into green, inclusive and just transition pathways. The analysis focuses on the municipality of Megalopolis, a structurally vulnerable post-lignite region in Greece, where residential decarbonisation intersects with broader socio-economic and post-lignite transition challenges. By coupling the dissertation’s modelling framework with a participatory scenario design approach, the chapter explores alternative residential transition pathways that differ in technology choices, household engagement, and local development orientations. The analysis assesses how these pathways shape decarbonisation outcomes, household energy costs, affordability concerns, and broader energy justice implications, highlighting the role of citizen participation, locally adapted transition strategies, and place-based reorientation in supporting a more inclusive and equitable low-carbon transition.

Chapter 5 – Discussion and conclusions: The final chapter synthesises the findings across the three thematic research questions and addresses the overarching research question of the dissertation. It discusses how the modelling framework approached within this dissertation can support effective residential energy transition strategies that address decarbonisation, energy resilience, and energy justice across different governance scales. The chapter reflects on the policy relevance of the results, outlines the main scientific contributions of the dissertation, and discusses limitations of the research. It concludes by identifying directions for future work and potential extensions of the modelling framework to other contexts and applications.

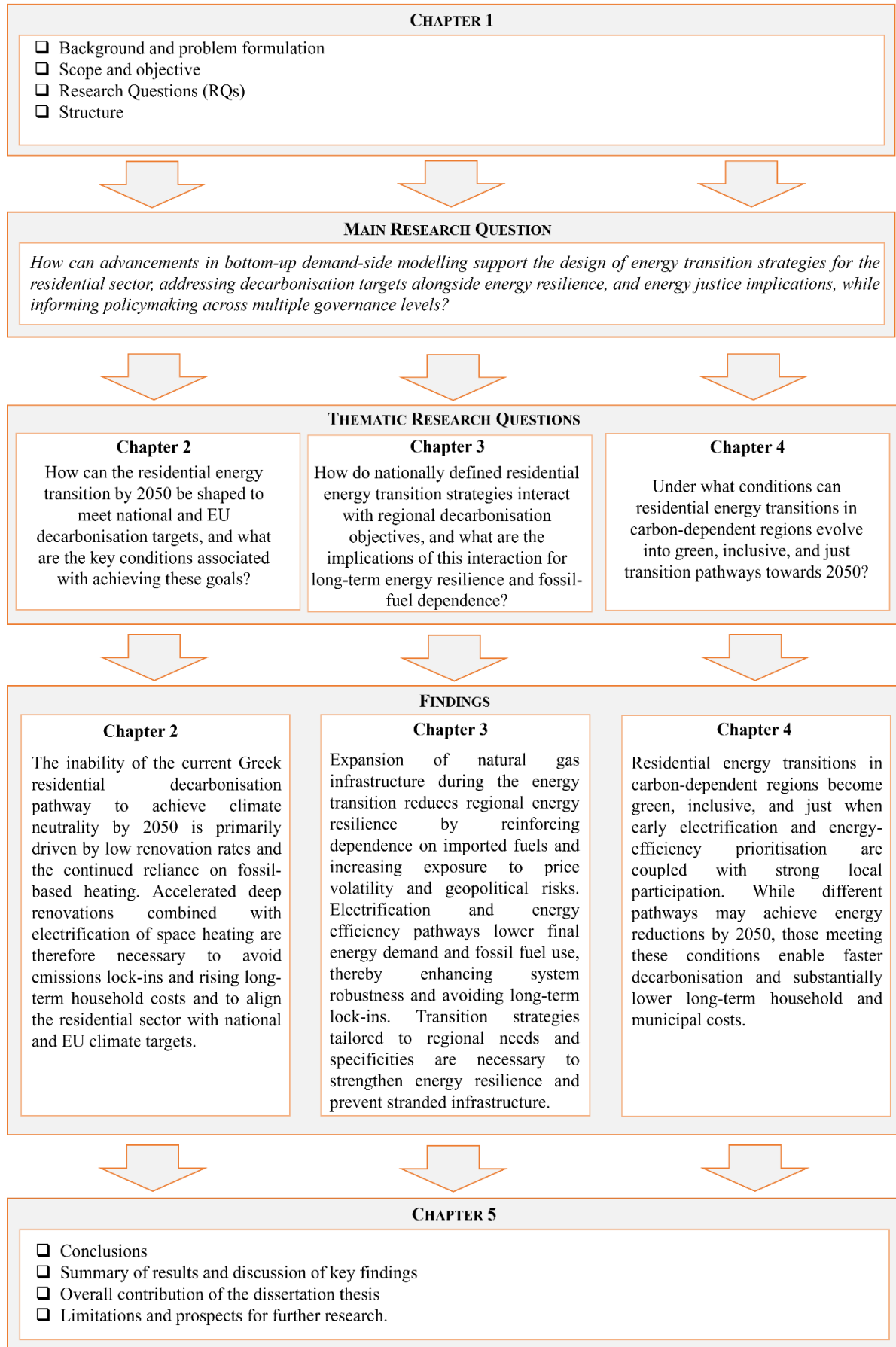


Figure 1.1. Graphical overview and structure of the dissertation thesis.

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Chapter 2 - Analysing energy transition impacts at the national level in view of the national and EU decarbonisation targets

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Nomenclature

Acronyms & abbreviations			
CO ₂	Carbon Dioxide	PPD	Predicted Percentage of Dissatisfaction
DREEM	Dynamic high-Resolution dEmand-side Management	RC	Resistance-Capacity
ELSTAT	Hellenic Statistical Authority	T _o	Mean outdoor air temperature
EPBD	Energy Performance of Buildings Directive	T _{air}	Mean indoor air temperature
ETS	Emission Trading System	TEESlab	Technoeconomics of Energy Systems laboratory
HBS	Household Budget Survey	TEEM	TEESlab Modelling suite
NECPs	National Energy and Climate Plans	TMY	Typical Meteorological Year
PMV	Predicted Mean Vote	TUS2013	Time of Use Survey 2013

2. Towards decarbonisation or lock-in to natural gas? A bottom-up modelling analysis of the energy transition ambiguity in the residential sector by 2050

Abstract

While a green transition in the Greek building sector is considered critical towards a secure and resilient energy system by 2050, national policymaking continues to support schemes and investments on the expansion of the natural gas grid in the mainland, viewing natural gas as a transition fuel, especially in the residential sector. In this context, this article uses a bottom-up high-resolution demand-side model to simulate different transition scenarios in the Greek residential sector by 2050, as these are extracted from the current existing policy planning and political decisions, recent amendments currently under public consultation, and relevant national experts' feedback. Simulation outcomes provide the evolution of the energy mix by 2050, along with the respective economic and environmental implications, for the different scenarios under study. Based on these outcomes, two key findings are derived: first, the existing renovation rate as set by national policymaking is not enough to lead to decarbonisation by 2050. If the goal is to achieve decarbonisation by 2050, then the current annual renovation rate of 1.5% must be updated to 2.5%, while, if a more ambitious goal of achieving decarbonisation by 2040 is to be adopted, the annual renovation rate must be updated to 3.5%. Second, the scenarios that promote electrification and the early phase out of natural gas result in lower costs, at both the national and the household level, and in lower levels of carbon emissions by 2050, implying that the current national reliance on natural gas may result in a missed opportunity of a green and inclusive energy transition, or even worse in a potential lock-in effect. Overall, this study provides critical and actionable insights to inform the development of national planning initiatives and support policymakers in crafting strategies that align with the overarching objectives of decarbonisation, climate neutrality, and energy security.

Keywords: Natural gas; Electrification; Decarbonisation; Energy transition; Energy efficiency; Residential sector

2.1. Introduction

The European Union's (EU) building sector is responsible for more than 40% of the final energy consumption and one-third of the total carbon dioxide (CO₂) emissions (Ruusu et al. 2019), while more than 65% of the buildings' energy is used for heating, and almost half of buildings are currently using inefficient fossil fuel-based boilers that have exceeded their technical lifetime (Matthias Buck et al. 2019). Moreover, more than half of the energy consumed in buildings is attributable to the residential sector, constituting nearly one-third of the EU's cumulative final energy consumption (Eurostat 2022). Consequently, achieving the overall vision of making Europe the first climate-neutral continent by 2050 necessitates a concerted effort to reduce energy consumption in the building sector and improve its environmental footprint (Papantonis et al. 2022b).

To realise this vision, the European Commission has established several strategies, directions, and regulations focusing on the key role of implementing energy efficiency measures (N.-A. Spyridaki et al. 2020), especially considering the geopolitical developments of the past few years, which have raised several concerns about rising energy prices and energy security (Tzani et al. 2023). As a result, the European Commission has developed the "REPowerEU" plan (2022) (European Commission 2022c), which along with the "Fit-for-55" package (2021) (European Commission (EC) 2021), the revised Energy Efficiency Directive (EED) (2023), and the soon to be revised Energy Performance of Buildings Directive (EPBD) (2024), aim to bring major changes in the use of fossil fuels in buildings (European Commission 2023a). Especially the targets of (i). cutting the EU's dependence of Russian natural gas, (ii). enhancing the role of energy efficiency, (iii). phasing out fossil fuel boilers, and (iv). pricing emissions stemmed from heating in the building sector via a new parallel Emissions Trading System (ETS), increase the need of investing in fossil fuel alternatives such as electrification (Chyong and Henderson 2024).

In this direction, priorities at the pan-European level are being re-examined, including the design of new revised National Energy and Climate Plans (NECPs) in Member States. According to the EU's Regulation on the Governance of the Energy Union and Climate Action (European Parliament and Council of the European Union 2018), each Member State is obliged to produce an updated ten-year NECP starting from 2024 and also incorporating the new ambitious energy and environmental targets set by the "Fit-for-55" and "REPowerEU" strategies.

When it comes to the case of Greece, and in the context of the abovementioned EU's strategic visions and targets, a green transition in the building sector, and especially in the residential sector, which is responsible for around 25% of the country's final energy consumption, is considered critical towards a secure and resilient energy system by 2050. In addition to the latter, households are also highly exposed to energy poverty as Greece is one of the Member States that significantly suffer from the phenomenon, displaying high recorded values based on relevant indicators (Greek Ministry of Environment and Energy 2021). Apart from the socioeconomic causes attributed to the phenomenon of energy vulnerability (high energy prices, low income, etc.) though, another major influencing factor is also the poor energy performance of the existing residential stock (European Commission (EC) 2023); 55% of the dwellings in Greece are constructed before 1980, having, thus, low performance standards, or no thermal insulation (Boemi and Papadopoulos 2019).

In this context, the latest official NECP's version has established a goal for approximately 12-15% of Greece's dwellings to undergo a full or partial renovation by 2030, while also prioritising the consumption of natural gas (Greek Ministry of Environment and Energy 2019). However, given the geopolitical developments of the past few years, with Russia's invasion of Ukraine and the consequential energy crisis and high inflation rates since then, doubts regarding the efficacy of the current planning have surfaced, underscoring the pressing need for its amendment. These doubts are

mainly concentrated around Greece's persistent reliance on natural gas as a transition fuel and the subsequent investments in new fossil-fuel infrastructure, along with the slow progress in energy efficiency improvements, and the modest decarbonisation objectives set in the residential sector.

While natural gas has been viewed as a transition fuel in Greece, recent events highlight the risks associated with relying to it. Uncertainty in the natural gas market, compounded by factors like potential price volatility due to weather conditions and disruptions in Russian gas deliveries, highlights the risk of a potential lock-in effect and necessitates a comprehensive reconsideration of energy planning (Su et al. 2019). This reliance exposes Greece to significant vulnerabilities related to price fluctuations, particularly impacting households already grappling with energy poverty or on the brink of it. Sudden increases in gas prices can exacerbate financial strain, making it challenging for these households to meet basic energy needs. As a result, subsidies may be allocated to address emerging issues, as witnessed during the recent energy crisis; from September 2021 to November 2022, Greece dedicated around €9 billion to energy subsidies and other measures to help consumers pay utility bills (European Commission 2023c). However, while subsidies may provide short-term relief, they fail to address the underlying issue and merely serve as temporary solutions. This approach risks postponing the inevitable and perpetuating a cycle where the problem resurfaces, leading to continued public expenditures (ACER 2023).

In addition to these concerns, a growing debate among different energy system actors surround the compatibility of natural gas with Greece's vision to conform with the EU's goals and achieve decarbonisation (Weidner and Guillén-Gosálbez 2023). This debate also finds support in the scientific literature, which suggests that shifting focus from natural gas to electrification of heating, not only enhances energy security, but also offers significant climate benefits by reducing CO₂ emissions, thereby facilitating progress towards decarbonisation targets (Wu et al. 2024). All these concerns underscore the necessity of the evidence-based amendment of the Greek national planning, indicating the challenge posed by the absence of scientific research focused on national policy strategies. Without quantified research outcomes, policymakers lack the insights needed to design effective strategies that align with the latest developments and evolving climate ambitions (Süsser et al. 2022). This lack of information not only hampers the ability to accurately assess the impact of current policies and identify areas for improvement, but also contributes to the persistence of significant gaps during their amendment (Michas et al. 2020). Therefore, there is a pressing need for rigorous scientific research and quantitative outcomes towards better-informed decision-making and evidence-based policymaking to amend national planning and ensure alignment with evolving EU directives and climate goals (Kleanthis et al. 2022).

This article seeks to shed light in the current policy debate in the Greek residential sector by analysing different energy transition scenarios by 2050, with the aim to ensure that the country's energy planning trajectory remains robust and aligned with the evolving EU's climate and energy ambitions and respective targets. The overarching hypothesis of this study posits that the current national planning and its reliance on natural gas as a transition fuel might lead to a missed opportunity of a green and fair transition, unable to achieve the desired decarbonisation targets by 2050 and resulting in higher charges for households, especially when compared to alternative strategies that promote electrification and phase out of natural gas.

To explore this hypothesis, the following research questions are formulated: (a). "Is the existing national planning in Greece ambitious enough to achieve the vision of decarbonisation in the residential sector by 2050, or significant adjustments are required in view of the upcoming NECP's amendment?", (b). "What is the most cost-effective technology mix towards decarbonisation in the Greek residential sector?", (c). "Should policymaking at the national level proceed with the current strategic planning, investing in natural gas as a transition fuel, also increasing the country's energy dependence on fossil

fuels?”. To provide answers to the overarching hypothesis and the individual research questions of this work, a bottom-up dynamic high-resolution demand-side management model is used to simulate the energy demand evolution in the Greek residential sector by 2050 under different transition scenarios, as these are extracted from the current existing policy planning and political decisions, recent amendments under public consultation, and relevant national experts’ feedback.

However, a recent review article on existing tools, user needs, and required model adjustments for energy demand modelling of a carbon-neutral Europe by 2050, published by Chatterjee et al., (2022), highlights that energy demand and demand-side management models need to assist model users more when it comes to the short- and the mid-term time horizons of the energy transition (2030 & 2040), as most of the existing tools mainly deal with long-term time horizons (2050 and beyond up to 2100) (Chatterjee et al. 2022b). To assist decision-makers, demand-side models must also adapt to shorter time resolutions, as sector coupling, fuel swapping in final energy uses, and modifications in efficiency will lead to changes in the future demand profiles in the near future; not only in terms of absolute numbers but also in their shape, as the analysis of load curves becomes crucial for the design of future energy systems (Prina et al. 2020). Nevertheless, it is common for impact assessment models in the field of energy demand and demand-side management in the building and the residential sectors to focus on long-term transitions, while, most of them, calculate energy demand through a top-down approach, mainly based on macroeconomic indices and parameters (Pavlović, Živković, and Ivezić 2023). Such an approach does not allow for easily linking the energy system to economic developments and technological breakthroughs (i.e., inclusion of alternative energy technologies and/ or carriers at interim (milestone) simulation years) towards more accurate future demand projections and assessment (Mastrucci et al. 2023).

In addition, when it comes to the case of Greece, previous scientific efforts have either focused on regional levels, as seen in Katsaprakakis et al. (2022) (Katsaprakakis et al. 2022), or primarily on behavioural changes (Koasidis et al. 2022), or on specific aspects of the energy transition, such as Nikas et al. (2020) (Nikas et al. 2020). On the other hand, comprehensive national-level analyses in the residential sector, like those by Vlachou and Pantelias (Vlachou and Pantelias 2022), Karamaneas et al. (2023) (Karamaneas et al. 2023), and Streimikiene et al. (2021) (Streimikiene et al. 2021), do not follow a bottom-up modelling approach, as the one presented in this article. To the best of the authors' knowledge, thus, this is the first time that a bottom-up high-resolution demand-side management model is used to explore different energy transition scenarios in such detail in the case of Greece, also evaluating the feasibility of the national planning and the respective NECP’s targets, and their alignment with the commitment to the EU’s most updated policy developments.

Considering all the above mentioned, the novel contribution of this work is twofold, addressing existing gaps in the scientific literature by:

- Using a dynamic bottom-up demand-side modelling approach, which, compared to other existing tools in the field, allows for a more realistic and in-depth representation of the dynamic system that the residential sector is, not only in the long term, but also in the short- and the mid-term time horizon. This approach allows for a more detailed evaluation of different energy transition scenarios, linked to policy and economic developments and technological breakthroughs, towards more accurate demand projections and holistic assessment.
- Delving into the alignment between the current national planning in the Greek residential sector and the latest policy developments at the EU level, by evaluating the feasibility of the current NECP’s targets towards decarbonisation by 2050, also providing policymakers and other relevant decision-makers with insightful details on alternative pathways that could promote a green and

fair transition, compared to the current reliance on natural gas, which could result in a potential “lock-in” effect.

2.2. Methods

To explore the overarching hypothesis of this study and answer the individual research questions formulated, the Dynamic high-Resolution dEmAnd-sideE Management (DREEM) model, a fully-integrated energy demand and demand-side management simulation model, focusing on the building sector, is used. The DREEM model expands the computational capabilities of existing Building Energy System and demand-side models, by not only calculating energy demand, but by also assessing the benefits and limitations of demand flexibility, primarily for the main end-users (consumers/ citizens), and, then for other energy system actors involved (suppliers, retailers, Distribution System Operators, etc.).

To address the needs of the current study, the model’s original architecture and capacities, as originally presented by Stavrakas and Flamos (2020) (Stavrakas and Flamos 2020), have been expanded, as part of the work undertaken in the context of the EC-funded Horizon 2020 projects “SENTINEL⁹”, “ENCLUDE¹⁰”, and “ENPOR¹¹”, while the updated modelling structure is presented in **Fig. 2.1**. Here, a description of the new components and respective modules that have been developed and integrated to the original model’s structure is provided, along with the components and modules that have been used for the application at hand, based on **Table 2.1**.

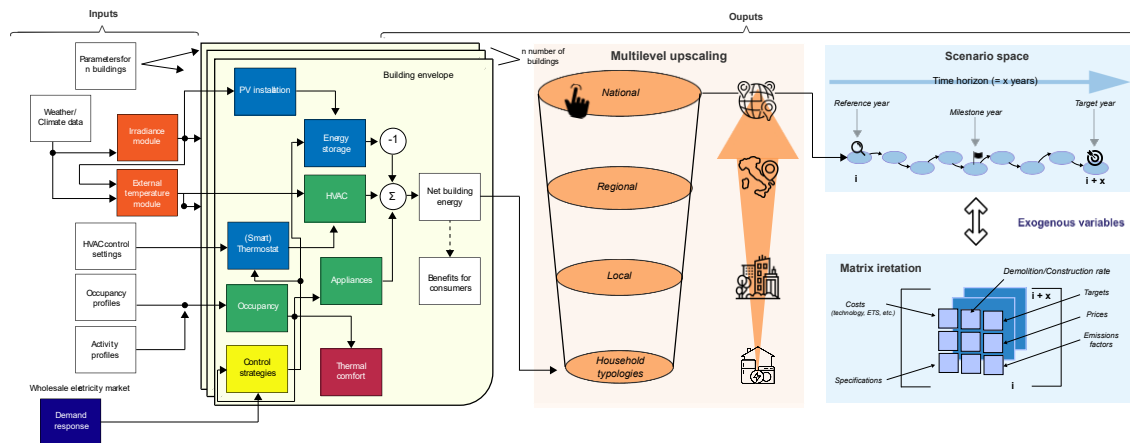


Fig. 2.1. Expanded architecture of the DREEM model as it currently stands.

Table 2.1. Hierarchical structure of the expanded version of the DREEM model as used in this study: Short description of the main components and modules.

Components	Modules	Description	Developed
C ₁ : Weather/Climate data	-	This single-module component is responsible for generating climatic boundary conditions. It reads weather data from the respective files and then provides them to the other components, where and when necessary.	Modelica
C ₂ : Building envelope	-	This single-module component models different building typologies with the corresponding characteristics, properties, and heat conduction elements.	Modelica Python

⁹ <https://sentinel.energy/>

¹⁰ <https://encludeproject.eu/>

¹¹ <https://www.enpor.eu/>

C ₃ : Energy demand	<i>C₃M₁: Occupancy</i>	This module defines and sets the parameters for the behaviour and the activities of the occupants by generating and storing default patterns.	Modelica
	<i>C₃M₂: Appliances</i>	This module is responsible for generating energy demand profiles from appliances, using statistics describing their mean total daily energy demand and associated power use characteristics, including steady-state consumption, or typical use cycles, based on occupancy patterns.	
	<i>C₃M₃: Heating, ventilation, and air conditioning</i>	This module is responsible for heating, ventilation, and air conditioning inside the building.	
C ₄ : Thermal comfort	-	This single-module component is responsible for determining, based on international standards, appropriate conditions and temperature ranges that result in occupants' thermal satisfaction.	Modelica Python
C ₈ : Multilevel upscaling	-	This new single-module component is responsible for applying an upscaling approach to compute cumulative energy consumption patterns in the building sector, at the scale of interest, using parameters and statistics obtained from survey and/ or census data. It receives inputs from the "C ₂ : Building envelope" and the "C ₃ : Energy demand" components.	Python
C ₉ : Transition matrix	<i>C₉M₁: Scenario space</i>	This module is responsible for designing the scenario space (in terms of the transition pathways and the respective exogenous variables) inside of which the transition matrix is initiated and updated, based on relevant policy documents' specifications and practical experts' feedback.	Python
	<i>C₉M₂: Matrix iteration</i>	This module is responsible for initialising the transition matrix and updating it at each time interval (i.e., iteration), following the scenario space's specifications (i.e., targets and constraints) derived from the " <i>C₉M₁: Scenario space</i> " module.	

All the model's modules have been developed using the "Buildings" library (Wetter 2011), an open-source, freely available Modelica library for building energy and control systems (Bünning, Sangi, and Müller 2017; Wetter, Bonvini, and Nouidui 2016; Zuo et al. 2016a). Alongside to the Modelica models, Python scripts have been developed to model parts of the model's components and to enable the interface with the Dymola simulation environment. DREEM is part of the Technoeconomics of Energy Systems laboratory (TEESlab) Modelling suite (TEEM); the model is open access¹² under the "GNU Affero General Public License".

¹² <https://github.com/TEESlab-UPRC/DREEM>

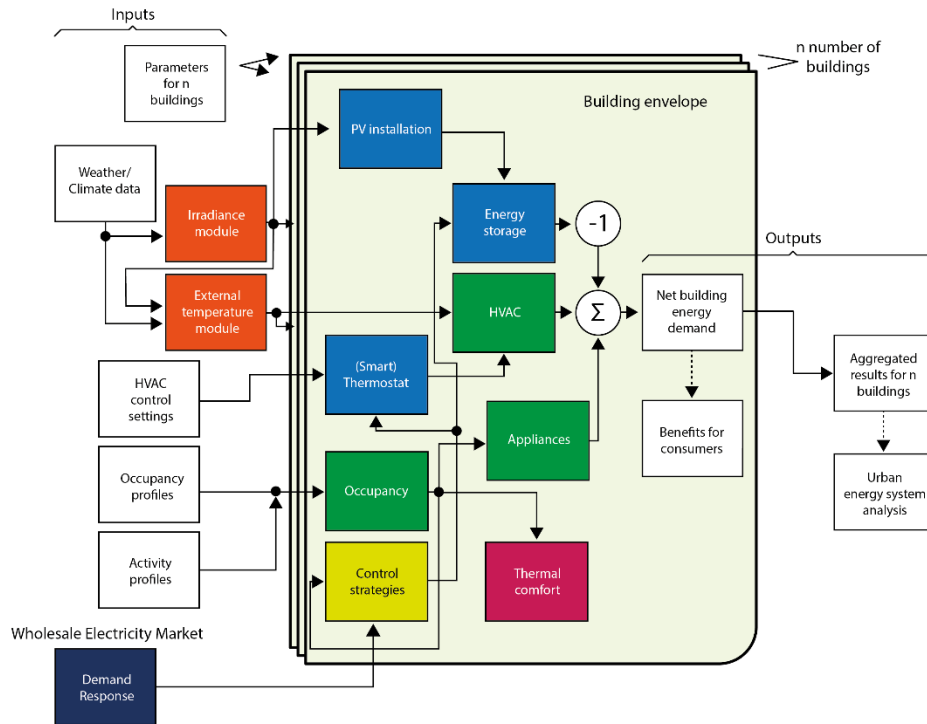


Fig. 2.2. The original architecture of the DREEM model as presented by (Stavrakas and Flamos 2020).

2.2.1. C₁: Weather/ Climate data

Seasonal variability to reflect the changing level of demand between winter and summer is an important aspect of demand-side management modelling, often omitted or addressed in an oversimplified manner by existing models in the field. Accurately capturing seasonal fluctuations is essential for realistic energy planning, as it allows for a more precise simulation of energy consumption patterns throughout the year.

The DREEM model addresses this issue thoroughly through the inclusion of a single module component dedicated to generating accurate climatic boundary conditions based on historical weather data. To do so, the component uses Typical Meteorological Year (TMY) (Cebecauer and Suri 2015) weather data format, and in particular the TMY3 format, while it is then configured to provide a common set of irradiance and temperature data for the geography under study, with the respective irradiance and temperature profiles having appropriate time-diversity (i.e., hourly analysis) to enable higher resolution. Temporal resolution and seasonal variability in the model are captured each time based on the needs of each particular application at hand. For example, a high temporal resolution of 1 hour, 30', 15', etc., is required when studying the effects of demand response, as it allows to properly capture the impacts of seasonal weather fluctuations on energy consumption patterns

2.2.2. C₂: Building envelope

The DREEM model builds on the concept of 'reduced (low)-order' thermal network modelling, which represents a thermal zone by thermal resistances and capacities (RC-network), using the electrical circuit analogy, in which voltage is analogous to temperature and current is analogous to convective and radiative heat transfer (Harish and Kumar 2016). The respective module represents all main thermal masses of the building under study as four elements, accompanied with supportive features for consideration of solar radiation (as visualised by Stavrakas and Flamos (2020) (Stavrakas and Flamos 2020)).

Thermal network models generally focus on one-dimensional heat transfer calculations. A geometrically correct representation of all the walls of a thermal zone is thus not possible. To reduce

simulation effort, it is, thus, reasonable to aggregate walls to representative elements with similar thermal behaviour. The number of a wall's elements depends on the thermal properties of the walls and their excitation (e.g., through solar radiation), on the excitation frequencies. The same applies for the number of RC-elements per wall. There is the option between models with one to four wall elements, and to define the number of RC-elements per wall for each wall. The latter can be done by setting n_k , which is the length of the vectors for resistances R_k and capacities C_k . Each wall element uses reduced-order models to describe heat conduction and storage within the wall, depending on if the wall contributes to heat transfer to the outdoor environment (exterior walls), or it can be considered as simple heat storage elements (interior walls). All the exterior walls and windows provide a heat port to the outside. All the wall elements (exterior walls, windows, and interior walls) are connected. This component's modelling architecture is defined in the German Guideline VDI 6007 Part 1 (German Association of Engineers 2012), which describes a dynamic thermal building model for calculations of indoor air temperatures and heating/cooling power. The important modelling parameters that are used to parameterise the “C₂: Building envelope” component in the DREEM model are as follows:

- $n...$ defines the length of chain of RC-elements per wall.
- $R...[n]$ is the vector of resistances for the wall element. It moves from indoor to outdoor.
- $C...[n]$ is the vector of capacities for the wall element. It moves from indoor to outdoor.
- $R..._{Rem}$ is the remaining resistance between $C[end]$ and outdoor surface of the wall element. This resistance can be used to ensure that the sum of all the resistances and coefficients of heat transfer is equal to the U-value. It represents the part of the wall that cannot be activated and thus does not take part at heat storage.

The thermal behavior of a homogeneous wall layer v of arbitrary thickness s , for one-dimensional heat flow and periodic case problem, is illustrated by the following matrix notation (**Fig. 2.3**):

$$\begin{pmatrix} \underline{\theta}(x=0) \\ \underline{q}(x=0) \end{pmatrix}_v = \mathbf{A}_v \cdot \begin{pmatrix} \underline{\theta}(x) \\ \underline{q}(x) \end{pmatrix}_v$$

where x is the coordination towards the normal wall.

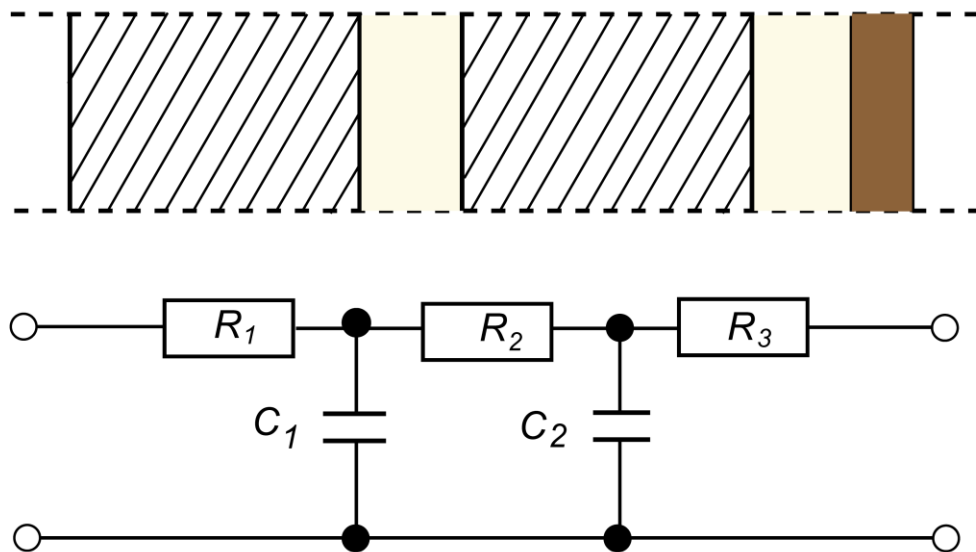


Fig. 2.3. Graphical representation of the thermodynamic model used in DREEM for one wall element.

The chain matrix A_v for a wall layer can be written:

$$A_v = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}_v = \begin{bmatrix} Rea_{11} & Ima_{11} & Rea_{12} & Ima_{12} \\ -Ima_{21} & Rea_{11} & -Ima_{12} & Rea_{12} \\ Rea_{21} & Ima_{21} & Rea_{22} & Ima_{22} \\ -Ima_{21} & Rea_{21} & -Ima_{22} & Rea_{22} \end{bmatrix}_v$$

while the elements of the chain matrix for a wall of layer v are obtained as:

$$\begin{aligned} Rea_{11} &= Rea_{22} = \cosh \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \cos \sqrt{\frac{1}{2} \omega_{BT} RC} \\ Ima_{11} &= Ima_{22} = \sinh \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \sin \sqrt{\frac{1}{2} \omega_{BT} RC} \\ Rea_{12} &= R \cdot \sqrt{\frac{1}{2 \omega_{BT} RC}} \cdot \left(\cosh \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \sin \sqrt{\frac{1}{2} \omega_{BT} RC} + \sinh \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \cos \sqrt{\frac{1}{2} \omega_{BT} RC} \right) \\ Ima_{12} &= R \cdot \sqrt{\frac{1}{2 \omega_{BT} RC}} \cdot \left(\cosh \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \sin \sqrt{\frac{1}{2} \omega_{BT} RC} - \sinh \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \cos \sqrt{\frac{1}{2} \omega_{BT} RC} \right) \\ Rea_{21} &= \frac{-1}{R} \cdot \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \left(\cosh \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \sin \sqrt{\frac{1}{2} \omega_{BT} RC} - \sinh \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \cos \sqrt{\frac{1}{2} \omega_{BT} RC} \right) \\ Ima_{21} &= \frac{-1}{R} \cdot \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \left(\cosh \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \sin \sqrt{\frac{1}{2} \omega_{BT} RC} + \sinh \sqrt{\frac{1}{2} \omega_{BT} RC} \cdot \cos \sqrt{\frac{1}{2} \omega_{BT} RC} \right) \end{aligned}$$

where:

- R is the thermal resistance of the wall's layer per unit area in $\frac{m^2 \cdot K}{W}$ with $R = \frac{s}{\lambda}$,
- C is the heat capacity of the wall's layer per unit area in $\frac{J}{m^2 \cdot K}$, $C = c \cdot \rho \cdot s$,
- ω is the angular frequency in $\frac{1}{s}$, $\omega = \frac{2 \cdot \pi}{86,400 \cdot T}$,
- T is the period of the fundamental in days. For the calculations we select a period time of $T=7$ days, based on ISO 13786 - Thermal performance of building components - Dynamic thermal characteristics - Calculation methods (EN ISO 13786 2010),
- s is the thickness of the wall's layer in m ,
- λ is the thermal conductivity of the wall's layer in $\frac{W}{m^2 \cdot K}$,
- $c \cdot \rho$ is the heat storage capacity of the wall layer in $\frac{J}{m^2 \cdot K}$.

The chain matrix $A_{1,n}$ of the total wall is calculated by multiplying the matrices A_v of the individual wall's layers ($v = 1, \dots, n$), as:

$$A_{1,n} = A_1 \cdot A_2 \cdot A_3 \cdot \dots \cdot A_{n-1} \cdot A_n$$

Based on the chain matrix $A_{1,n}$ of the total wall, the resistances and capacities of the replacement model are estimated as:

$$R_1 = \frac{1}{A} \cdot \frac{(Rea_{22} - 1) \cdot Rea_{12} + Ima_{22} \cdot Ima_{12}}{(Rea_{22} - 1)^2 + Ima_{22}^2}$$

$$R_2 = \frac{1}{A} \cdot \frac{(Rea_{11} - 1) \cdot Rea_{12} + Im a_{11} \cdot Im a_{12}}{(Rea_{11} - 1)^2 + Im a_{11}^2}$$

$$C_1 = A \cdot \frac{1}{\omega_{BT}} \cdot \frac{(Rea_{22} - 1)^2 + Im a_{22}^2}{Rea_{12} \cdot Im a_{22} - (Rea_{22} - 1) \cdot Im a_{12}}$$

$$C_2 = A \cdot \frac{1}{\omega_{BT}} \cdot \frac{(Rea_{11} - 1)^2 + Im a_{11}^2}{Rea_{12} \cdot Im a_{11} - (Rea_{11} - 1) \cdot Im a_{12}}$$

Where A is the total area of the wall in m^2 . The resistance R_3 is then calculated as the difference between the total heat transfer resistance of the wall and the sum of the equivalent model resistors R_2 and R_1 , as:

$$R_3 = \left(\frac{1}{A} \cdot \sum_{v=1}^n \frac{S_v}{\lambda_v} \right) - R_2 - R_1$$

The model can now be reduced to a simplified model (**Fig. 2.4**) that comprises of a total resistance R_w and heat capacity $C_{1,korr}$. For one-sided thermal stress, the replacement model simplifies the case of thermal load according. The total resistance R_w is equal to:

$$R_w = R_3 + R_2 + R_1 = R_{REM} + R_1,$$

while the corrected heat storage capacity $C_{1,korr}$ is equal to:

$$C_{1,korr} = A \cdot \frac{1}{R_1 \cdot \omega_{BT}} \cdot \frac{R_w - Rea_{12} \cdot Rea_{22} - Im a_{12} \cdot Im a_{22}}{Rea_{22} \cdot Im a_{12} - Rea_{12} \cdot Im a_{22}}$$

An external window is a special case of the replacement model and in this case, the heat storage capacity $C_{1,korr}$ should practically be set to zero.

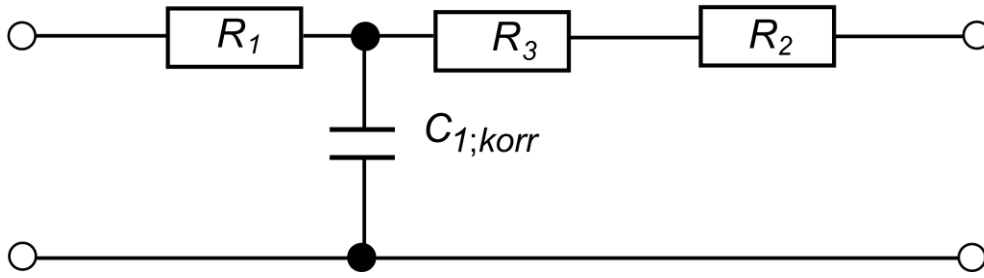


Fig. 2.4. Graphical representation of a simplified model for the thermal behaviour of components under asymmetrical loading.

2.2.3. C₃: Energy demand

The DREEM model aims to generate accurate and realistic energy demand profiles, avoiding unnecessary computational complexity, by building on the concept of stochastic modelling and providing simulated data about households' energy demand, with statistics suitable for the task at hand (Stavrakas and Flamos 2020). This component uses a bottom-up approach to simulate energy consumption considering buildings' occupancy, use of appliances, and heating, cooling, and ventilation measures. The component's individual modules use many simplified assumptions to simulate various aspects of energy demand (occupancy and building occupants' activity/ behaviour profiles, sharing of

appliances, etc.) and focuses on parameters and statistics obtained from survey and/or census data.

2.2.4. C₄: Thermal comfort

The DREEM model focuses on addressing the- often overlooked by other models in the field- aspect of occupants' thermal comfort, by utilising an individual component that aligns with international standards (DIN EN ISO 7730 (DIN EN ISO 7730 2005a), ASHRAE 55 (Taleghani, Tenpierik, Kurvers, and van den Dobbela 2013), EN 15251 (Fanger and others 1970)). Built upon the Fanger approach, it employs the characteristic Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) indices (Fanger and others 1970). To determine optimal indoor thermal conditions for occupants, the model calculates PMV and PPD, by considering weather and other parameters, such as dynamic metabolic rates and clothing insulation, adjusted based on seasonal variations. By doing so, it offers a comprehensive approach to accurately model thermal comfort and fill existing modelling gaps. The acceptable ranges of the PMV and PPD indices are presented in **Table 2.2**.

Table 2.2. PMV and PPD expectation levels according to the EN 15251 standard (CEN Ce. CEN Standard EN15251. In: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, 2007. n.d.).

PPD (%)	PMV	Description
< 6	$-0.2 < \text{PMV} < +0.2$	Increased expectation level: recommended for spaces inhabited by highly vulnerable individuals with specific needs, like sick children, elderly persons, etc.
< 10	$-0.5 < \text{PMV} < +0.5$	Standard expectation level: new and renovated buildings.
< 15	$-0.7 < \text{PMV} < +0.7$	Moderate expectation level (acceptable range): existing buildings.
< 20	$-1 < \text{PMV} < +1$	Minimum expectation levels: values acceptable only for limited parts of the day.
> 20	$\text{PMV} < -1$ or $\text{PMV} > +1$	Unacceptable expectation levels: values deviating acceptable criteria, deemed tolerable only for a very limited part of the year.

To configure the appropriate indoor temperature ranges and to define the proper indoor temperature setpoints for each simulation period, our analysis follows the approach outlined by Stavrakas and Flamos (2020) (Stavrakas and Flamos 2020), based on the correlation between the mean indoor air temperature (T_{air}) and the mean outdoor air temperature (T_o) across all the four climate zones in Greece ("Climate Zone A", "Climate Zone B", "Climate Zone C", and "Climate Zone D") during various weather conditions in three different periods:

- Period 1 (mild weather): April, May, October, and November.
- Period 2 (warm weather): June-September.
- Period 3 (cold weather): December-March.

For Period 1, indoor temperature setpoints maintaining thermal comfort were determined using the de Dear and Brager adaptive model designed for HVAC applications (de Dear and Brager G.S. 1998), while for Periods 2 and 3, acceptable indoor temperature ranges were established by studying the correlation between PMV values and indoor temperatures as done in previous relevant studies (Brennan and Owende 2010). Critical PMV values and indoor temperatures were simulated, leading to linear trendlines used to define acceptable temperature setpoints. The resulting ranges are presented in **Table 2.3**, categorised based on the minimum PMV values for heating and the maximum PMV values for cooling, aiming to ensure a comprehensive consideration of adaptive thermal comfort for different weather condition periods.

Table 2.3. Acceptable indoor temperature ranges for each climate zone under study throughout the three different weather periods of the year.

Climate zone	Period 1								Period 2	Period 3
	April		May		October		November		Min-Max T _{air} (°C)	Min-Max T _{air} (°C)
	T _o	T _{air}	T _o	T _{air}	T _o	T _{air}	T _o	T _{air}		
A	15.6	23.5	20.3	24.0	19.3	23.9	14.9	23.4	22.1-26.7	20.7-24.5
B	15.2	22.9	19.8	23.4	18.8	23.3	14.5	22.8	21.5-26.0	20.2-23.9
C	14.9	22.4	19.4	22.9	18.4	22.8	14.2	22.4	21.1-25.5	19.8-23.4
D	13.8	20.8	18.0	21.2	17.1	21.2	13.2	20.7	19.5-23.6	18.3-21.7

2.2.5. C₈: Multilevel upscaling

This newly developed single-module component allows DREEM to serve as a modelling tool of accurate energy demand profiles in the building sector, within the broader field of local, regional, and national energy systems, in different geographical/ climate and socioeconomic contexts of interest. It uses an upscaling approach, building on parameters and statistics obtained from survey and/ or census data, to calculate cumulative energy consumption in the building sector, at the local, the regional, or the national level, according to the needs of each application at hand. After having specified the individual building typologies of interest under the “C₂: Building envelope” component and simulating their individual energy consumption patterns, based on the specifications and the parameterisation of the “C₃: Energy demand” component, this component computes cumulative energy consumption patterns at the scale under study as the product of each individual building typology’s energy consumption and the number of the respective buildings per typology and number of occupants (as extracted by available statistical data).

2.2.6. C₉: Transition matrix

The DREEM model has been developed to allow for producing outputs at a high resolution (i.e., one minute), also accounting for seasonal variability to reflect the changing level of demand between winter and summer, while its modular structure provides the necessary computational efficiency to simulate large numbers of buildings in the short-, the mid-, and the long-term transition, with the appropriate demand diversity and accuracy (due to its bottom-up structure), also reducing the simulation complexity owing to the multidisciplinary nature of energy demand models and their input data requirements (Chatterjee et al. 2022b). In this context, this newly developed component creates a scenario space, based on the policy specifications of each application at hand, which is further updated based on the evolution of exogenous variables (e.g., costs, prices, technological specifications) and is stored in a matrix to provide detailed information on the energy transition in the building sector for the time horizon (e.g., 2030, 2040, 2050) and the time interval (e.g., one hour, one year, five years) of interest.

C₉M₁: Scenario space

This module is responsible for designing the scenario space inside of which the transition matrix is initialised and updated. It starts with setting the modelling time horizon, i.e., reference year (simulation start year), interim milestone years (where and if necessary), and the target year (simulation end year), based, each time, on the specifications of the application under study. The initial scenario space is parameterised mainly based on recent policy documents, in accordance with the emission caps of the updated mitigation targets for 2030 and 2050, in the context of the “Fit for 55” package and the European Green Deal strategy. As a next step, relevant stakeholders’ and policy practitioners’ feedback is also considered to diversify and expand the initial scenario space, and eventually account for possible uncertainties and different potential evolutions of the future energy

system. Finally, the scenario space is further populated with the evolution of different exogenous variables, e.g., emission factors, evolution of relevant energy prices and costs, technological costs and relevant updated configurations, demolition rate of old buildings and construction rate of new ones, rate of population change, benefits for occupants and/ or other power actors involved.

C₉M₂: Matrix iteration

This module is responsible for initialising the transition matrix and updating it, at each time interval (as specified by the user at the simulation start time), based on inputs of cumulative energy consumption patterns (received from the “C₈: Multilevel upscaling” component) and the state of the scenario space (received from the “C₉M₁: Scenario space” module). At the simulation end time, this module derives the final transition matrix, containing detailed information on the different energy transition pathways in the building sector, at the resolution, and for the time horizon specified by the user, in each application at hand.

Fig. 2.5 visualises the methodological flowchart of the newly developed “C₈: Multilevel upscaling” and “C₉: Transition matrix” components, illustrating their individual operation and how they interact with each other to produce relevant outcomes at the scale of interest.

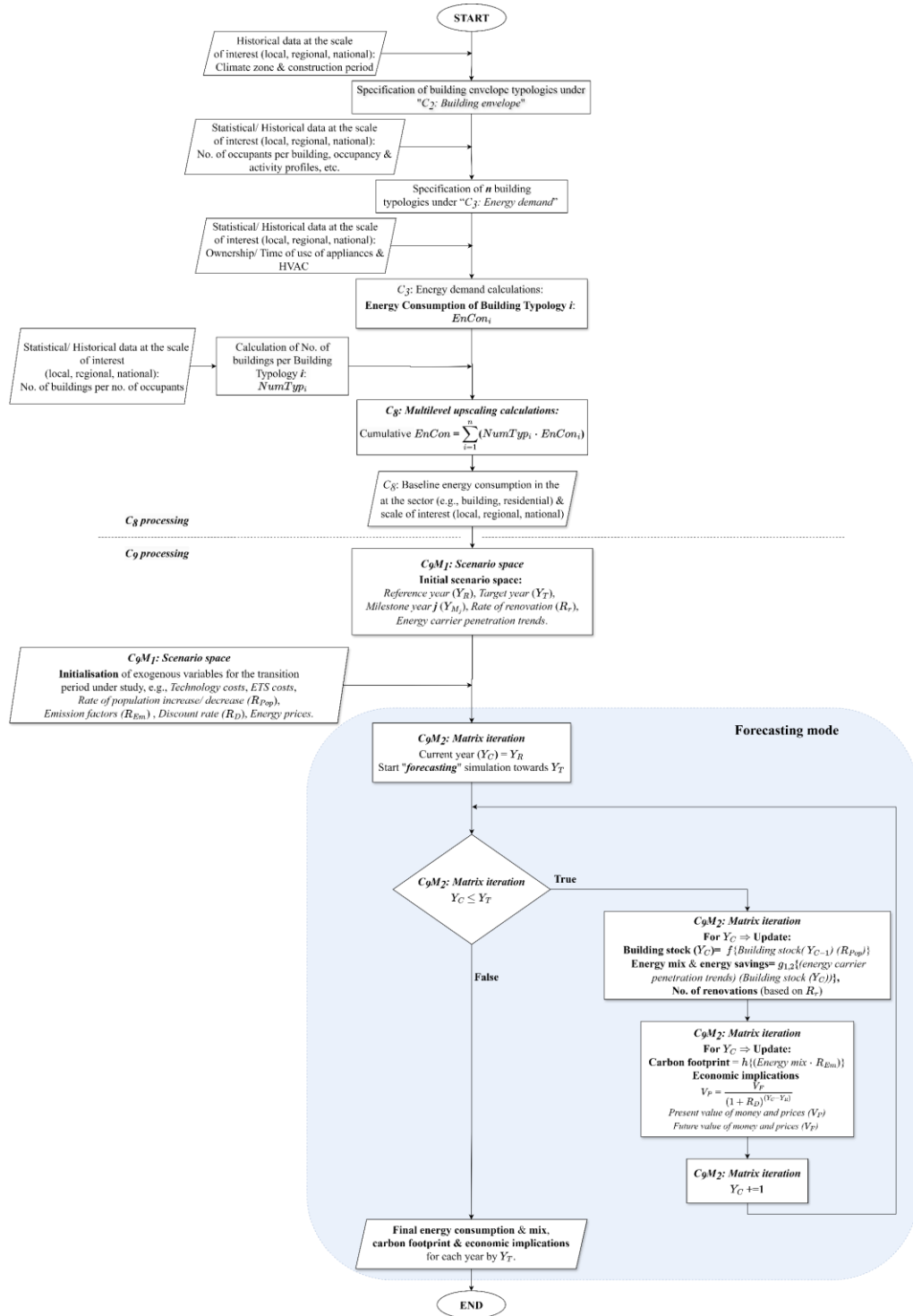


Fig. 2.5. Methodological flowchart of the newly developed “C8: Multilevel upscaling” and “C9: Transition matrix” components, illustrating their individual operation and how they both interact with each other.

2.3. Model application to the residential sector in Greece

In this section, the parameterisation of the DREEM model's individual components and modules required for this application is presented, along with the main data inputs, the scenario design, and the assumptions made for the Greek residential sector. Located in Southern Europe, Greece is divided into 13 regions, namely Attica, Central Greece, Central Macedonia, Crete, Eastern Macedonia and Thrace, Epirus, Ionian Islands, North Aegean, Peloponnese, Southern Aegean, Thessaly, Western Greece, and Western Macedonia (ACER 2023).

2.3.1. C₁: Weather/ Climate data

Greece is divided into four climate zones, namely "Climate Zone A" including the regions of Crete, Southern Aegean, and part of the region of Peloponnese and Ionian Islands, "Climate Zone B" including the regions of Attica, Central, Western Greece and Northern Aegean, as well as parts from the regions of Peloponnese, Thessaly, and Ionian Islands, "Climate Zone C" including parts of the regions of Thessaly, Central Macedonia, and Eastern Macedonia and Thrace, and "Climate Zone D" including parts the region of Western Macedonia and parts of the region of Eastern Macedonia and Thrace (Hellenic Ministry of Environment and Energy 2010).

To configure the DREEM model, weather/ climate data from the database of the World Meteorological Organisation is used (World Meteorological Organisation 2021). The data is formatted as TMY3, accumulating a 14-year period (2007-2021) of data values, and including information on latitude, longitude, and time zone in relation to Greenwich Mean Time, as well as temperature, relative humidity, wind speed and direction, sun direction and radiation values, on an hourly basis. For each region and climate zone under study, meteorological data available from several available locations are selected (Kapsomenakis et al. 2013). Indicatively, for "Climate Zone A", data from the regions of Crete (e.g., city of Heraklion, etc.), Peloponnese (e.g., the city of Kalamata) and Southern Aegean (e.g., Samos Island, etc.) is used, for "Climate Zone B", data from the regions of Attica (e.g., city of Athens, etc.), Central Greece (e.g., city of Lamia, etc.), Thessaly (e.g., city of Volos), and Western Greece (e.g., city of Agrinio, etc.), for "Climate Zone C", from the regions of Thessaly (e.g., city of Trikala, etc.), Central Macedonia (e.g., city of Thessaloniki, etc.), Epirus (e.g., city of Ioannina), and Eastern Macedonia and Thrace (e.g., city of Alexandroupolis, etc.). Finally, for "Climate Zone D" data from the region of Western Macedonia (e.g., city of Florina, etc.) is used.

2.3.2. C₂: Building envelope

For the parameterisation of this component, data from the different building typologies in the Greek residential sector is used, according to the "TABULA" database, which contains information on national residential typologies in different European countries, classified per climate zone and construction period (European Union 2017). For Greece and according to the transcription of the EPBD into the national law back in 2011, and its subsequent amendments in the following years (Daskalaki et al. 2011), the webtool distinguishes between four different construction periods, namely dwellings constructed: (i). before 1981, (ii). during the period 1981-2000, (iii). during the period 2001-2011, and (iv). after 2011.

2.3.3. C₃: Energy demand

For this component data for Greece and all its regions is used, as obtained from the "2020 Household Budget Survey (HBS2020)", which, to the best of the authors' knowledge, is the latest official survey conducted by the Hellenic Statistical Authority (ELSTAT) on households' energy consumption in Greece (Hellenic Statistical Authority ELSTAT 2020).

C₃M₁: Occupancy

This module uses household composition, and occupancy patterns derived from historical and statistical data. The first key factor to properly configure this module is the number of members per household, while the second key factor concerns the time that occupants spend being active at their homes, which is strongly connected to their employment status and work schedules. To quantify these parameters, i.e., the number of members per household, according to the different dwelling typologies, as specified in the “C₂: Building envelope” component, and occupants’ activity levels when they are at home, the HBS2020 data is used (Hellenic Statistical Authority ELSTAT 2020). In addition, to quantify the parameter on time that occupants spend at and away from home, based on their work schedule, statistical data from the ELSTAT’s “Time of Use Survey 2013 (TUS2013)” is used, which again, to the best of the authors’ knowledge, is the most recent survey data collected (Hellenic Statistical Authority (ELSTAT) 2014). The HBS2020 and the TUS2013 data allowed to come up with 12 different household typologies in the four climate zones of Greece, based on the most statistically significant data on dwelling typologies (**Table A1** in **Appendix A** (Hellenic Statistical Authority ELSTAT 2020)), occupancy schedules, and activity levels, as presented in **Table 2.4**.

Table 2.4. 12 household typologies in the Greek residential sector, based on dwellings’ climate zone and construction period, number of residents per dwelling, number of employed and non-economically active/unemployed, and their overall occupancy profiles.

a/a	Climate zone	Construction period	Members	Employed members	Non-economically active/unemployed members	Overall occupancy profiles
1	A	Before 1981	1	0	1	1 elderly person
2		1981-2000	2	1	1	1 employee & 1 unemployed person
3		After 2000	2	1	1	2 employed persons
4	B	Before 1981	3	1	2	1 employed, 1 unemployed person & 2 children
5		1981-2000	4	2	2	2 employed person & 2 children
6		1981-2000	2	2	0	1 employed & 1 unemployed person
7		After 2000	1	1	0	1 employed person
8	C	Before 1981	4	2	2	2 employed persons & 2 children
9		Before 1981	3	2	1	2 employed persons & 1 child
10		1981-2000	2	1	1	1 employed & 1 unemployed person
11		After 2000	1	1	0	1 employed
12	D	Before 1981	1	0	1	1 elderly person

C₃M₂: Appliances

The HBS2020 data is used to configure the final set of appliances in the model based on information on appliances’ ownership rate, nominal power, and time of use (**Table 2.5**).

Table 2.5. The final set of appliances, as parameterised in the DREEM model, along with their ownership rates, nominal power capacities, and time of use schedules, as derived from the HBS2020 data.

Appliances	Ownership rate (%)	Nominal power (W)	Time of Use (hours/day)
Cooking			
Hobs	92.56%	1,600	1.22
Oven	86.50%	2,150	1.24
Microwave oven	46.57%	1,150	1.10
Toaster	68.51%	1,300	0.35
Coffee maker	40.92%	1,100	0.69
Water boiler	48.97%	1,250	0.93
Cooker hoods	92.44%	108	1.20
Other appliances			
Fridge freezer	77.25%	150	24.00
Dishwasher	33.15%	1,350	1.10
Washer	94.69%	500	1.15
Iron	93.40%	1,000	0.85
Vacuum cleaner	85.24%	450	0.93
Television	97.25%	100	2.63
DVD or VCR	26.63%	40	0.59
Home cinema	5.66%	200	0.68
Stereo	30.39%	24	1.64
Computer	60.97%	300	1.89
Peripheral devices (e.g., printer, scanner, etc.)	9.84%	50	0.79
Internet devices (e.g., router, etc.)	95.72%	10	24.00
Video Game Console	7.36%	160	1.28
Domestic hot water electric boiler	60.41%	4,000	1.19

2.3.4. C₄: Thermal comfort

Detailed information on the methodology followed to define the appropriate indoor temperature ranges and indoor temperature setpoints is presented in **Section 2.2.4**.

2.3.5. C₈: Multilevel upscaling

After simulating energy consumption for each household typology presented in **Table 2.2**, the HBS2020 is once again used to compute the cumulative energy consumption patterns in the Greek residential sector for the reference year. According to the statistics used, the total number of households in Greece is 4,076,189, while the number of households per number of occupants used for upscaling each typology is presented in **Table 2.6**.

Table 2.6. Number of households per number of occupants in the Greek residential sector (Hellenic Statistical Authority ELSTAT 2020).

Number of occupants	Number of households
1 member	1,046,566
2 members	1,201,270
3 members	806,377
4 + members	1,022,384
Total	4,076,189

2.3.6. C₉: Transition matrix

Based on the thematic focus of this study as explained above, this component's individual modules are parameterised as follows.

C₉M₁: Scenario space

For the initial state of the scenario space, 2023 is set as the reference year, 2050 as the target year, while as interim milestone years, the years 2025, 2030, 2035, 2040, and 2045 are selected. In terms of policy specifications, the initialisation of the scenario space is based on the current energy planning in Greece ("Scenario 1"), as derived from relevant documentation. This documentation mainly concern the existing Greek NECP (Greek Ministry of Environment and Energy 2019) and the Greek Just Transition Development Plan (Ministry of the Environment and Energy Hellenic Government 2020) which foresee expanding natural gas infrastructure in Greece and using natural gas as a transition fuel. This initial scenario space is revised and expanded with three extra scenarios ("Scenario 2", "Scenario 3", and "Scenario 4"), based on feedback received from different relevant stakeholders and policy practitioners during consultation activities that took place from September 2021 until November 2022, in the context of the EC-funded Horizon 2020 projects "ENPOR" and "SENTINEL".

These four "forecasting"¹³ scenarios maintain the same national renovation target as set in the Greek NECP (12-15%, which, at the national level, translates to ~60,000 dwellings fully renovated on an annual basis), while altering the final technology mix in the residential sector by 2050. They also envision different stakeholders' perspectives on the potential timeline of initiating the phase out of natural gas, while prioritising investments in electrification, showcasing different levels of ambition towards degasification, which could be adopted by national policymaking.

Furthermore, during consultation activities, policy actors and representatives from the Greek Ministry of Environment and Energy were keen on specifying the necessary renovation rates to achieve the vision of complete decarbonisation in the Greek residential sector by 2050; they were also keen on the more ambitious alternative of achieving complete decarbonisation by 2040. To this end, the revised scenario space is supplemented with a series of additional "backcasting"¹⁴ scenarios foreseeing complete decarbonisation in the Greek residential sector by 2050 (primary target) and 2040 (ambitious target), while maintaining the current planning of investing in natural gas as a transition fuel (i.e., Scenario 5_a and Scenario 6_a, respectively). In terms of modelling configurations, the latter means that, in these scenarios, the renovation rate parameter is not specified, but an extra target in the model is set- either the target of decarbonisation by 2050 (for Scenario 5_a and Scenario 5_b), or the target of decarbonisation by 2040 (for Scenario 6_a and Scenario 6_b)- leaving the model to solve and find the optimal solution to achieve the specified target. **Fig. 2.6** provides a visual illustration of the methodological approach followed.

¹³ "Forecasting" in energy modelling involves anticipating future developments in an energy system by analysing the potential impacts of various actions (Farzaneh 2019).

¹⁴ "Backcasting" in energy modelling involves constructing a vision of desired future outcomes and then working backward to identify the steps needed to connect that future to the present (Farzaneh 2019).

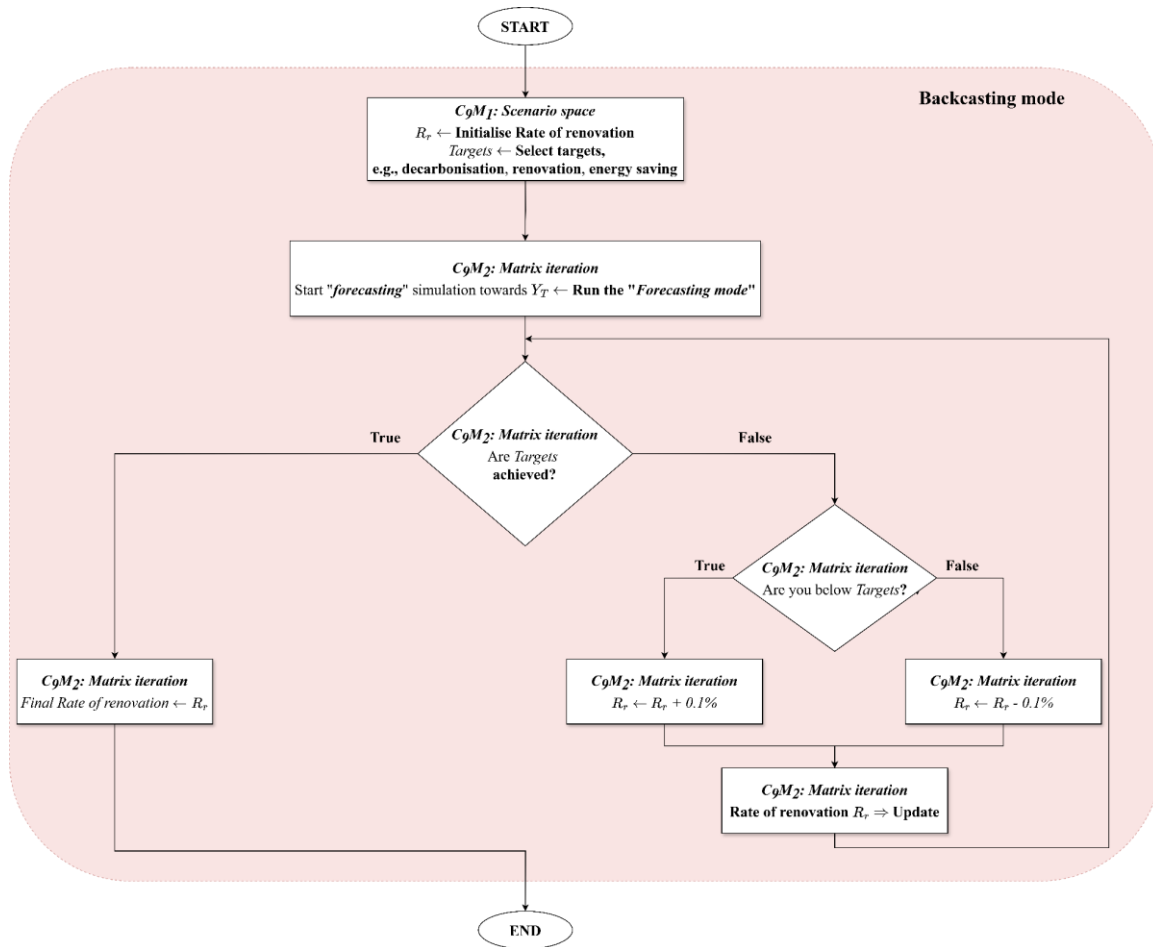


Fig. 2.6. Methodological approach followed in the “backcasting” scenarios to compute the specific renovation rates towards decarbonisation in the Greek residential sector by 2050 (primary target) and 2040 (ambitious target).

For the final scenario space (**Table 2.7**), and based on Ministry representatives’ feedback, it is assumed that all the dwellings built before 2000, which have their heating technology substituted, are also renovated through envelope and window upgrades; in particular, the dwellings built before 1981 are renovated with exterior wall insulation and window upgrades, while the dwellings built during the period 1981-2000 are renovated with exterior wall insulation.

Table 2.7. Final scenario space to be simulated with the DREEM model to study the energy transition by 2050 and 2040 in the Greek residential sector.

a/a	Title	Milestone years	Description
Current renovation strategy - (“Forecasting”) scenarios			
1	<i>“The current strategy: Natural gas as a transition fuel”</i>	(2023-2030)	Annual natural gas penetration according to the NECP’s 2030 target (15.1% of total consumption).
		(2031-2035)	Annual penetration rate to achieve a 300% increase in heat pump installations.
		(2036-2050)	Substitution of oil boilers with heat pumps.
2	<i>“A hybrid transition strategy: Investing in electrification, and using natural gas by 2035”</i>	(2023-2050)	Phase out of the remaining natural gas installations, substituting them with heat pumps.
		(2036-2050)	Substitution of oil boilers with heat pumps following the NECP’s renovation target.

3	<i>“A hybrid transition strategy: Investing in electrification, and using natural gas by 2030”</i>	(2023-2050)	Substitution of oil boilers with heat pumps following the NECP’s renovation target.
		(2030-2050)	Phase out of the remaining natural gas installations, substituting them with heat pumps.
4	<i>“An alternative transition strategy; Investing in electrification and phase-out natural gas from the beginning”</i>	(2023-2050)	Phase out of the existing oil and natural gas boilers, substituting them with heat pumps, following the NECP’s renovation target.
Decarbonisation (“Backcasting”) scenarios			
5 _a	<i>“Decarbonisation by 2050: Investing in natural gas by 2030”</i>	(2023-2030)	Annual natural gas penetration according to the NECP’s 2030 target (15.1% of total consumption). Substitution of oil boilers with heat pumps for the remaining households.
		(2031-2050)	Phase out of the remaining natural gas installations, substituting them with heat pumps.
5 _b	<i>“Decarbonisation by 2050: Investing in electrification”</i>	(2023-2050)	Substitution of the existing oil and natural gas installations with heat pumps.
6 _a	<i>“Decarbonisation by 2040: Investing in natural gas by 2030”</i>	(2023-2030)	Annual natural gas penetration according to the NECP’s 2030 targets (15.1% of total consumption). Substitution of oil boilers with heat pumps for the remaining households.
		(2031-2040)	Phase out of the remaining natural gas installations, substituting them with heat pumps.
6 _b	<i>“Decarbonisation by 2040: Investing in electrification”</i>	(2023-2040)	Substitution of the existing oil and natural gas installations with heat pumps.

Finally, the scenario space is further enhanced with projections on the evolution of different useful exogenous variables to extract meaningful and policy-relevant conclusions on the socioeconomic and environmental implications of the transition scenarios under study. More specifically, in terms of energy prices, also considering the great uncertainty in their future evolution, two different cases are explored. As shown in **Table A2 (Appendix A)**, in the first case (i.e., “Low-price evolution”) the initial values are the ones prior to energy crisis (i.e., January 2021), while in the second case (i.e., “High-price evolution”), values post energy crisis (i.e., September 2022 and beyond) are considered. In both cases, to extract the future evolution the projection trends provided in the Greek “Long-Term Strategy towards 2050” are followed (Hellenic Ministry of Environment and Energy 2019). The analysis also includes projections on the future evolution of technological costs by 2050, i.e., the costs to be paid by end-users for the implementation of the measures foreseen in the transition scenarios, e.g., natural gas/ heat pump installations, envelope upgrades, etc. (**Table A3 in Appendix A**). Furthermore, the ETS-relevant costs are quantified based on their expected evolution (€/tn) (**Table A4 in Appendix A**), and the CO₂ emissions derived in each scenario. The latter is calculated using the emission factor projections from the Greek “Long-Term Strategy towards 2050” (Hellenic Ministry of Environment and Energy 2019) in the case of electricity, while in the case of heating oil, natural gas, and biomass the respective emission factors are kept constant by 2050 (**Table A5 in Appendix A**). All prices and future monetary flows are discounted using Greece’s current discount rate of 4% (Eurostat, 2023) (Eurostat 2023). Additionally, to account for the impact of population changes on future projections of energy demand,

the projected population evolution by 2050, as reported by up-to-date global population data and demographics (World Population Review. 2023), is also considered.

C₉M₂: Matrix iteration

The overall time horizon of this application is 27 years, while the time interval is set to one year (i.e., annual energy demand calculation). The final transition matrix contains detailed results on the energy transition in the Greek residential sector by 2050, based on the scenario space defined.

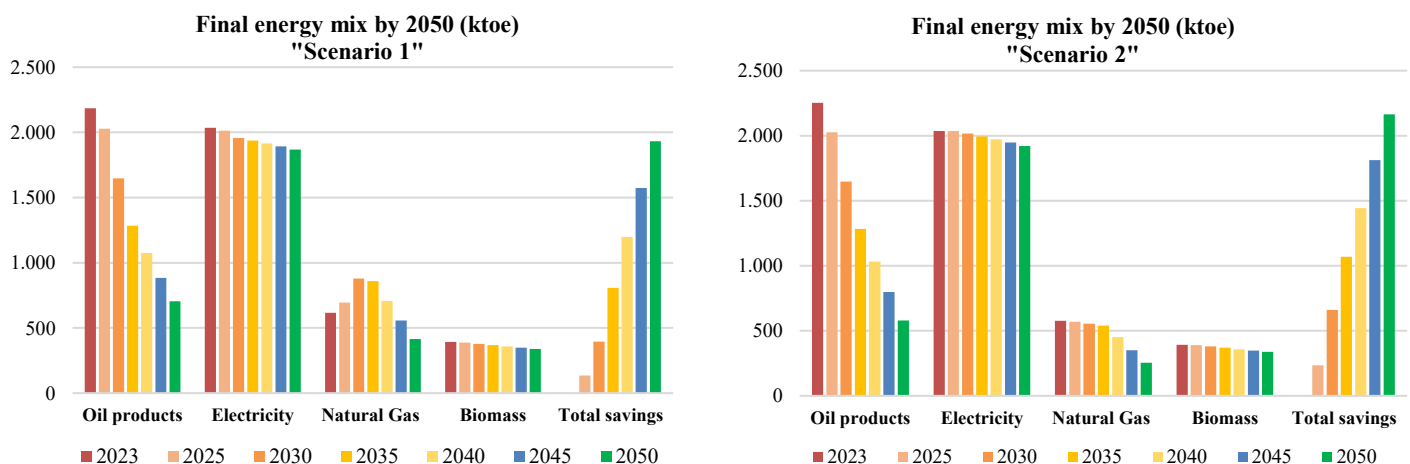
2.4. Results

This section presents simulation results on final energy consumption and energy mix in the Greek residential sector by 2050 under the current planning (“forecasting”) and decarbonisation (“backcasting”) scenarios, followed by an analysis of the CO₂ footprint and economic implications for all the scenarios under study.

2.4.1. Final energy consumption and mix by 2050: Current planning and “forecasting” scenarios

By comparing simulation outcomes of “Scenario 1” with those of “Scenario 2”, “Scenario 3”, and “Scenario 4” (**Fig. A1** in **Appendix A**), a nuanced trend is noted; “Scenario 1”, which prioritises natural gas as a transitional fuel, exhibits a slightly higher final energy consumption projected for 2050, estimated at approximately 3,325 ktoe. On the other hand, “Scenario 2”, “Scenario 3”, and “Scenario 4”, which emphasise the role of electrification while differing on the timing of the natural gas phase out, result in comparable levels of final energy consumption, ranging from 3,086 to 3,094 ktoe. However, the most important message, as visualised in **Fig. 2.7**, is that none of the scenarios under study result in complete phase out of fossil fuel-based products, i.e., heating oil and natural gas. In particular, “Scenario 1” displays higher oil and natural gas consumption, resulting in a total of 1,118.3 ktoe; “Scenario 2” results in a total of 834.2 ktoe of fossil fuel-based products, “Scenario 3” results in a total of 827.1 ktoe of fossil fuel-based products, and “Scenario 4” results in a total of 829.6 ktoe of fossil fuel-based products.

Overall, the analysis of the four current planning scenarios highlights that the use of fossil fuel-based resources persists in 2050 in all the cases under study, which is primarily attributed to the current renovation rate and its insufficiency to achieve the overarching target of decarbonisation. The latter holds true regardless of the pathway followed, or the timing of the natural gas’ phase out (i.e., 2035, 2030, or 2023).



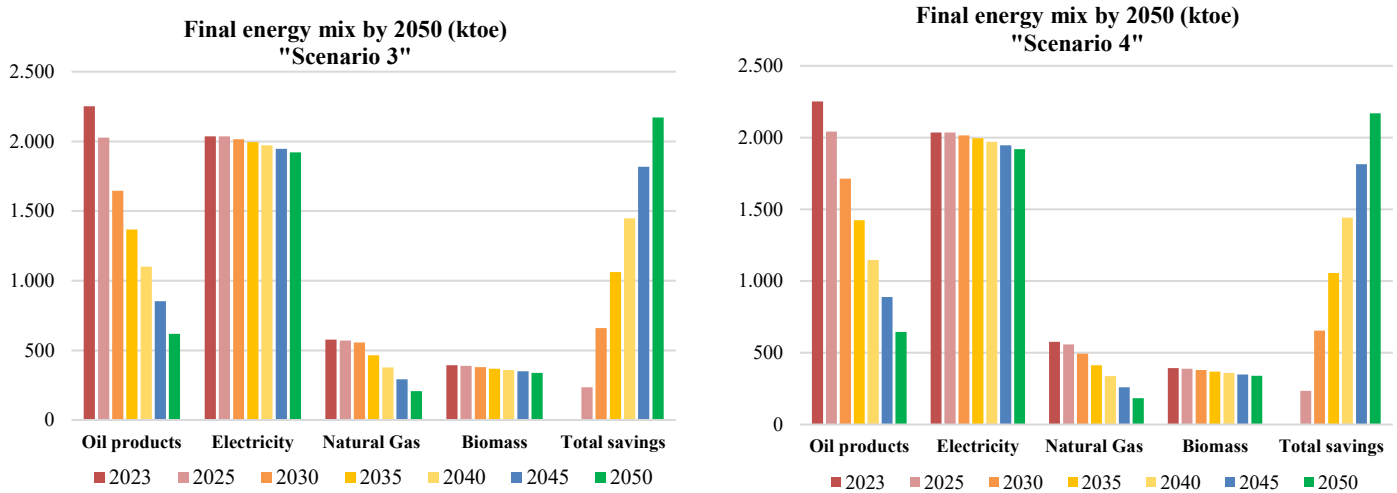


Fig. 2.7. Final energy mix and total energy savings achieved (in ktoe) by 2050 in the Greek residential sector for the four “forecasting” scenarios under study.

2.4.2. Decarbonisation potential in the Greek residential sector: “Backcasting” scenarios

Since the renovation target set by the NECP falls short to achieve the necessary trajectory towards decarbonisation by 2050, and in accordance with the EU’s ambitious objectives, it becomes evident that national policymaking in Greece must establish higher renovation targets if decarbonisation is the real goal.

If decarbonisation by 2050 is the real goal

Based on simulation results from “Scenario 5_a” and “Scenario 5_b”, achieving decarbonisation in the Greek residential sector by 2050 demands an annual renovation rate of 100,000 households, equivalent to nearly 2.5% of the residential stock. Under this renovation rate, “Scenario 5_a”, which foresees natural gas as a transition fuel, results in marginally higher final energy consumption across all the milestone years (i.e., 2030, 2035, 2040, 2045), compared to “Scenario 5_b”, which foresees a transition pathway based on electrification and energy efficiency actions (**Fig. A2**). In addition, under this renovation rate, both scenarios achieve decarbonisation by 2050; as depicted in **Fig. 2.8**, both scenarios demonstrate the complete phase out of fossil fuel-based products from the final energy mix by 2050. An intriguing observation arising from the comparison between “Scenario 5_a” and “Scenario 5_b” is that in “Scenario 5_b”, the consumption of fossil fuel-based products consistently remains lower throughout the entire transition period compared to “Scenario 5_a”. This trend persists across all the milestone years.

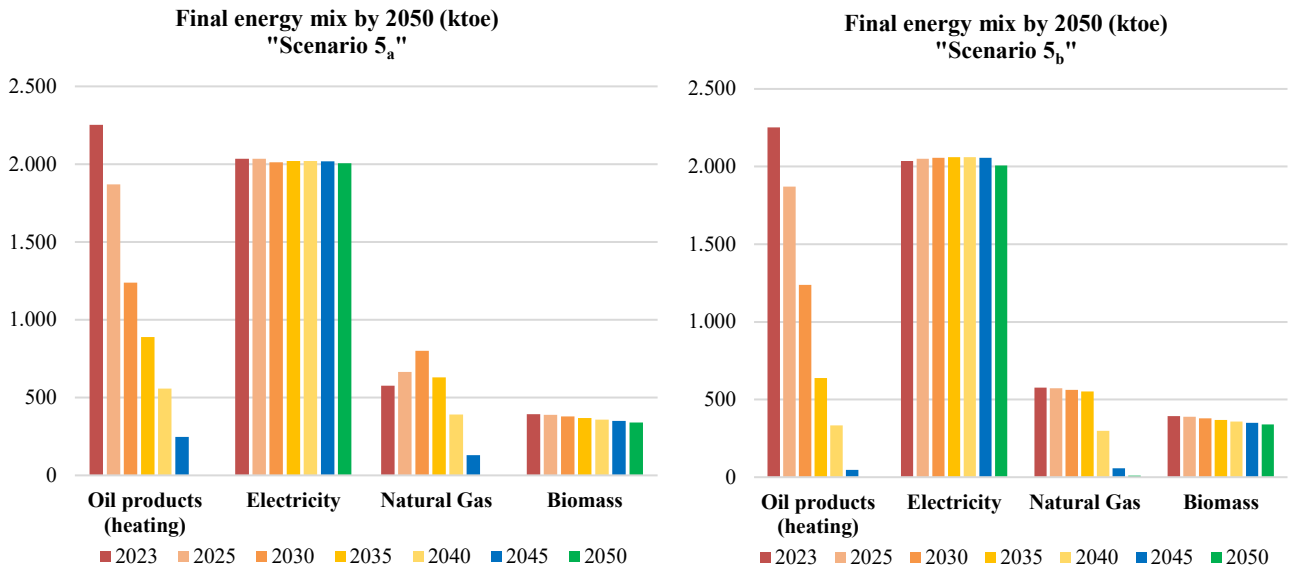


Fig. 2.8. The evolution of the energy mix (in ktoe) by 2050 in the Greek residential sector for “Scenario 5_a” and “Scenario 5_b”.

If decarbonisation by 2040 is the ambition

If a more ambitious target of achieving complete decarbonisation in the Greek residential sector by 2040 is set, simulation results from “Scenario 6_a” and “Scenario 6_b” indicate that a need for a higher annual renovation rate of 145,000 households, or nearly 3.5% of the building stock, is required. Under this renovation rate, both scenarios result in equivalent levels of final energy consumption by 2040. However, “Scenario 6_a”, which foresees natural gas as a transition fuel, results in marginally higher final energy consumption across all the milestone years (i.e., 2030 and 2035) up until 2040, compared to “Scenario 6_b”, which foresees a transition pathway based on electrification and energy efficiency actions (**Fig. A3**). In addition, the trend observed in “Scenario 5_a” and “Scenario 5_b” extends to “Scenario 6_a” and “Scenario 6_b”, as depicted in **Fig. 2.9**. Once again, in both scenarios, the phase out of fossil fuel consumption aligns with the set targets, with complete elimination of all the fossil fuel-based products by 2040. It is noteworthy, though, that “Scenario 6_b” consistently exhibits lower consumption of oil heating and natural gas throughout the entire transition period. This pattern is evident across all the milestone years, i.e., 2025, 2030, and 2035.

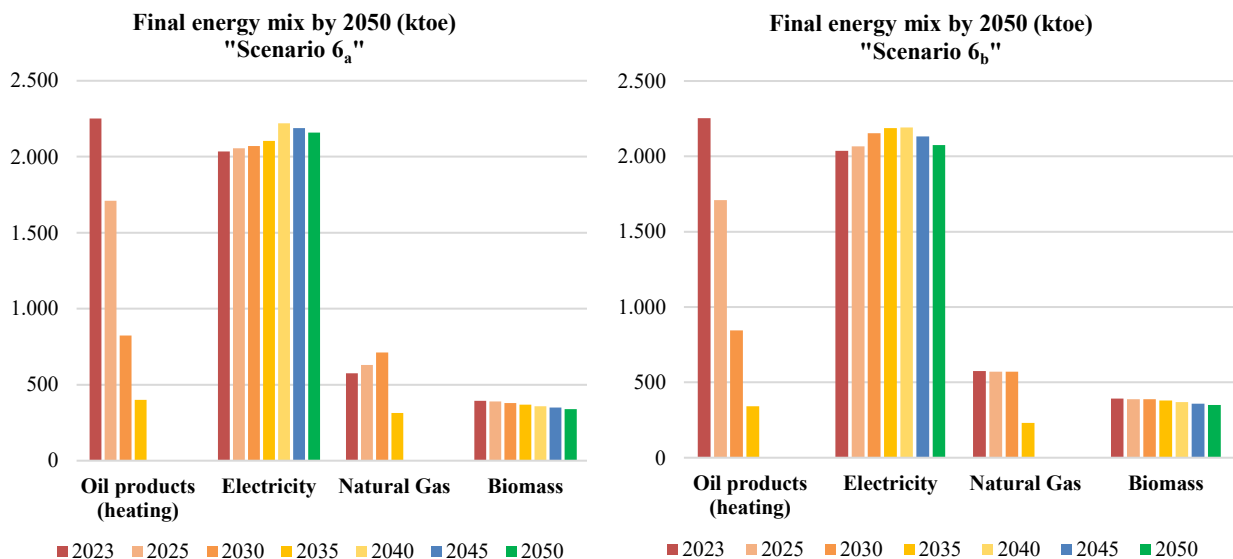


Fig. 2.9. The evolution of the energy mix (in ktoe) by 2050 in the Greek residential sector for “Scenario 6_a” and “Scenario 6_b”.

2.4.3. Carbon footprint: Current renovation strategy versus decarbonisation

As depicted in **Fig. 2.10**, modelling outcomes reveal that “Scenario 1” results in higher levels of annual and cumulative CO₂ emissions by 2050 compared to “Scenario 2”, “Scenario 3”, and “Scenario 4”, while, on the other hand, decarbonisation scenarios (i.e., “Scenario 5_a”, “Scenario 5_b”, “Scenario 6_a”, and “Scenario 6_b”) result in a significant reduction of CO₂ emissions. Furthermore, when it comes to decarbonisation, scenarios that promote electrification instead of further investments in natural gas (i.e., “Scenario 5_b” and “Scenario 6_b”) result in a less detrimental environmental footprint, with a greater avoidance of expected tonnes of CO₂ emissions. More specifically, during the period under study, these scenarios demonstrate lower annual CO₂ emissions and consequently lower cumulative levels of CO₂ emissions by 2050; in addition, “Scenario 6_b” (i.e., decarbonisation by 2040) also results in lower annual and cumulative levels of CO₂ emissions compared to “Scenario 5_b” (i.e., decarbonisation by 2050). The latter suggests that electrification is the most environmentally friendly transition pathway in the Greek residential sector, while an increased decarbonisation ambition could lead to even greater environmental benefits.

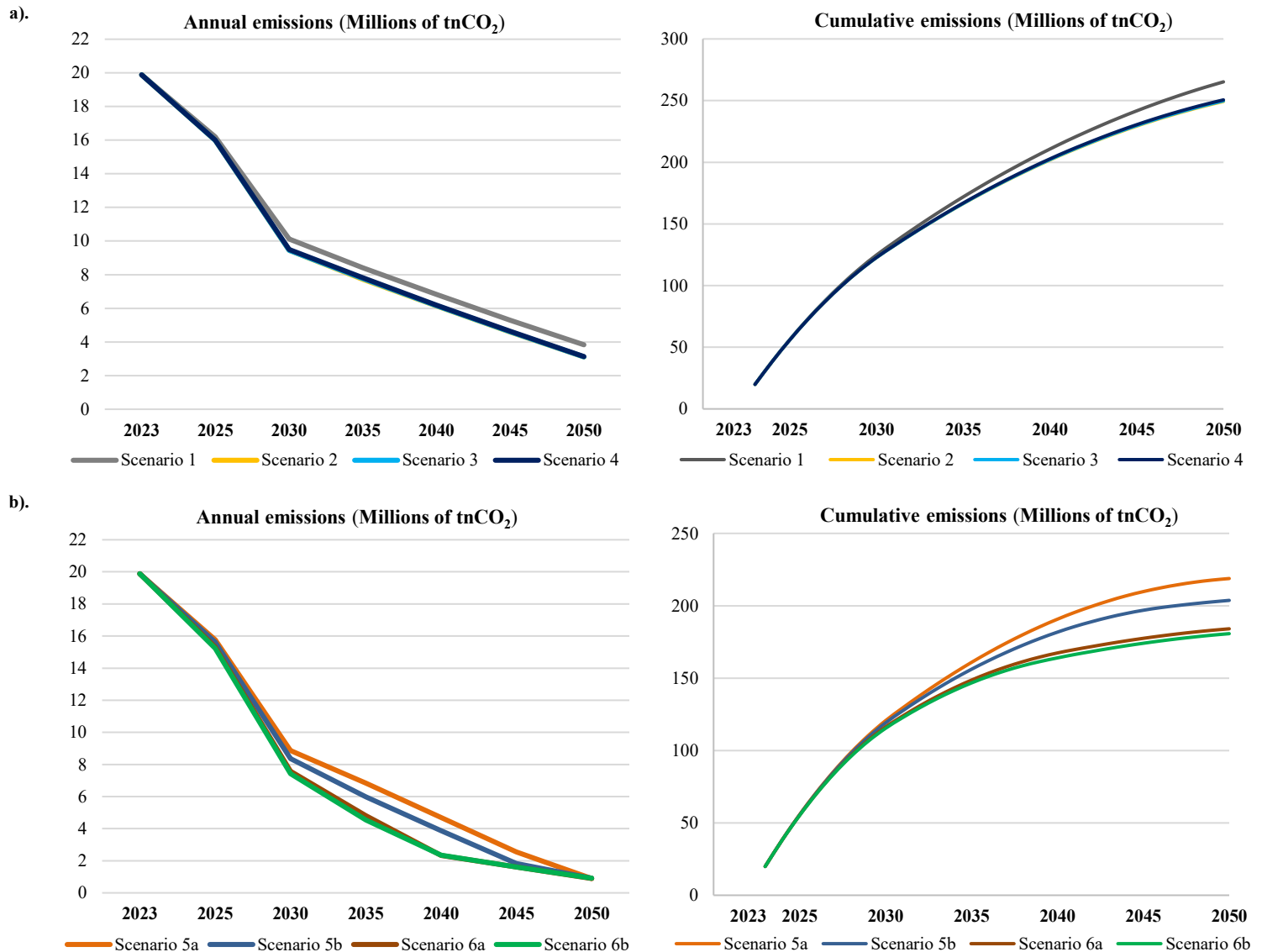


Fig. 2.10. a). Evolution of the CO₂ emission footprint by 2050 (annual and cumulative in millions of tnCO₂) for the “forecasting” scenarios under study and the current renovation target, b). Evolution of the CO₂ emission footprint by 2050 (annual and cumulative in millions of tnCO₂) for the “backcasting” scenarios under study and the renovation target required to achieve decarbonisation by 2050 and 2040.

2.4.4. Economic implications at the national and the household level: Current renovation strategy versus decarbonisation

Simulation results provide information on the economic implications of the energy transition by 2050 in the Greek residential sector for both the “forecasting” and the “backcasting” scenarios under study. More specifically, **Fig. 2.11** and **Fig. 2.12** present the evolution of fuel costs (i.e., costs paid by consumers for household heating, cooling, and use of appliances) by 2050 and cumulative fuel costs in 2050, respectively, for the “forecasting” and “backcasting” scenarios, in the two price evolution cases under study (**Table A2** in **Appendix A**). Overall, it is evident that in both cases, scenarios based on the current renovation strategy, i.e., “Scenario 1”, “Scenario 2”, “Scenario 3”, and “Scenario 4”, result in higher fuel costs compared to the decarbonisation scenarios, i.e., “Scenario 5_a”, “Scenario 5_b”, “Scenario 6_a”, and “Scenario 6_b”. In addition, among the scenarios of the current renovation strategy, “Scenario 1”, which reflects on the existing national policy priorities and the decision to expand the existing natural gas infrastructure, results in higher fuel costs in both price evolution cases compared to “Scenario 2”, “Scenario 3”, and “Scenario 4”, which also introduce electrification in the energy mix; €210 billion for “Scenario 1” compared to a range of €195-197 billion for the remaining scenarios, in the “High-price evolution” case, whereas almost around €108 billion for “Scenario 1”, compared to around €106 billion for the remaining scenarios, in the “Low-price evolution” case.

On the other hand, simulation results show that decarbonisation scenarios demonstrate lower annual and cumulative fuel costs. In particular, in the “High-price evolution” case, “Scenario 5_a” results in cumulative fuel costs of around €188 billion, while “Scenario 6_a” results in cumulative fuel costs of €171 billion, saving almost €18 billion. In the case of electrification, “Scenario 5_b” results in cumulative fuel costs of €179 billion, while “Scenario 6_b” results in cumulative fuel costs of €168 billion. Similar trends are observed in the “Low-price evolution” case, where “Scenario 6_a” saves around €6 billion compared to “Scenario 5_a”, and “Scenario 6_b” saves around €4 billion compared to “Scenario 5_b”. Furthermore, when comparing the scenarios that focus on natural gas with those that focus on electrification, i.e., “Scenario 5_a” with “Scenario 5_b” and “Scenario 6_a” with “Scenario 6_b”, it is once again observed that prioritising electrification is more beneficial as it reduces fuel costs; saving of around €9 billion in the “High-price evolution” and €2 billion in the “Low-price evolution” case for “Scenario 5_b” and around €3 billion and €0.5 billion in the “High-price evolution” and “Low-price evolution” case, respectively, for “Scenario 6_b”.

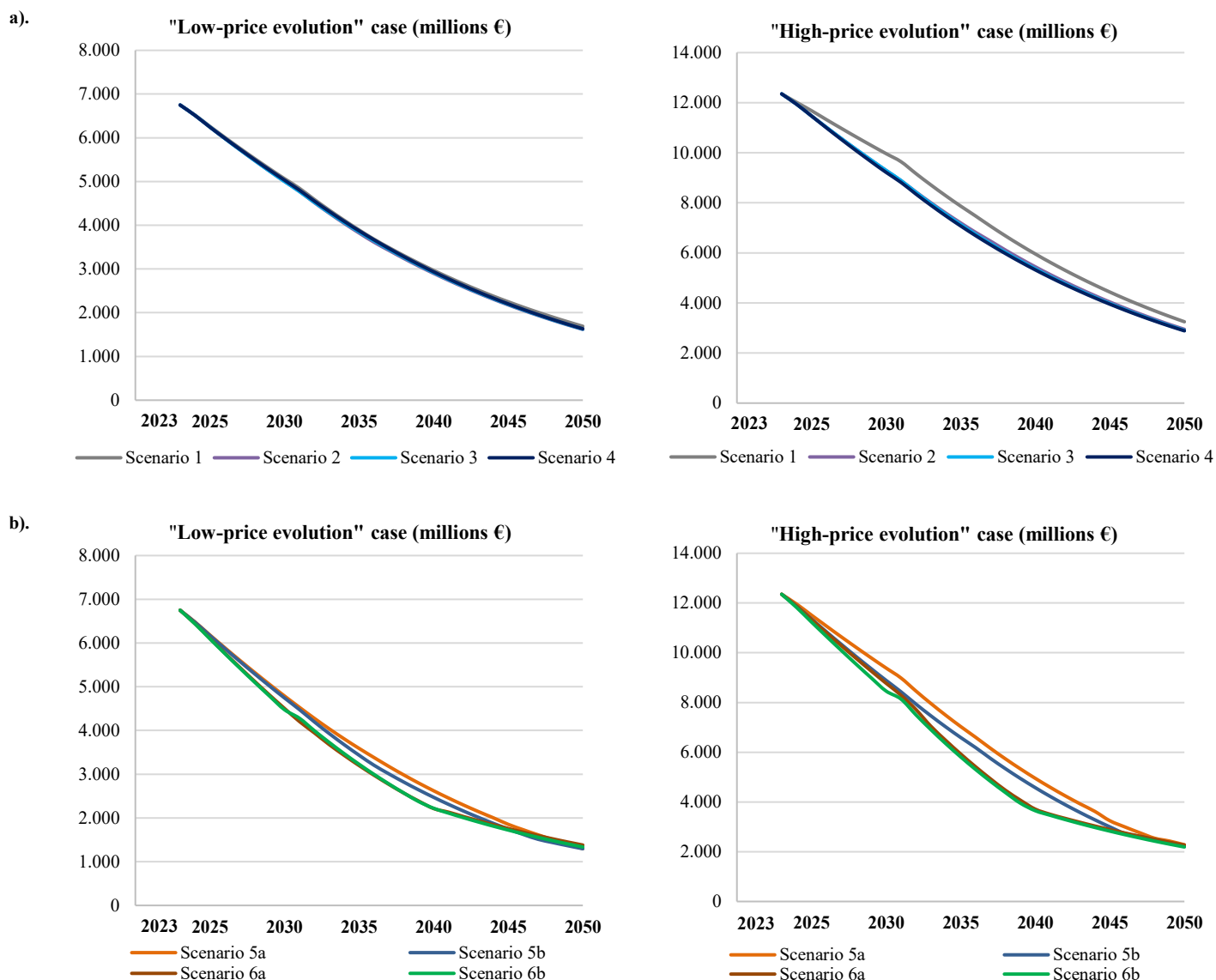


Fig. 2.11. Annual evolution of fuel costs by 2050 in the Greek residential sector in the “Low-price evolution” and the “High-price evolution” cases for: a). the “forecasting” scenarios under study and the current renovation target, and b). the “backcasting” scenarios under study and the renovation target required to achieve decarbonisation by 2050 and 2040.

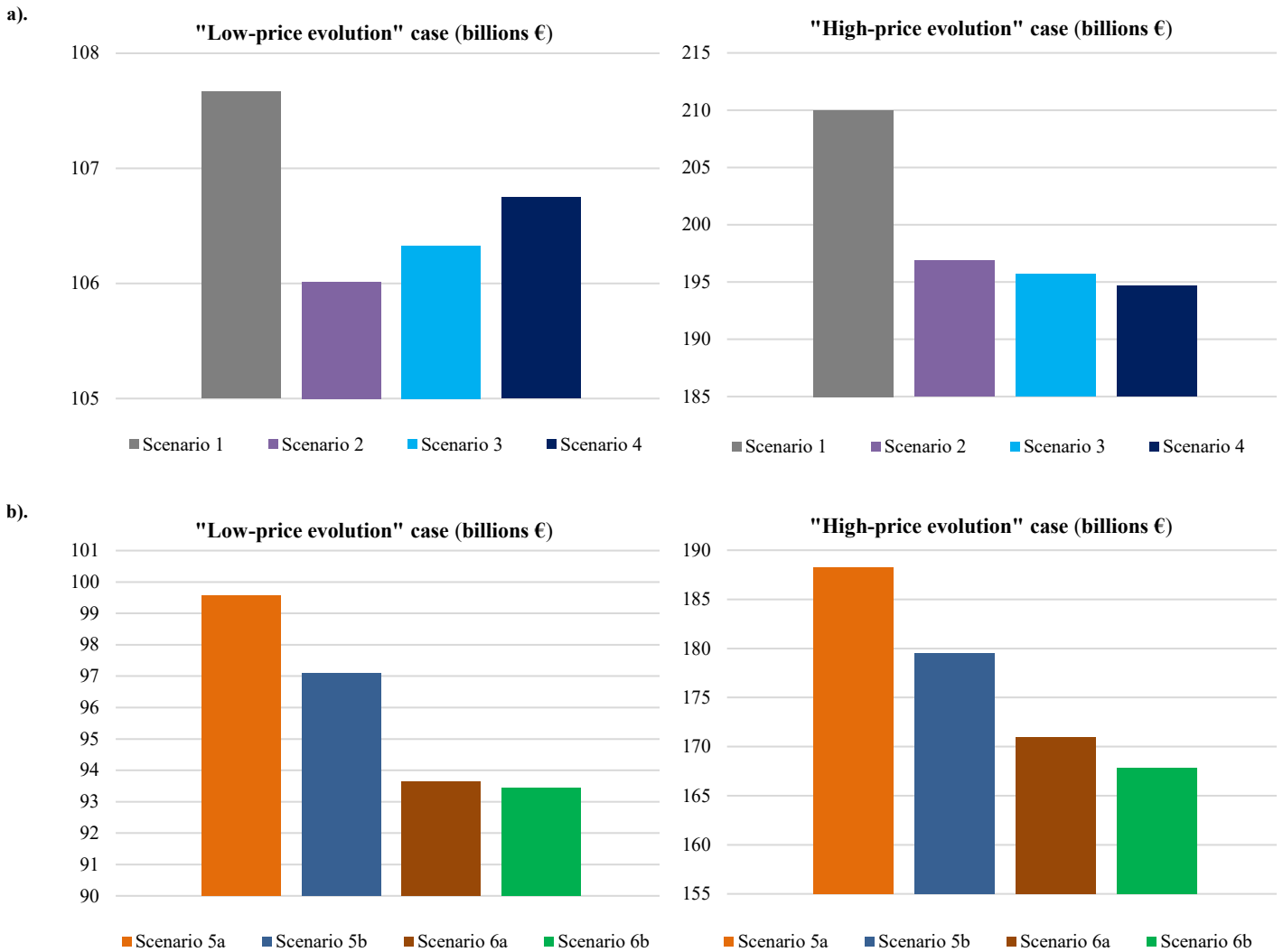


Fig. 2.12. Cumulative fuel costs (in billions of €) in 2050 in the Greek residential sector in the “Low-price evolution” and the “High-price evolution” cases for: a). the “forecasting” scenarios under study and the current renovation target, and b). the “backcasting” scenarios under study and the renovation target required to achieve decarbonisation by 2050 and 2040.

To supplement the economic analysis of the scenarios under study, simulation results also provide information on the renovation costs, based on the evolution of the technological costs presented in **Table A3**. As presented in **Fig. 2.13**, prioritising electrification over natural gas shows higher renovation costs across the current renovation strategy scenarios (i.e., “Scenario 2”, “Scenario 3”, and “Scenario 4” compared to “Scenario 1”). On the other hand, in the case of the decarbonisation scenarios, the opposite trend is observed (“Scenario 5_b” and “Scenario 6_b” compared to “Scenario 5_a” and “Scenario 5_a”, respectively). This divergence can be attributed to the strategic avoidance of duplicative expenditures inherent in electrification scenarios. Specifically, when focusing on natural gas, the increased renovation rates foreseen in the decarbonisation scenarios require the initial installation of natural gas boilers, followed by subsequent replacement with heat pumps. This duplication of expenditure for the same households is avoided in the case of electrification scenarios, contributing to reduced renovation costs.

Furthermore, it is evident that the earlier the decarbonisation, the higher the cumulative renovation costs by 2050, as more extensive actions in a narrower time span are required; for the current renovation

strategy scenarios, cumulative renovation costs range from €8 billion to €11 billion, while for the decarbonisation scenarios, costs range from €17 billion to €22 billion.

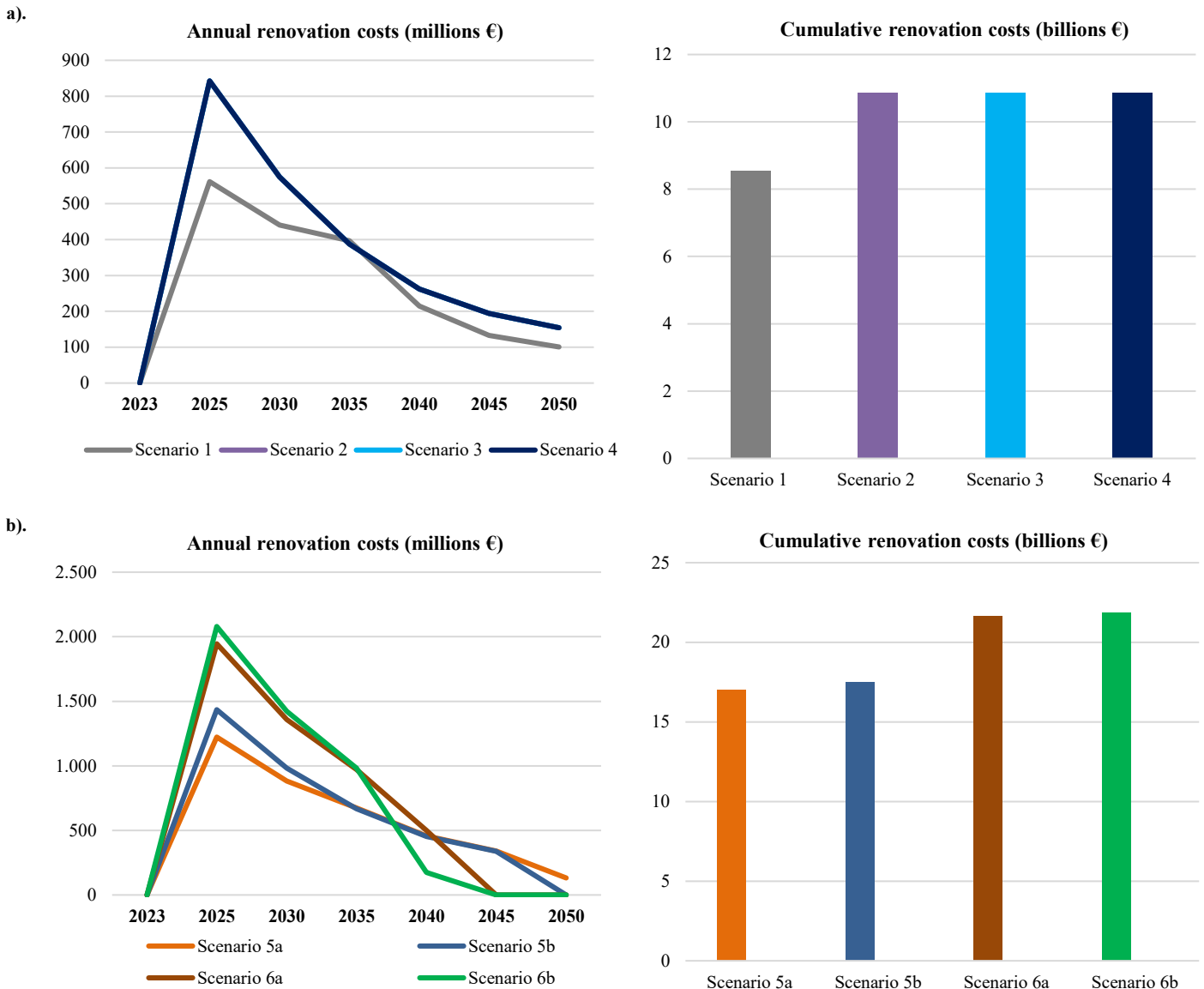


Fig. 2.13. a). Evolution of the annual renovation costs by 2050 (in millions of €) and cumulative renovation costs in 2050 (in billions of €) for the “forecasting” scenarios under study and the current renovation target, b). Evolution of the annual renovation costs by 2050 (in millions of €) and cumulative renovation costs in 2050 (in billions of €) for the “backcasting” scenarios under study and the renovation target required to achieve decarbonisation by 2050 and 2040.

Moreover, simulation results further supplement the economic analysis with the quantification of the costs related to the inclusion of the EU’s building sector in a parallel ETS, which is expected to start in 2026. Based on the assumed evolution of the parallel ETS charges (**Table A4**), **Fig. 2.14** presents the evolution of the annual ETS-related costs by 2050 and the cumulative ETS-related costs in 2050, at the national level, for both the current renovation strategy and the decarbonisation scenarios under study. More specifically, when observing simulation results, it becomes evident that “Scenario 2”, “Scenario 3”, and “Scenario 4” demonstrate lower ETS-related costs compared to “Scenario 1”, underscoring once again the benefits of investing in electrification instead of continuing the reliance on natural gas.

On the other hand, simulation results also indicate that the current renovation strategy scenarios result in higher ETS-related costs compared to the decarbonisation scenarios. In particular, “Scenario 1”, “Scenario 2”, “Scenario 3”, and “Scenario 4” result in a total of ETS-related costs of around €6.6-7.5 billion in 2050, while “Scenario 5a”, “Scenario 5b”, “Scenario 6a”, and “Scenario 6b” result in a total of around €2.5-5.1 billion. In addition, when it comes to decarbonisation, investing in electrification instead of natural gas, as well as aiming for earlier decarbonisation, result in lower ETS-related costs.

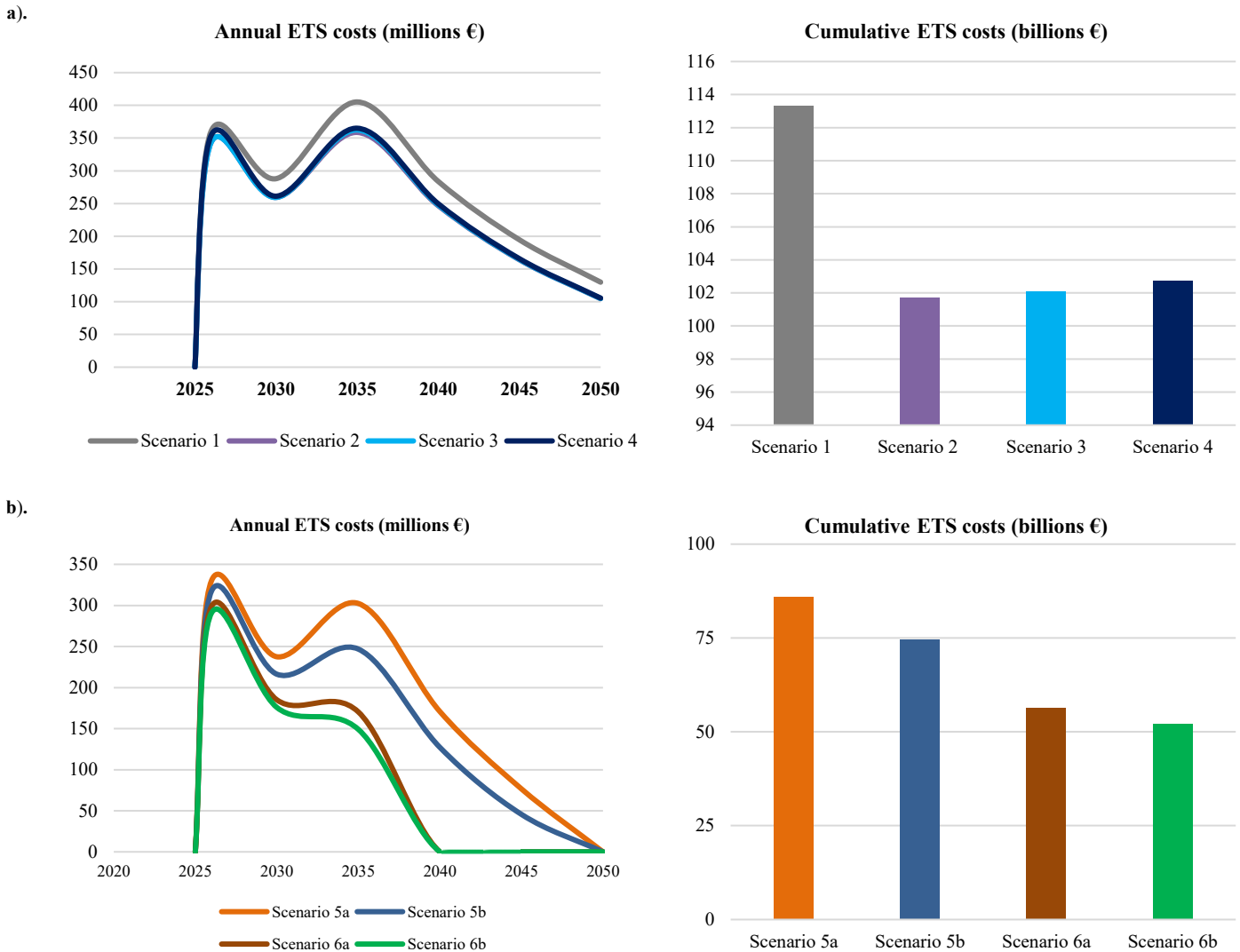


Fig. 2.14. a). Evolution of the annual ETS-related costs by 2050 (in millions of €) and cumulative ETS-related costs in 2050 (in billions of €) for the “forecasting” scenarios under study and the current renovation target, b). Evolution of the annual ETS-related costs by 2050 (in millions of €) and cumulative ETS-related costs in 2050 (in billions of €) for the “backcasting” scenarios under study and the renovation target required to achieve decarbonisation by 2050 and 2040.

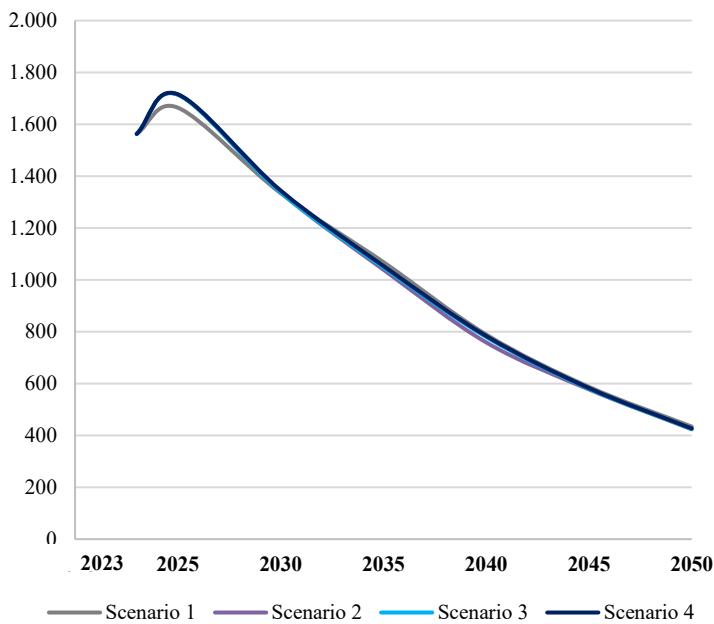
By calculating all the individual costs above, this study seeks to have a holistic understanding of the economic implications related to the energy transition by 2050 in the Greek residential sector. Assuming that these cumulative costs are equally divided among all the households in Greece, it is feasible to scale down costs at the household level and quantify the expected annual charges of the energy transition for consumers.

Fig. 2.15 shows the evolution of annual and cumulative costs by 2050 at the household level in Greece, for both the “forecasting” and the “backcasting” scenarios in the “Low-price evolution” case. Results

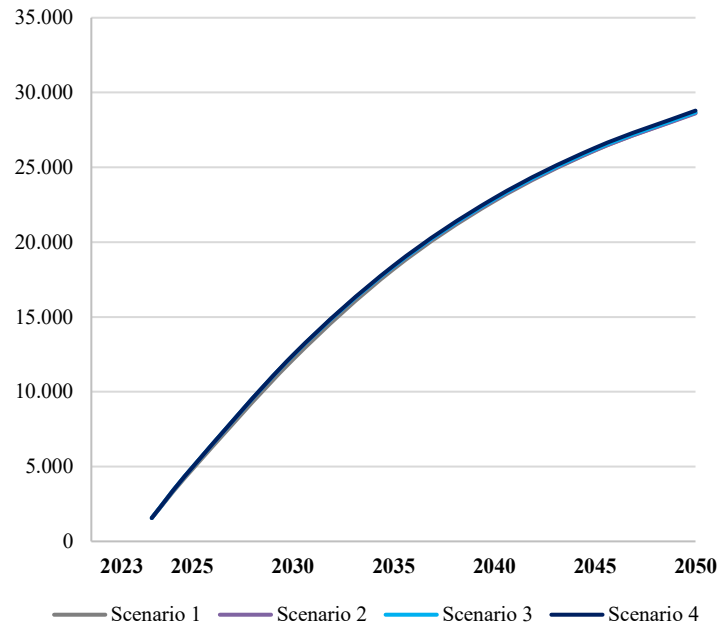
suggest that the existing renovation strategy scenarios (i.e., “Scenario 1”, “Scenario 2”, “Scenario 3”, and “Scenario 4”) result in higher annual and cumulative charges at the household level, approximately amounting to approximately €28,500 per household by 2050. On the other hand, for the “backcasting” scenarios (i.e., “Scenario 5_a”, “Scenario 5_b”, “Scenario 6_a” and “Scenario 6_b”), these costs range from €27,400 to €28,100 per household. Furthermore, when comparing these scenarios, it becomes evident that cumulative charges per household, associated with achieving decarbonisation by 2040 (i.e., “Scenario 6_a” and “Scenario 6_b”), are lower than those associated with achieving decarbonisation by 2050 (i.e., “Scenario 5_a” and “Scenario 5_b”). The scenarios of decarbonisation by 2040 begin to yield lower annual and cumulative charges at the household level around 2035. It is also noteworthy that investing in electrification (i.e., “Scenario 5_b” and “Scenario 6_b”) is more financially attractive compared to investing in natural gas (i.e., “Scenario 5_a” and “Scenario 6_a”).

a).

Annual costs - "Low-price evolution" case (€)



Cumulative costs - "Low-price evolution" case (€)



b).

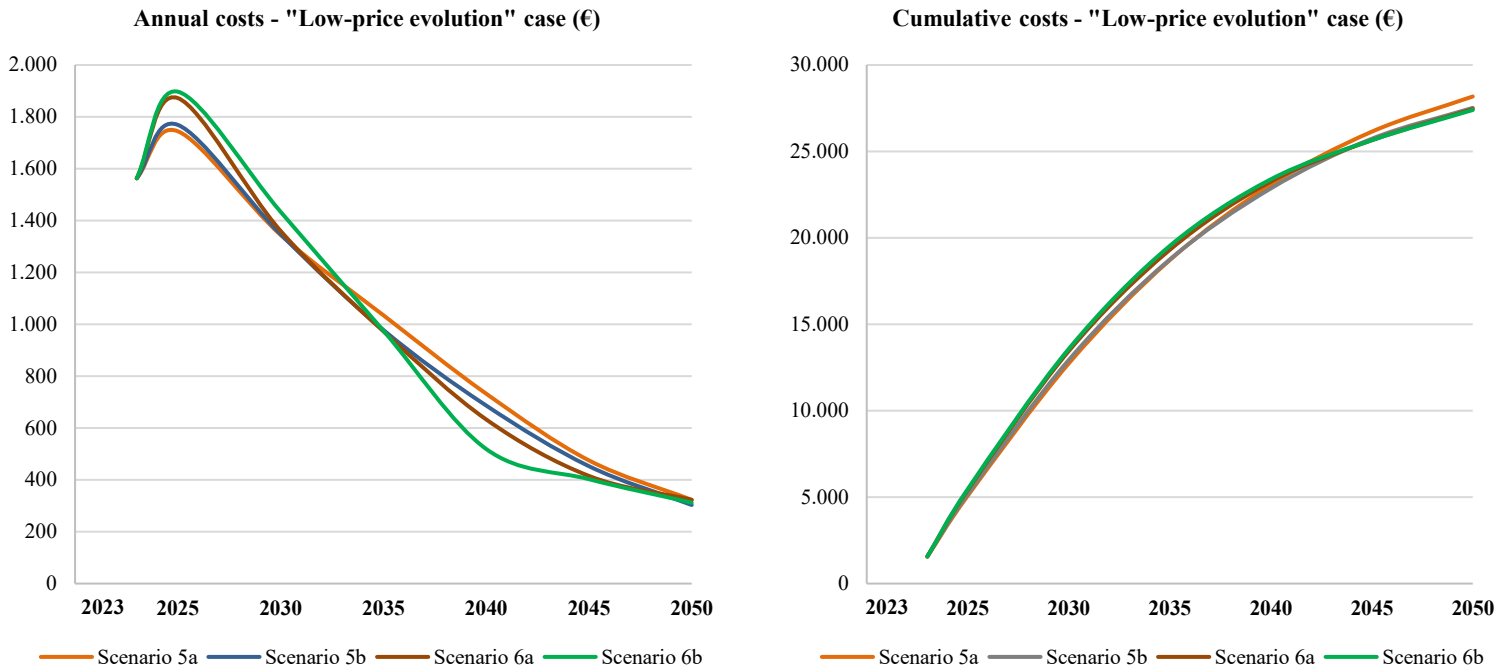
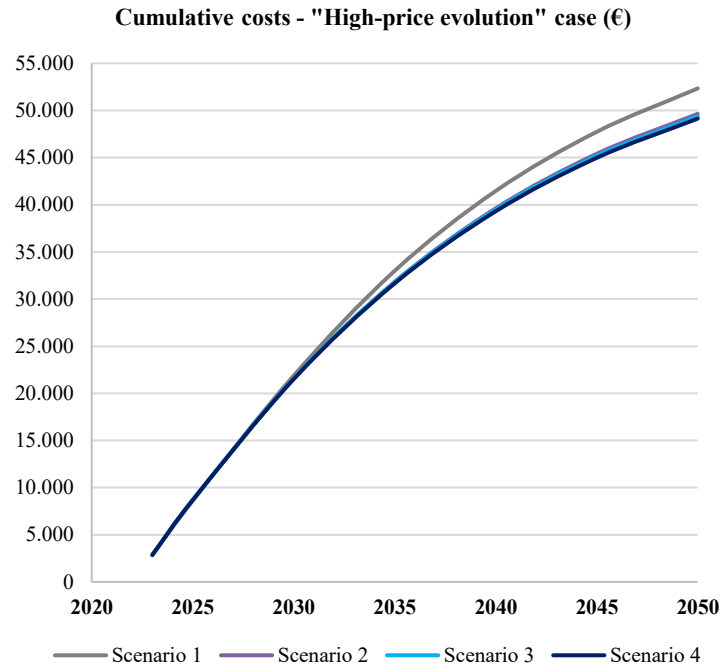
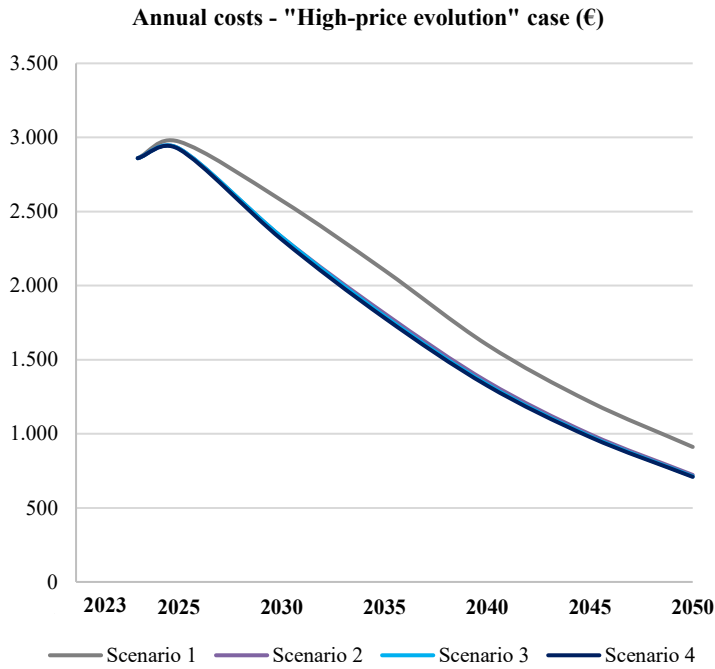


Fig. 2.15. Evolution of annual and cumulative costs per household by 2050 in Greece in the “Low-price evolution” case for: **a).** the “forecasting” scenarios under study and the current renovation target, and **b).** the “backcasting” scenarios under study and the renovation target required to achieve decarbonisation by 2050 and 2040.

Fig. 2.16 also shows the evolution of annual and cumulative costs by 2050 at the household level in Greece, for both the “forecasting” and the “backcasting” scenarios in the “High-price evolution” case. It is observed that among the current renovation strategy scenarios, “Scenario 1” (which reflects the current national planning) results in higher expected charges for consumers, compared to “Scenario 2”, “Scenario 3”, and “Scenario 4” (which reflect different variations of the current national planning in terms of increased electrification and a more limited role of natural gas). It is also observed that the decarbonisation scenarios under study result in lower expected charges for consumers in 2050- ranging from ~€44,500 to ~€48,600 in total- compared to the current renovation strategy scenarios- ranging from ~€49,100 to ~€52,300 in total.

In addition, and as expected, decarbonisation by 2040 (i.e., “Scenario 6_a” and “Scenario 6_b”) also results in lower expected charges by 2050 per household compared to decarbonisation by 2050 (i.e., “Scenario 5_a” and “Scenario 5_b”). They also begin to yield lower annual and cumulative charges at the household level around 2027. It is also evident that for the same renovation rate, investing in electrification, i.e., “Scenario 5_b” and “Scenario 6_b”, is more financially attractive compared to the current national policy priorities about expanding the existing natural gas infrastructure, i.e., “Scenario 5_a” and “Scenario 6_a”, respectively.

a).



b).

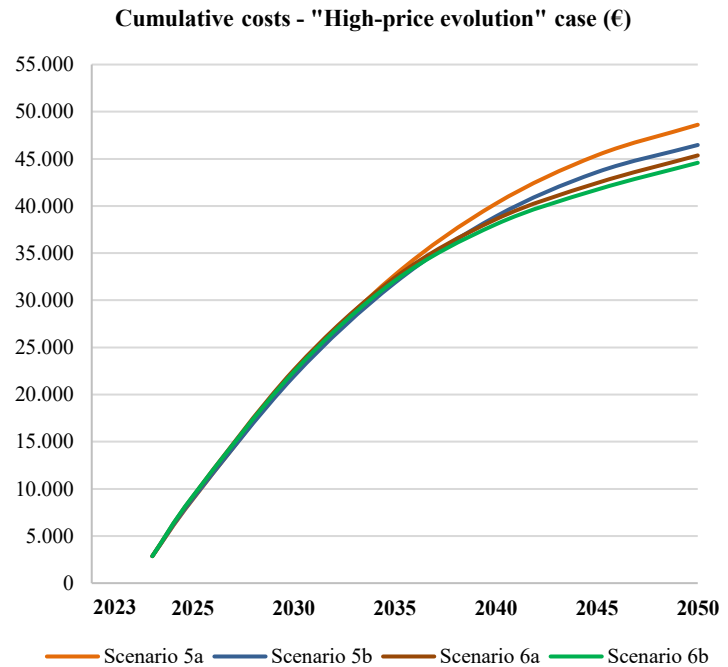
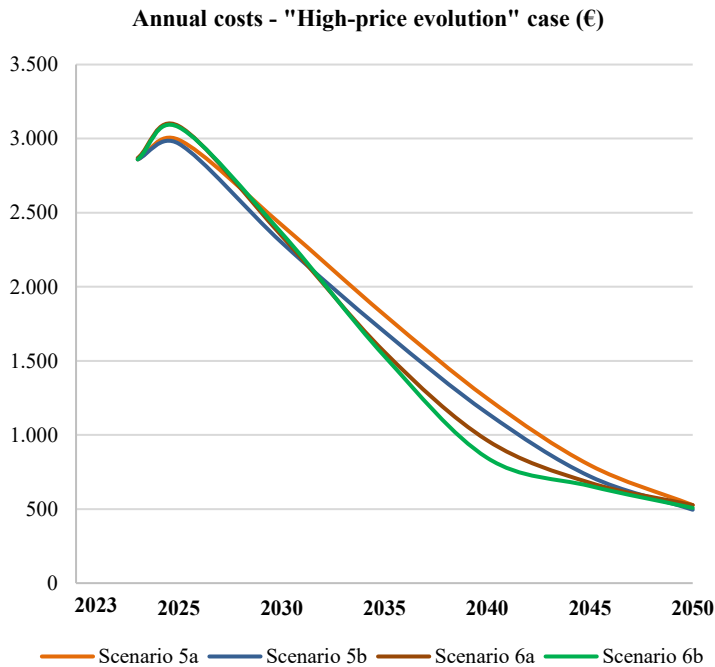


Fig. 2.16. Evolution of annual and cumulative costs per household by 2050 in Greece in the “High-price evolution” case for: a). the “forecasting” scenarios under study and the current renovation target, and b). the “backcasting” scenarios under study and the renovation target required to achieve decarbonisation by 2050 and 2040.

Finally, **Table 2.8** summarises the cumulative charges at the household level and cumulative costs at the national level in the Greek residential sector, by 2050, for the “backcasting” scenarios under study in both the “Low-price evolution” and the “High-price evolution” cases. Simulation results suggest that decarbonisation by 2040 and investing in electrification (i.e., “Scenario 6_b”) is the more economically beneficial scenario, as, in the “Low-price evolution” case, it results in cumulative costs of €27,395 at the household level and in cumulative costs of €111.7 billion at the national level, while, in the “High-price evolution” case, it results in cumulative costs of €44,581 at the household level and in cumulative costs of €181.7 billion at the national level.

In addition, it is also observed that monetary savings of investing in electrification rather than in natural gas, are greater in the “High-price evolution” case compared to the “Low-price evolution” case, both at the household and the national level. Indicatively, “Scenario 5_b” saves almost €8.7 billion compared to “Scenario 5_a”, at national level, and “Scenario 6_b” saves almost €3.2 billion compared to “Scenario 6_a”, while in the “Low-price evolution” case these savings amount to €2.7 billion and €0.3 billion, respectively. Similar observation can be drawn when comparing these scenarios in terms of their decarbonisation potential; indicatively, “Scenario 6_a” saves almost €13.3 billion compared to “Scenario 5_a” and “Scenario 6_b” saves almost €7.7 billion compared to “Scenario 6_a”, while in the “Low-price evolution” case these savings amount to €2.9 billion and €0.5 billion, respectively. These findings suggest that (a). even if Greece increases its renovation ambition to achieve decarbonisation in the residential sector, investing in electrification seems to be the more economically beneficial transition pathway by 2050, compared to investing in natural gas as a transition fuel, and (b). if decarbonisation in the Greek residential sector is the true goal, then an increased ambition and revised renovation targets to achieve this goal by 2040 could eventually lead to better economic benefits at both the household and the national level.

Table 2.8. Cumulative charges at the household level and costs at the national level in the Greek residential sector, by 2050, for the “backcasting” scenarios under study in both the “Low-price evolution” and the “High-price evolution” cases.

“Low-price evolution” case		
Scenarios	Household level	National level
“Scenario 5 _a ”	€28,176	€114.8 billion
“Scenario 5 _b ”	€27,520	€112.2 billion
“Scenario 6 _a ”	€27,446	€111.9 billion
“Scenario 6 _b ”	€27,395	€111.7 billion
“High-price evolution” case		
Scenarios	Household level	National level
“Scenario 5 _a ”	€48,615	€198.2 billion
“Scenario 5 _b ”	€46,468	€189.4 billion
“Scenario 6 _a ”	€45,361	€184.9 billion
“Scenario 6 _b ”	€44,581	€181.7 billion

Table 2.8 provides an average estimate of transition costs at both the household and the national level in Greece by 2050. Note that equal division of costs at the household level aims to provide policymakers with preliminary and useful insights about the expected expenses of different transition pathways at the residential sector by 2050, towards better-informed policy design and fair allocation of resources between the different energy sectors.

2.5. Discussion

Key findings underscore the urgency for Greece to refine its national strategy and policy framework towards a green and inclusive energy transition in the residential sector. In this context, and to align with the EU's vision for decarbonisation by 2050, or to adopt an even more ambitious vision for decarbonisation by 2040, adjustments and policy revisions of the existing national strategy and renovation goals are needed.

In particular, modelling results show that existing renovation rates, as set by the most recent version of the NECP, are not able to lead to complete decarbonisation by 2050, even in the case of investing in electrification and energy efficiency as early as possible. National policymaking should reevaluate renovation rates in view of the upcoming amendment of the NECP; to achieve decarbonisation by 2050, the annual renovation target must be set to 2.5% of the existing housing stock (i.e., ~100,000 households to be fully renovated on an annual basis), while to achieve decarbonisation by 2040, the annual renovation target must be set to 3.5% of the existing housing stock (i.e., ~145,000 households to be fully renovated on an annual basis), which also aligns better with the renovation target recently set at the EU level (European Commission 2020a).

To that end, it is crucial that the National Strategic Reference Framework and other existing national subsidy programmes (e.g., the “Energy Saving at Home” programme (Patlitzianas 2011)) are channelled in a well-targeted manner and used efficiently to finance investments in electrification of heating in the residential sector, i.e., through the substitution of heating oil and natural gas boilers with heat pumps as well as deep renovation actions that will increase the energy performance of the existing building stock, especially in the case of dwellings built before 2000. To ensure their effectiveness and enhance their robustness, these policy actions should be coupled with initiatives focused on the administrative streamline of processes, the increase of public awareness, and the collaboration among all the relevant parties; the vision of climate neutrality is no longer characterised by a single spatial focus or location, and there is a clear need for a variety of actions by a wide range of actors at different levels of influence and for improved governance structures and collaboration across different policymaking and administrative levels (Intergovernmental Panel on Climate Change (IPCC) 2022).

In addition, findings also highlight the importance of prioritising investments in electrification as an effective strategy to reduce reliance on fossil fuels. By opting for electrification in the residential sector, Greece can significantly decrease the demand for heating oil and natural gas, thereby diminishing the overall environmental impact associated with the use of fossil fuel-based products. Simulation results on the CO₂ footprint of each transition pathway under study demonstrate the positive environmental impact of investing in electrification and energy efficiency actions, which also presents an opportunity for Greece to further achieve an even more sustainable footprint. Embracing strategies that increase the proportion of renewable energy sources in the electricity generation mix could further enhance these outcomes, potentially leading to even lower emission factors by 2050 (Kılıkış et al. 2022). The latter underscores the ongoing need for the development and implementation of more ambitious policies, alongside strategic interventions on both the demand and the supply side to align the overarching national strategies with the goals of achieving decarbonisation, and eventually climate neutrality, by either 2050, or even 2040.

Simulation results also suggest that prioritising electrification and energy efficiency actions along with ambitious renovation and decarbonisation targets are the most economically sustainable transition pathways in the Greek residential sector. The latter could also be crucial in addressing social justice concerns, by substantially reducing fuel costs and ensuring a fairer and more equitable energy transition, particularly beneficial for vulnerable households experiencing energy poverty. Even in the case that renovation costs appear to be higher, as is the case of the electrification pathways in the current

renovation strategy scenarios, it is important to remember that this concerns the higher costs of substituting oil boilers with natural gas boilers, which will be then substituted again with heat pumps (in the case of the current national planning and the use of natural gas as a transition fuel by 2035, compared to the transition pathways foreseeing electrification of heating as early as possible, in which there is only the cost of directly substituting oil boilers with heat pumps) and that renovation costs represent only one facet of the cumulative costs attributed to the energy transition in the residential sector. On the other hand, when it comes to costs of electrification, it is also noteworthy that renovation costs by 2030 can be high, mainly due to the current high capital costs of heat pumps. However, this is not going to be the case beyond 2030, as capital costs of heat pumps are expected to radically decrease due to the learning curve effect, as also indicated by recent forecasts published by the European Heat Pump Association (European Heat Pump Association 2022).

In addition, investing in electrification and energy efficiency actions results in a greener energy mix as early as possible, with high levels of CO₂ emissions avoided, and, thus, lower ETS-related costs. Overall, all these reflections on costs speak of the necessity to design and implement renovation subsidy programmes that focus on supporting a wider citizen inclusion, especially of the most vulnerable groups, towards the implementation of measures that lead to increased overall benefits (e.g., enhanced comfort, reduced energy expenses, achievement of climate targets) (Tzani et al. 2022).

Furthermore, by examining costs and other energy-related charges at the household level and assessing the economic impact of the energy transition for consumers- also considering the introduction of a parallel ETS in the EU's building sector starting in 2026, and assuming equal distribution of costs among all households in Greece- it is found that prioritising early decarbonisation and investment in electrification consistently leads to the lowest expected charges for consumers, enhancing inclusivity and justice. This is particularly beneficial for Greece, a country with increased number of vulnerable households experiencing energy poverty, further underlining the importance of prioritising electrification in achieving both environmental and social objectives.

Finally, the derived outcomes indicate that if Greece seeks to develop a plan that promotes sustainability, environmental awareness, and social justice, national policymaking should refrain from further investment in fossil-fuel infrastructure. This stance is underscored by the latest climate policy framework published by the EC, advocating for climate-proofing infrastructural projects during the 2021-2027 period and adopting the "Energy Efficiency First" principle as a guiding criterion for investment evaluations. Such a policy direction could potentially jeopardise investments in the operation and maintenance of existing natural gas infrastructures and the expansion of new ones in Greece (European Parliament and Council of The European Union 2021). However, Greece, along with other Member States, benefit from a legislative opportunity to finance new fossil-fuel infrastructure using public or EU funding through unspent amounts from past 2014-2020 Operational Programmes, as seen in the case of new natural gas grid infrastructure across various regions in Greece. Nevertheless, this approach could lead to stranded assets since they should be re-financed before their payback period (15-20 years) again with public funding, towards the transition to cleaner fuels in accordance with the EU's relevant directives.

2.6. Conclusions

In this article, energy transition scenarios in the Greek residential sector by 2050 are analysed, considering the latest developments in the EU's energy landscape and the expected revision of the Greek NECP. This work is motivated by the lack of comprehensive research and quantifiable outcomes, crucial for informing national policymaking, while the aim is to identify potential transition lock-ins and develop effective strategies for a successful and just energy transition in the Greek residential sector. To do so, the DREEM model, a bottom-up dynamic high-resolution demand-side management

model, is used to simulate the energy demand evolution by 2050 under different transition scenarios, as these are extracted from the current existing policy planning and political decisions, the recent amendments under public consultation, and relevant national experts' feedback.

Simulation outcomes provide us with the evolution of the final energy mix and final energy consumption in the Greek residential sector by 2050, for scenarios envisioning the current policy planning and scenarios that foresee an alternative transition strategy based on electrification and energy efficiency actions. However, results show that the current national planning and the renovation target set by the most recent version of the NECP are not enough to achieve decarbonisation by 2050. In particular, if decarbonisation by 2050 is the real target, the annual renovation rate must increase to 2.5% of the housing stock (~100,000 dwellings to be fully renovated on an annual basis), while, if decarbonisation by 2040 is the ambition, the annual renovation rate must increase to 3.5% of the housing stock (~145,000 dwellings to be fully renovated on an annual basis).

Simulation outcomes also inform us on the environmental impact of the different transition pathways under study, highlighting the importance of investing in electrification instead of natural gas as well as achieving decarbonisation as early as possible, i.e., by 2040. They also provide a comprehensive understanding of the projected transition costs by 2050 at the national and the household level. These costs consider various factors, including anticipated changes in fuel costs, technological investments, and expenses associated with the anticipated implementation of a parallel ETS in the EU's building sector starting in 2026. In addition, results reveal that achieving decarbonisation target by 2050, or even increasing ambition and efforts to achieve it by 2040, while also prioritising electrification, ultimately translate into substantial benefits in terms of lower cumulative expected charges at the household level. This highlights the economic benefits and long-term cost savings associated with accelerating the transition towards green solutions and achieving decarbonisation targets ahead of schedule.

Overall, this article seeks to pave the way for a resilient and equitable energy future in Greece, in line with the EU's overarching vision for climate neutrality and social justice, providing actionable insights that inform the development of national planning initiatives, geared towards fostering a green and inclusive energy transition in the Greek residential sector and supporting policymakers in crafting and executing strategies that align with the overarching objectives of decarbonisation and energy independence.

Nevertheless, the authors acknowledge limitations in their study due to challenges in addressing broader financial, social, and regulatory implications and data gaps that are essential for a comprehensive understanding of the energy transition nexus in the residential sector. For example, lack of data is responsible for assuming a constant evolution of biomass levels by 2050 due to insufficient information on its future role in Greece's energy mix, or for not fully including infrastructure costs, such as those for new natural gas networks or grid upgrades (this omission does not affect findings as demand-side flexibility actions are expected to mitigate the additional grid strain (Toleikyte et al. 2023), ensuring that overall benefits of electrification and early decarbonisation remain robust). In this respect, the authors intend to enhance the study's scenarios by incorporating more structured participatory and deliberative processes to obtain updated, policy-relevant feedback from experts and key stakeholders, including representatives from the Greek Ministry of Environment and Energy. This approach will enable access to more detailed data and the development of new scenarios, ensuring a stronger linkage between scenario narratives, measures, and societal needs, ultimately improving both the study's content and accuracy of results.

Future scenarios could include a broader range of innovative measures related to energy transition, such as small-scale photovoltaic systems, increased prosuming (Stavrakas, Kleanthis, and Flamos 2020b), battery energy storage systems (Michas et al. 2019a), and electric vehicles (Dawahdeh and Al-Nimr 2023). Evaluating the impacts of such actions on self-consumed energy, transition costs, environmental

footprint, and other relevant factors will provide a more nuanced understanding of the evolving energy landscape towards 2050. Additionally, future research should refine the methodological approach by incorporating broader financial, social, and regulatory inputs, including infrastructure costs and a more detailed analysis of energy transition costs across different household typologies.

Finally, building on the replicability potential of their study, the authors plan to expand their work by also exploring similar transition scenarios in diverse geographic and socioeconomic contexts within the EU and beyond, as part of the EC-funded Horizon Europe “IAMCOMPACT¹⁵” project, which aims to support the assessment and the design of the next round of national policy planning in several EU member states beyond 2030. This will facilitate comparisons and provide guidelines to aid EU and national bodies in designing effective and inclusive energy strategies. Furthermore, the authors aim to conduct similar studies at the regional and the local level in Greece and other territories across the EU to address the often-overlooked input from regional and local authorities, which is crucial for implementing climate and energy transitions and can lead to conflicts with national planning.

¹⁵ <https://www.iam-compact.eu/>

Appendix A

Table A1. The number of Greek households in each construction period.

Dwelling's Construction Period	Number of Households
Before 1981	1,945,813
1981-2000	1,650,443
After 2000	479,933
Total	4,076,189

Table A2. Projections on the future evolution of prices by 2050 in Greece for all the scenarios under study.

Year	2022	2030	2050	Source(s)
“High-price evolution” case (<i>post energy crisis</i>)				
Heating oil (€/MWh)	123.2	166.5	199.0	(Hellenic Ministry of Development 2022b, 2022c, 2022a; Hellenic Ministry of Environment and Energy 2019)
Natural gas (€/MWh)	276.8	325.2	389.9	
Electricity (€/MWh)	295.2	281.8	248.4	
“Low-price evolution” case (<i>prior to energy crisis</i>)				
Heating oil (€/MWh)	76.3	103.1	123.2	(Grigoriou, Mayer, and Pallicska 2022; Hellenic Ministry of Development 2021; Hellenic Ministry of Environment and Energy 2019)
Natural gas (€/MWh)	48.2	56.6	67.9	
Electricity (€/MWh)	175.2	167.3	147.4	

Table A3. Projections on the future evolution of technological costs by 2050 in Greece for all the scenarios under study.

Year	2022	2030	2050	Source(s)
Natural gas boilers (€)	5,000	4,904	4,713	
Heat pumps ¹⁶ (€)	12,000	7,680	4,086	

¹⁶ Nominal capacity of heat pump for a typical Greek household 8.7kW_{th} (Sakellariou et al. 2023).

				(The European Heat Pump Association tells us about the future of the industry - Renewable Heating Hub n.d.; De Vita, Kielichowska, Mandatowa, Capros, Dimopoulou, Evangelopoulou, Fotiou, Kannavou, Siskos, Zazias, De Vos, et al. 2018)
Building envelope and window upgrades (€)	5,000	5,000	5,000	

Table A4. Projections on the potential future evolution of the ETS costs by 2050 in the EU's building sector.

Period	(2022-2025)	(2026-2030)	(2031-2050)	Source
Carbon price (€/tn)	0	50	100	Estimation of cost evolution based on the evolution of the EU's established ETS system (EU Carbon Permits - 2022 Data - 2005-2021 Historical - 2023 Forecast - Price - Quote n.d.).

Table A5. Projections on the future emission factors for electricity, heating oil, natural gas and biomass as derived from the Greek "Long-Term Strategy towards 2050" (Hellenic Ministry of Environment and Energy 2019).

Electricity	
Year	Emission factor (tnCO ₂ /ktoe)
2023	5,006
2025	4,476
2030	3,947
2035	3,418
2040	2,889
2050	2,360
Heating oil	
Year (2023-2050)	Emission factor (tnCO ₂ /ktoe)
	2,821
Natural gas	
Year (2023-2050)	Emission factor (tnCO ₂ /ktoe)
	2,332
Biomass	
Year	Emission factor (tnCO ₂ /ktoe)

(2023-2050)

2,337

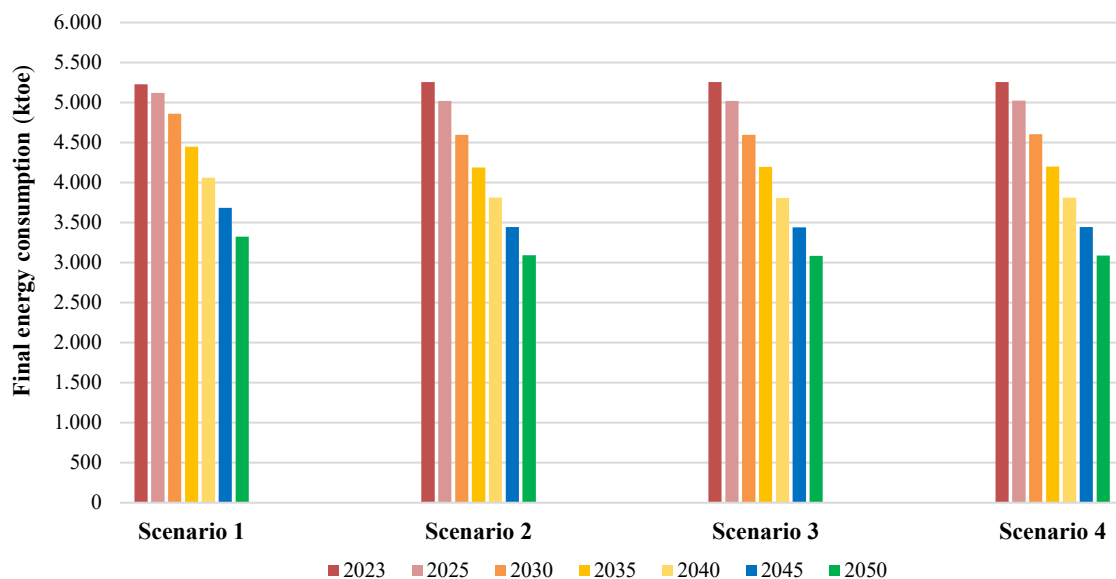


Fig. A1. Final energy consumption (in ktoe) by 2050 in the Greek residential sector for the four “forecasting” scenarios under study.

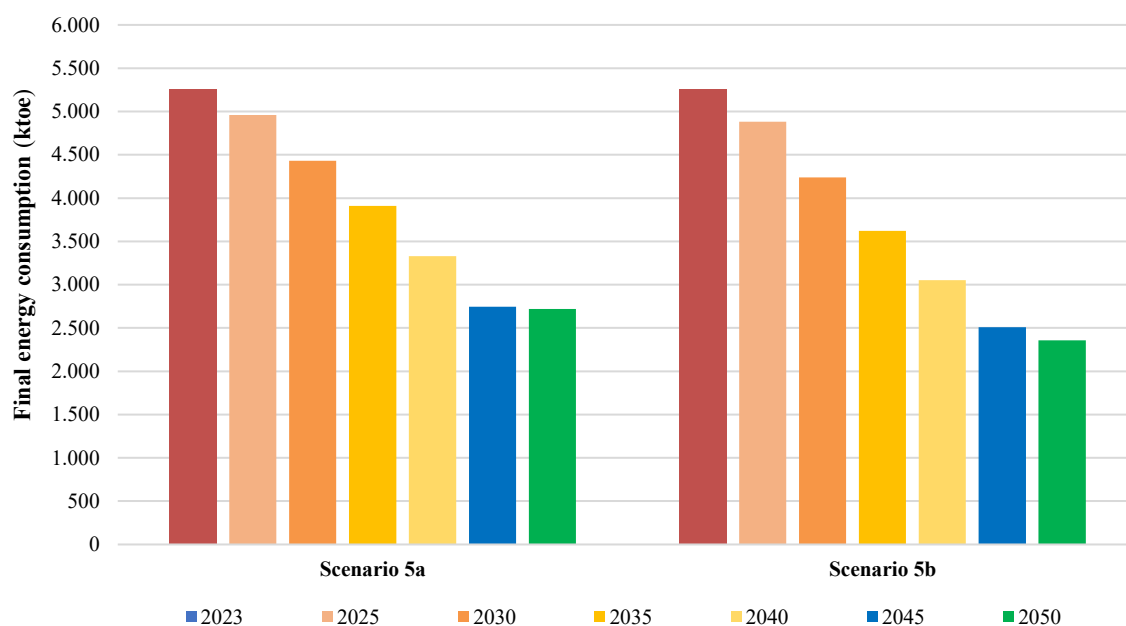


Fig. A2. Final energy consumption (in ktoe) by 2050 in the Greek residential sector for “Scenario 5_a” and “Scenario 5_b”.

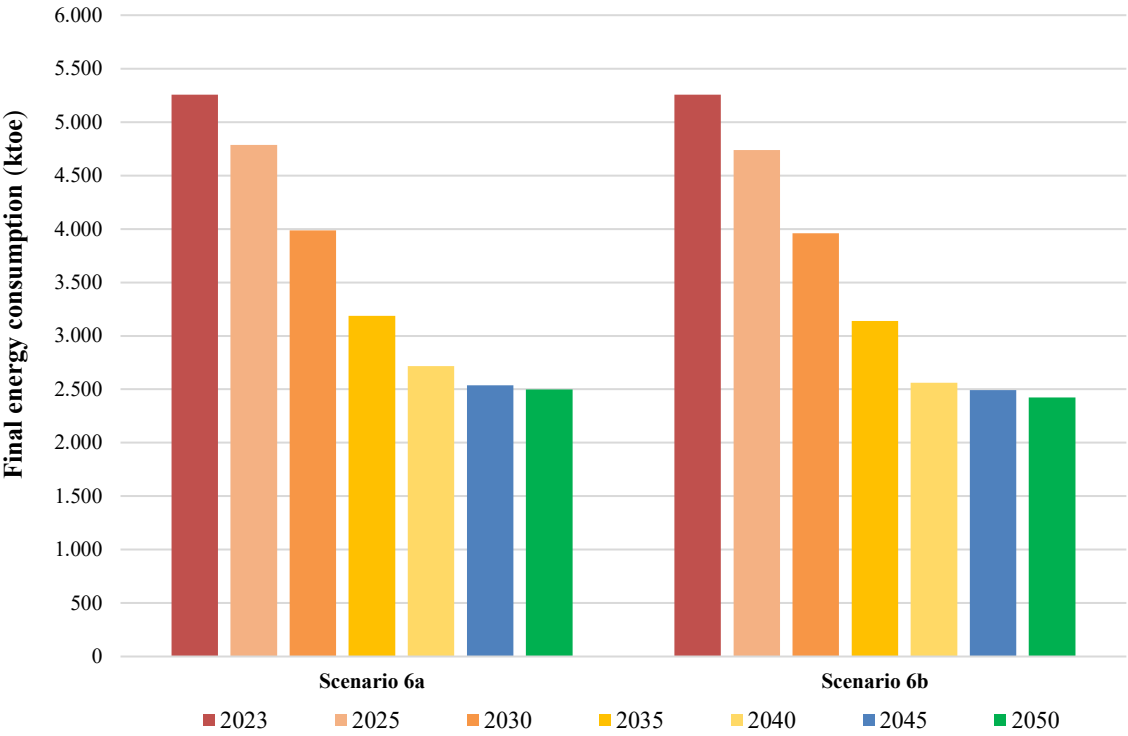


Fig. A3. Final energy consumption (in ktoe) by 2050 in the Greek residential sector for “Scenario 6_a” and “Scenario 6_b”.

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Nomenclature

Acronyms & abbreviations			
BES	Building Energy System	NECPRs	National Energy and Climate Progress Reports
DREEM	Dynamic high-Resolution dEmand-side Management	PMV	Predicted Mean Vote
ETS	Emissions Trading System	PPD	Predicted Percentage of Dissatisfaction
EPBD	Energy Performance of Buildings Directive	RES	Renewable Energy Sources
EC	European Commission	TEESlab	Technoeconomics of Energy Systems laboratory
EU	European Union	TEEM	TEESlab Modelling suite
ELSTAT	Hellenic Statistical Authority	TUS2013	Time of Use Survey 2013
HBS2020	Household Budget Survey 2020	TMY	Typical Meteorological Year
NECP	National Energy and Climate Plan	WMO	World Meteorological Organisation

3. Expanding natural gas infrastructure in Greece: Good practice or missed opportunity of a green and inclusive transition?

Abstract

The vision of climate neutrality is no longer characterised by a single spatial focus as there is a clear need for collaboration at, and across, different governance levels. This is particularly important as regional and local authorities are given a more active role in implementing energy transitions; when it comes to policymaking, though, their needs are not always considered, and decisions are mainly taken at the national level. Such an example is the Peloponnese region in Greece, where many actors criticise the ongoing construction of a new natural gas distribution network. In this article, we explore if this expansion is a good practice, or a missed opportunity of a green and inclusive transition. To do so, we couple high-resolution modelling with policy knowledge and experts' insights to simulate different transition pathways by 2050. We show that an alternative strategy promoting electrification of heating along with energy efficiency could lead to more benefits at both the regional and the household levels. We also show that if decarbonisation is the real goal, more ambitious renovation targets should be set, while a supporting strategy that assures a fair participation of citizens should be devised.

Keywords: Natural gas; Electrification; Energy transition; Energy efficiency; Residential sector; Regional governance

3.1. Introduction

Buildings are responsible for 40% of the energy consumption and 36% of the carbon dioxide (CO₂) emissions in the European Union (EU) (Siddique, Bergaentzlé, and Gunkel 2022). Moreover, more than two-thirds of the energy consumed in the EU's building sector is used for space heating, while almost half of the building stock is equipped with inefficient fossil-fuel boilers, many of which have exceeded their technical lifetime (D'Agostino et al. 2024). Striving to become the world's first net-zero continent by 2050, the EU's vision of climate neutrality makes it imperative to reduce energy consumption in the building sector, also improving its environmental footprint (Siksnelyte-Butkiene, Streimikiene, and Balezentis 2022). In this direction, the European Commission (EC) has established several strategies, directions, and regulations focusing on the key role of implementing energy-efficiency measures (Papantonis et al. 2022b), especially considering the geopolitical developments of the past few years, which have raised several concerns about rising energy prices and energy security (Liu, Zhou, and Liu 2023).

As a result, the EC has developed the “REPowerEU” plan (2022), which along with the “Fit-for-55” package (2021) (Erbach et al. 2024), the revised “Energy Efficiency Directive” (2023) (European Commission 2023a), and the recast of the “Energy Performance of Buildings Directive” (2024), aim to bring major changes in the use of fossil fuels in buildings (European Commission 2022b). Especially the targets of (i). cutting the EU's dependence of Russian natural gas, (ii). enhancing the role of energy efficiency, (iii). phasing out fossil-fuel boilers, and (iv). pricing emissions stemmed from heating in the building sector via a new parallel Emissions Trading System (ETS), increase the need of investing in fossil-fuel alternatives such as electrification (Chyong and Henderson 2024).

When it comes to the case of Greece, and in the context of the abovementioned EU's strategic visions and targets, a green transition in the building sector, and especially in the residential sector, which is responsible for around 25% of the country's final energy consumption, is considered critical towards a secure and resilient energy system by 2050. In addition to the latter, households are also highly exposed to energy poverty as Greece is one of the Member States that significantly suffer from the phenomenon, displaying high recorded values based on relevant indicators (Greek Ministry of Environment and Energy 2021). Apart from the socioeconomic causes attributed to the phenomenon (high energy prices, low income, etc.), a major influencing factor is also the poor energy performance of the existing residential stock (N. A. Spyridaki et al. 2020). 55% of the dwellings in Greece are constructed before 1980, having, thus, low performance standards, or no thermal insulation (Boemi and Papadopoulos 2019). In this context, the draft National Energy and Climate Plan (NECP) of 2023 sets a target of around 12-15% of the country's dwellings to be fully, or partially renovated by 2030, while, on the other hand, it continues to support schemes and investments on the expansion of the natural gas grid in the mainland (Greek Ministry of Environment and Energy 2019).

However, given the geopolitical developments of the past few years, with Russia's invasion of Ukraine and the consequential energy crisis and high inflation rates since then, questions about the effectiveness of the current national planning and the decisions already made arise (Nikas et al. 2024). Questions of this nature lead only to more ambiguous policy debates, especially when different governance levels are put under the microscope of the national strategy in Greece, as climate and energy transitions to alternative and sustainable futures are no longer characterised by a single spatial focus or location (Zhou, Chen, and Chen 2022). According to recent literature “*there is a risk of diluting the ambition at the national level, a persistent lack of coordination of national energy policies*” and a serious “*need to strengthen common financing, policy coordination, and governance tools*” (Defard 2023). This calls for a variety of actions by a wide range of actors at different levels of influence and for improved governance structures and collaboration across different policymaking levels (e.g., administrative levels within countries) (Wang et al. 2024).

Breaking transition lock-ins, therefore, is inherently a political endeavour, as transition pathways are intricately linked with political decisions and policies that foster, modify, and enable changes at different policy levels, which, however, are mostly taken at the national level. This is particularly important as regional and local authorities are given more responsibility and importance in implementing climate and energy transitions (Kleanthis et al. 2022); when it comes to policymaking at strategic levels, though, their contribution is not always considered, and legislation does not always support the regional and/ or the local level (Brandoni and Polonara 2012). This is not in line with Art.11 of the European Regulation on the Governance of the Energy Union and Climate Action 2018/ 1999, which states that Member States shall establish a multilevel climate and energy dialogue to deliver on the vision of climate neutrality by 2050 (European Parliament and Council of the European Union 2018). As of now, though, the EC's assessment of National Energy and Climate Progress Reports (NECPRs), submitted in March 2023, attached to the 2023 State of the Energy Union shows that the maturity of these multilevel governance structures is currently not at the ideal level (European Commission (EC) 2023).

Back to the case of Greece, such a region of ambiguous climate and energy debate is Peloponnese, a large peninsula constituting the southernmost part of mainland, characterised by a large diversity of climatic conditions. This diversity already makes Peloponnese a very interesting case of a climate and energy transition analysis. However, what makes it even more interesting is the policy decisions already made at both the national and the regional levels for the construction of a new natural gas distribution network and its interconnection to the remaining mainland; this currently ongoing project will allow the use of natural gas as an alternative heating fuel to traditional oil boilers primarily in the region's residential sector. Nevertheless, scientific literature lacks studies analysing climate and energy transition issues at the regional level, also investigating interactions with national policy planning. A key reason for that is the lack of consistent regional data on energy demand and supply, and their projections, as has been clearly demonstrated by relevant research in the field (e.g., under the EC-funded LIFE Programme "Regio1st¹⁷") (Stavrakaki and Konstantopoulos 2023).

In this context, thus, and in view of the expected amendment of the Greek NECP, our study seeks to examine different scenarios of energy transition by 2050 in the Peloponnese region's residential sector within the broader EU's framework and its implementation in the national context of Greece. The overarching hypothesis of our study suggests that existing regional planning, which focuses on expanding the use of natural gas as a transition fuel in the Peloponnese region, could result in a missed opportunity of a green and fair transition.

To explore this hypothesis, we seek to answer the following questions: (a). *"Is existing national policymaking adequate towards the vision of decarbonisation in the Peloponnese region's residential sector by 2050, or significant adjustments are required in view of the upcoming NECP's amendment?"*, (b). *"What is the most cost-effective technology mix towards decarbonisation in the Peloponnese region's residential sector?"*, and (c). *"Is the decision made at the national level for the ongoing construction of a new natural gas distribution network, also increasing the Peloponnese region's dependence to fossil fuels, a good practice of climate and energy governance at the regional level, or is it a missed opportunity of a green, fair, and inclusive transition by 2050?"*.

To answer these questions, we use a bottom-up dynamic high-resolution demand-side management model to simulate the energy demand evolution in the Peloponnese's residential sector by 2050, under different transition scenarios, as these are extracted from the existing policy planning and political decisions at the national level, and relevant national and regional experts' feedback. Overall, the novel contribution of our work to the scientific literature is twofold:

¹⁷ <https://ieecp.org/projects/regio1st/>.

- We study energy transition scenarios in the residential sector by 2050, at the regional level, while also evaluating specifications and targets set at the national level.
- We investigate the interaction of the current national planning at the regional level of Peloponnese, in accordance with the latest developments at the EU level, to provide insightful recommendations for policy and practice in view of the expected amendment of the Greek NECP and transition paradigms in other EU regions.

3.2. Methodological framework

We use the Dynamic high-Resolution dEmand-side Management (DREEM) model, a fully-integrated energy demand and demand-side management simulation model, focusing on the building sector, which expands the computational capabilities of existing Building Energy System (BES) and demand-side models, by not only calculating energy demand, but by also assessing the benefits and limitations of demand flexibility, primarily for the main end-users (consumers/ citizens), and, then for other energy system actors involved (suppliers, retailers, Distribution System Operators, etc.) to facilitate participatory and inclusive energy transitions. To address the needs of the current study, the model's original architecture and capacities, as originally introduced by Stavrakas and Flamos (2020) (Stavrakas and Flamos 2020), have been expanded, as part of the work undertaken in the context of the EC-funded Horizon 2020 projects “SENTINEL¹⁸” and “ENPOR¹⁹”, while the updated modelling structure is presented in **Fig. 3.1**. Here, we provide a description of the new components and respective modules that have been developed and integrated to the original model's structure, along with the components and modules that have been used for the application at hand, based on **Table 3.1**.

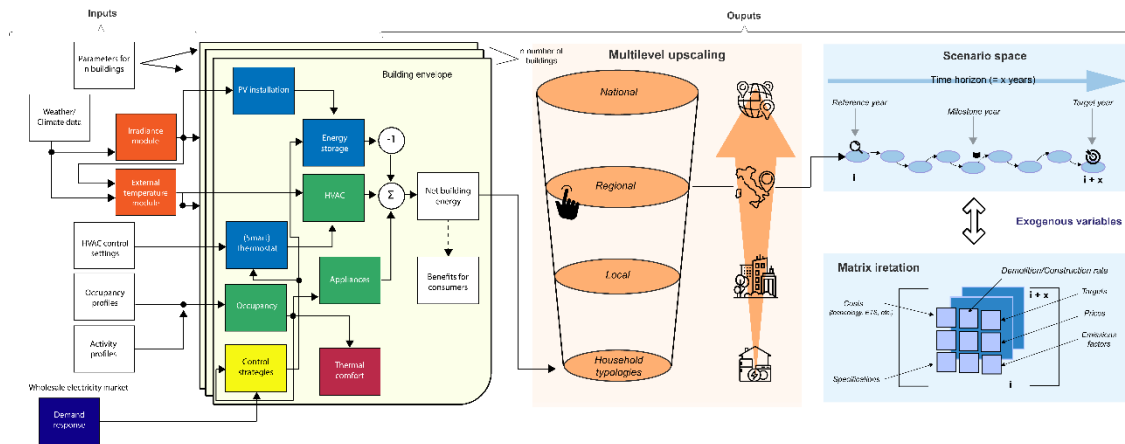


Fig. 3.1 Expanded architecture of the DREEM model as it currently stands (Papantonis, Stavrakas, Tzani, et al. 2025).

Table 3.1. Hierarchical structure of the expanded version of the DREEM model as used in this study: Short description of the main components and modules (Papantonis, Stavrakas, Tzani, et al. 2025).

Components	Modules	Description	Developed
C1: Weather/ Climate data	-	This single-module component is responsible for generating climatic boundary conditions. It reads weather data from the respective files and then provides them to the other components, where and when necessary.	Modelica

¹⁸ <https://cordis.europa.eu/project/id/837089>.

¹⁹ <https://cordis.europa.eu/project/id/889385>.

C2: Building envelope	-	This single-module component models different building typologies with the corresponding characteristics, properties, and heat conduction elements.	Modelica Python
C3: Energy demand	<i>C3M1: Occupancy</i>	This module defines and sets the parameters for the behaviour and the activities of the occupants by generating and storing default patterns.	Modelica
	<i>C3M2: Appliances</i>	This module is responsible for generating energy demand profiles from appliances, using statistics describing their mean total daily energy demand and associated power use characteristics, including steady-state consumption, or typical use cycles, based on occupancy patterns.	
	<i>C3M3: Heating, ventilation, and air conditioning</i>	This module is responsible for heating, ventilation, and air conditioning inside the building.	
C4: Thermal comfort	-	This single-module component is responsible for determining, based on international standards, appropriate conditions and temperature ranges that result in occupants' thermal satisfaction.	Modelica Python
C8: Multilevel upscaling	-	This new single-module component is responsible for applying an upscaling approach to compute cumulative energy consumption patterns in the building sector, at the scale of interest, using parameters and statistics obtained from survey and/ or census data. It receives inputs from the "C2: Building envelope" and the "C3: Energy demand" components.	Python
C9: Transition matrix	<i>C9M1: Scenario space</i>	This module is responsible for designing the scenario space (in terms of the transition pathways and the respective exogenous variables) inside of which the transition matrix is initiated and updated, based on relevant policy documents' specifications and practical experts' feedback.	Python
	<i>C9M2: Matrix iteration</i>	This module is responsible for initialising the transition matrix and updating it at each time interval (i.e., iteration), following the scenario space's specifications (i.e., targets and constraints) derived from the " <i>C9M1: Scenario space</i> " module.	

3.2.1. C₁: Weather/ Climate data

Seasonal variability to reflect the changing level of demand between winter and summer is an important aspect, which is often omitted or addressed in an oversimplified manner by existing demand-side models in the field. The DREEM model addresses this issue thoroughly compared to other approaches through the inclusion of a single module component dedicated to generating accurate climatic boundary conditions based on historical weather data. To do so, the component uses Typical Meteorological Year (TMY) (Cebecauer and Suri 2015) weather data format, and in particular the TMY3 format, while it is then configured to provide a common set of irradiance and temperature data for the geography under study, with the respective irradiance and temperature profiles having appropriate time-diversity to enable higher resolution.

3.2.2. C₂: Building envelope

The DREEM model builds on the concept of “reduced (low)-order” thermal network modelling, which represents a thermal zone by thermal resistances and capacities (RC-network), using the electrical circuit analogy, in which voltage is analogous to temperature and current is analogous to convective and radiative heat transfer (McKenna and Thomson 2016). The respective module represents all main thermal masses of the building under study as four elements, accompanied with supportive features for consideration of solar radiation (as visualised by Stavrakas and Flamos (2020) (Stavrakas and Flamos 2020)). The parameters for heat transfer coefficients, and thermal resistances and capacities, are determined using historical data and standards for the geographical context of interest

3.2.3. C₃: Energy demand

The DREEM model aims to generate accurate and realistic energy demand profiles, avoiding unnecessary computational complexity, by building on the concept of stochastic modelling and providing simulated data about households’ energy demand, with statistics suitable for the task at hand (Stavrakas and Flamos 2020). This component uses a bottom-up approach to simulate energy consumption considering households’ occupancy, use of appliances, and heating, cooling, and ventilation options. The component’s individual modules use many simplified assumptions to simulate various aspects of energy demand (occupancy and occupants’ activity/behaviour profiles, sharing of appliances, etc.) and focuses on parameters and statistics obtained from survey and/or census data.

3.2.4. C₄: Thermal Comfort

The model focuses on addressing the- often overlooked by other models in the field- aspect of occupants’ thermal comfort, by utilising an individual component that aligns with international standards (DIN EN ISO 7730 (DIN EN ISO 7730 2005a), ASHRAE 55 (Taleghani, Tenpierik, Kurvers, and van den Dobbelsteen 2013), EN 15251 (Fanger and others 1970)).

3.2.5. C₈: Multilevel upscaling

This newly developed single-module component allows the DREEM model to serve as a modelling tool of accurate energy demand profiles in the building sector, within the broader field of local, regional, and national energy systems, in different geographical/ climate and socioeconomic contexts of interest. It uses an upscaling approach, building on parameters and statistics obtained from survey and/ or census data, to calculate cumulative energy consumption in the building sector, at the local, the regional, or the national level, according to the needs of each application at hand. After having specified the individual building typologies of interest under the “C₂: Building envelope” component and simulating their individual energy consumption patterns, based on the specifications and the parameterisation of the “C₃: Energy demand” component, this component computes cumulative energy consumption patterns at the scale under study as the product of each individual building typology’s energy consumption and the number of the respective households per typology and number of occupants (as extracted by the available statistical data).

3.2.6. C₉: Transition matrix

The DREEM model has been developed to allow for producing outputs at a high resolution (i.e., one minute), also accounting for seasonal variability to reflect the changing level of demand between winter and summer, while its modular structure provides the necessary computational efficiency to simulate large numbers of buildings for the long-term transition with the appropriate demand diversity and accuracy (due to its bottom-up structure), also reducing the simulation complexity owing to the multidisciplinary nature of energy demand models and their input data requirements. In this context, this newly developed component creates a scenario space, based on the policy specifications of each application at hand, which is further updated based on the evolution of exogenous variables (e.g., costs, prices, technological specifications) and is stored in a matrix to provide detailed information on the

energy transition in the building sector for the time horizon (e.g., 2030, 2040, 2050) and the time interval (e.g., one hour, one year, five years) of interest.

C₉M₁: Scenario space

This module is responsible for designing the scenario space inside of which the transition matrix is initialised and updated. It starts with setting the modelling time horizon, i.e., reference year (simulation start year), interim milestone years (where and if necessary), and the target year (simulation end year), based, each time, on the specifications of the application under study. The initial scenario space is parameterised mainly based on the specifications of the most recent policy documents, in accordance with the emission caps of the updated mitigation targets for 2030 and 2050 in the context of the “Fit for 55” package and the European Green Deal strategy. As a next step, relevant stakeholders’ and policy practitioners’ feedback is also considered to diversify and expand the initial scenario space and eventually account for possible uncertainties and different potential evolutions of the future energy system. Finally, the scenario space is further populated with the evolution of different exogenous variables, e.g., emission factors, evolution of relevant energy prices and costs, technological costs and relevant updated configurations, demolition rate of old buildings and construction rate of new ones, benefits for occupants and/ or other power actors involved.

C₉M₂: Matrix iteration

This module is responsible for initialising the transition matrix and updating it, at each time interval (as specified by the user at the simulation start time), based on inputs of the cumulative energy consumption patterns (received from the “C₈: Multilevel upscaling” component) and the state of the scenario space (received from the “C₉M₁: Scenario space” module). At the simulation end time, this module derives the final transition matrix, containing detailed information on the energy transition in the building sector, for the resolution and the time horizon specified for the application at hand by the user.

Fig. 3.2 visualises the methodological flowchart of the newly developed “C₈: Multilevel upscaling” and “C₉: Transition matrix” components, illustrating their individual operation and how they interact with each other to produce relevant outcomes at the scale of interest.

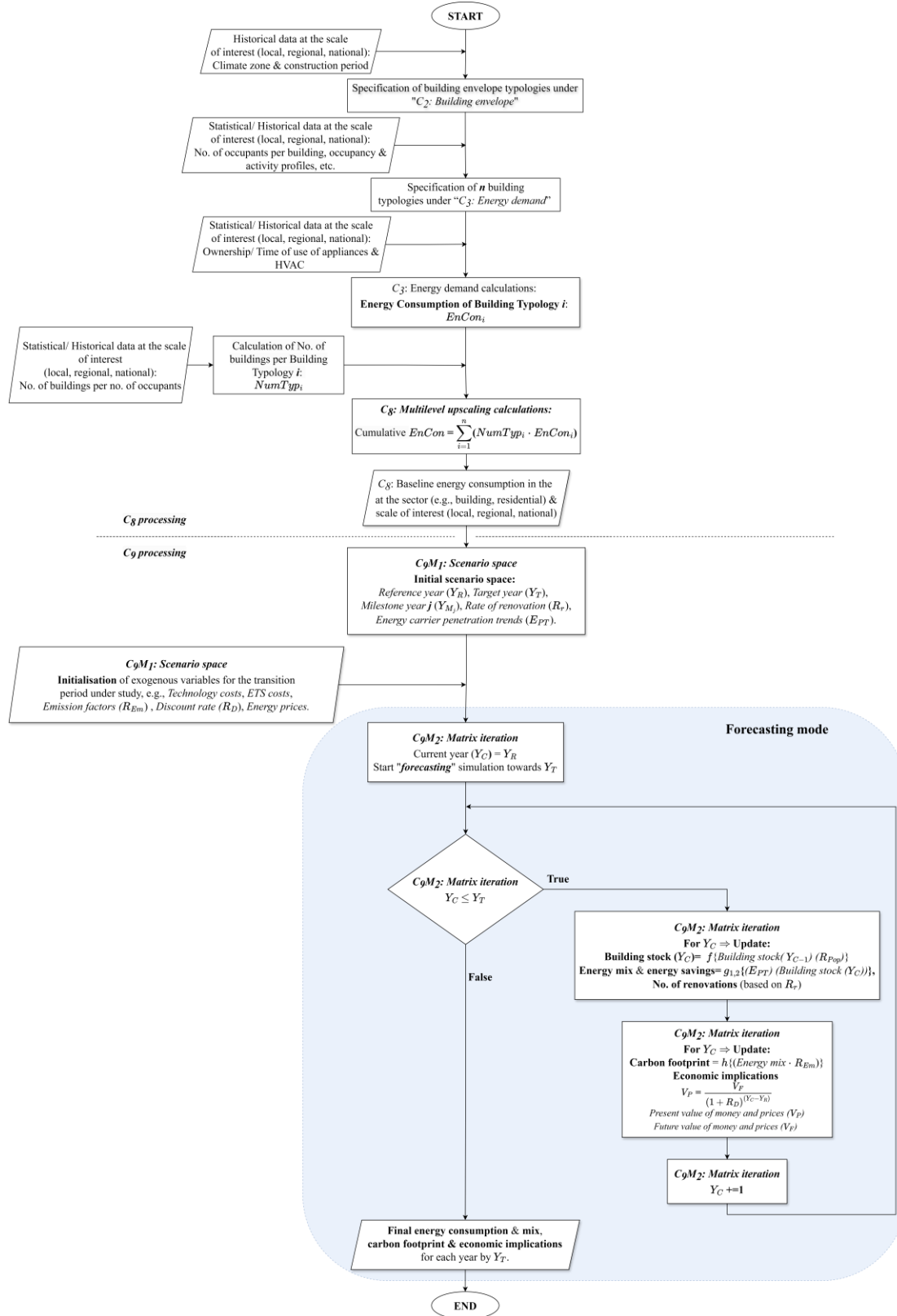


Fig. 3.2. Methodological flowchart illustrating the newly developed components, “C8: Multilevel upscaling” and “C9: Transition matrix”, showcasing their individual operations and how they interact with each other.

3.3. Model application to the residential sector in the Peloponnese region

We present the parameterisation of the individual components and modules in the DREEM model (the ones that are required for this application), along with the main data inputs, the scenario design, and the assumptions made, for the Peloponnese region's residential sector. Located at the southern tip of the mainland in Greece, Peloponnese is divided into seven major regional units, namely, Achaea (north), Corinthia (northeast), Argolis (east), Arcadia (centre), Laconia (southeast), Messenia (southwest), and Elis (west). However, from these regional units, only the five of them, namely, Arcadia, Argolis, Corinthia, Laconia, Messenia are under the Peloponnese Regional Authority's administrative jurisdiction, while Achaea and Elis are under the Western Greece Regional Authority's administrative jurisdiction. Since national planning on the installation of a new natural gas distribution system refers to the Peloponnese's administrative level, in this study, we include the five abovementioned regional units (European Commission 2022a).

3.3.1. C₁: Weather/ Climate data

The five regional units under study are located in the three of the four Greece's different climate zones; Argolis, Laconia, and Messenia are considered "Climate Zone A", Corinthia is considered "Climate Zone B", and Arcadia is considered "Climate Zone C" (Hellenic Ministry of Environment and Energy 2021). We use weather/ climate data from the database of the World Meteorological Organisation (WMO) (World Meteorological Organisation 2021). The data is formatted as TMY3, accumulating a 14-year period (2007-2021) of data values, and including information on latitude, longitude, and time zone in relation to Greenwich Mean Time, as well as temperature, relative humidity, wind speed and direction, sun direction and radiation values, on an hourly basis. For each climate zone under study, we select meteorological data available for their nearest location: for "Climate Zone A", we select meteorological data for the city of Kalamata; for "Climate Zone B", we select data for the city of Elefsis; while for "Climate Zone C", we select data for the city of Tripolis.

3.3.2. C₂: Building envelope

For the three different climate zones under study, we use the different building typologies for Greece's residential sector according to the "TABULA" database, which contains information on national residential typologies in different European countries, classified per climate zone and construction period (European Union 2017). For Greece and according to the transcription of the Energy Performance in Buildings Directive (EPBD) into the national law back in 2011 and its subsequent amendments in the following years (Daskalaki et al. 2011), the webtool distinguishes between four different construction periods, namely dwellings constructed: (i). before 1981, (ii). during the period 1981-2000, (iii). during the period 2001-2011, and (iv). after 2011.

3.3.3. C₃: Energy demand

We use data for the Peloponnese region and regional units of interest obtained from the "2020 Household Budget Survey (HBS2020)", which, to the best of our knowledge, is the latest official survey conducted by the Hellenic Statistical Authority (ELSTAT) on households' energy consumption in Greece (Hellenic Statistical Authority ELSTAT 2020).

C₃M₁: Occupancy

This module uses household composition and occupancy patterns derived from historical and statistical data. The first key factor to properly configure this module is the number of members per household, while the second key factor concerns the time that occupants spend being active at their homes, which is strongly connected to their employment status and work schedules. To quantify these parameters, i.e., the number of members per household, according to the different dwelling typologies, as specified in the "C₂: Building envelope" component, and occupants' activity levels when they are at home, we used the HBS2020 data (Hellenic Statistical Authority ELSTAT 2020). In addition, to quantify the

parameter on time that occupants spend at and away from home, based on their work schedule, we used statistical data from the ELSTAT's "Time of Use Survey 2013 (TUS2013)", which again, to the best of our knowledge, is the most recent survey data collected (Hellenic Statistical Authority (ELSTAT) 2014). Note that this data concerns the entirety of Greece's population, since there is no other such data, publicly available, especially at the regional level. The HBS2020 and the TUS2013 data allowed us to come up with 12 different household typologies in the five Peloponnese regional units' residential sector under study, based on the most statistically significant data on dwelling typologies (**Table B1** in **Appendix B** (Hellenic Statistical Authority ELSTAT 2020)), occupancy schedules, and activity levels, as presented in **Table 3.2**.

Table 3.2. 12 household typologies in the Peloponnese's residential sector, based on dwellings' climate zone and construction period, number of residents per dwelling, number of employed and non-economically active/unemployed, and their overall occupancy profiles.

a/a	Climate zone	Construction period	Members	Employed members	Non-economically active/unemployed members	Overall occupancy profiles
1	A	Before 1981	1	0	1	1 elderly person
2		Before 1981	4	2	2	2 employed persons & 2 children
3		1981-2000	2	2	0	2 employed persons
4		1981-2000	2	2	1	2 employed persons & 1 child
5		After 2000	2	1	1	2 employed persons & 1 child
6	B	Before 1981	1	1	0	1 employed person
7		Before 1981	2	1	1	1 employed & 1 unemployed person
8		1981-2000	5	2	3	2 employed persons & 3 children
9		After 2000	3	1	2	1 employed person, 1 unemployed persons & 1 child
10	C	Before 1981	4	1	3	1 employed person, 1 unemployed person & 2 children
11		1981-2000	2	1	1	1 employed & 1 unemployed person
12		After 2000	4	2	2	2 employed persons & 2 children

C₃M₂: Appliances

We use the HBS2020 data to configure the final set of appliances in the model, specifically for the Peloponnese region, based on information on appliances' ownership rate, nominal power, and time of use (**Table 3.3**).

Table 3.3. Final set of appliances, included in the model, along with their ownership rates, nominal power capacities, and time of use schedules, as extracted from the "2020 Household Budget Survey (HBS2020)" data.

Appliances	Ownership rate (%)	Nominal power (W)	Time of Use (hours/day)
Cooking			
Hobs	91.67%	1,600	1.59
Oven	87.18%	2,150	1.00
Microwave oven	43.91%	1,150	1.15
Toaster	72.44%	1,300	1.38
Coffee maker	28.53%	1,100	0.94
Water boiler	41.03%	1,250	0.92
Cooker hoods	93.59%	108	1.56
Other appliances			
Fridge freezer	83.97%	150	24
Dishwasher	33.33%	1,350	1.75
Washer	97.44%	500	1.21
Iron	96.15%	1,000	0.85

Vacuum cleaner	82.69%	450	0.93
Television	99.68%	100	5.42
DVD or VCR	15.71%	40	0.59
Home cinema	1.92%	200	0.68
Stereo	21.47%	24	0.67
Computer	57.05%	300	2.67
Peripheral devices (e.g., printer, scanner)	3.85%	50	0.88
Internet devices (e.g., router)	55.13%	10	24.00
Video game console	7.37%	160	0.89
Domestic hot water electric boiler	56.41%	4,000	1.19

C₃M₃: Heating, ventilation, and air conditioning

For the configuration of the heating, ventilation, and air conditioning (HVAC) systems we also use the HBS2020 data to acquire information on the systems' ownership rate and coefficient factors.

Table 3.4 presents the current ownership status of the main heating technologies in the residential sector in the Peloponnese region, based on the HBS 2020 data and **Table 3.5** the ownership status of domestic hot water (DHW) technologies in the region.

Table 3.4. Current ownership status of the main heating technologies in the residential sector in the Peloponnese region based on the HBS2020 data (Hellenic Statistical Authority ELSTAT 2020).

Heating technology	Number of households	Percentage of households
Oil boiler	91,485	48.7%
Natural gas boiler	0	0%
Electric heating system	84,910	45.2%
Heat pump	1,127	0.6%
Biomass	10,332	5.5%
Total	187,854	100%

Table 3.5. Current ownership status of the main DHW technologies in the residential sector in the Peloponnese region based on the HBS2020 data (Hellenic Statistical Authority ELSTAT 2020).

DHW technology	Number of households	Percentage of households
Oil boiler	9,031	4.9%
Electric heater	66,833	35.6%
Heat pump	602	0.3%
Solar water heater	111,388	59.3%
Total	187,854	100%

3.3.4. C₈: Multilevel upscaling

After simulating energy consumption for each household typology presented in **Table 3.2**, we use the HBS2020 data- which to the best of our knowledge is the most recent data available at the regional level in Greece- to compute the cumulative energy consumption patterns in the Peloponnese region's residential sector for the reference year. According to the statistics used, the total number of households in the Peloponnese region is 187,854, while the number of households per number of occupants used for upscaling each typology under **Table 3.2** is presented in **Table 3.6**.

Table 3.6. Number of households per number of occupants in the Peloponnese region.

Number of occupants	Number of households
1 member	32,693
2 members	60,457
3 members	39,545
4 + members	55,162

Total	187,854
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3.3.5. C₉: Transition matrix

Based on the thematic focus of this study as explained above, this component's individual modules are parameterised as follows.

C₉M₁: Scenario space

For the initial state of the scenario space, we set the reference year to 2022, the target year to 2050, while as interim milestone years we select the years 2025, 2030, 2035, 2040 and 2045. In terms of policy specifications, we based the initialisation of the scenario space on the current energy planning in Greece ("Scenario 1") and the political announcements so far. More specifically, "Scenario 1" is based on the current national and regional planning which concerns the expansion of the natural gas infrastructure in more regions in Greece, including the Peloponnese region, in order to cover (among others) the residential sector's heating needs. This expansion is aligned with the national targets set by the existing Greek NECP, which foresee a 16% use of natural gas use in the residential sector by 2030 (Greek Ministry of Environment and Energy 2019). In this regard, in "Scenario 1" we assume that the penetration of natural gas will follow a trend similar to the one foreseen in the existing national planning, leading to a 10% share of natural gas in residential energy consumption, with a gradual phase-out beginning by 2036.

On the other hand, "Scenario 3" is based on a shift towards increased electrification and energy efficiency, aligned with the objectives of the EU's "REPowerEU", "Fit-for-55", and the "European Green Deal" strategies. In "Scenario 3" we consider the same replacement rate of oil boilers, but instead of replacing them with natural gas ones, we use heat pumps, thereby envisioning the electrification of the sector from the beginning. "Scenario 2" represents a balanced strategy combining both approaches, with an annual natural gas penetration rate nearly half of the national target, emphasising in electrification.

Our approach seeks to provide a comparison among the most recent trajectories of energy policy and infrastructure development outlined by relevant authorities at the national and the EU levels. While "Scenario 1" aligns with current national policies, "Scenario 2" and "Scenario 3" represent more progressive pathways, aiming to exceed existing targets in line with broader EU goals. This comparative analysis ensures that our scenarios are both realistic and ambitious, providing valuable insights for future policy adjustments.

In addition, the design of the alternative scenarios, (i.e., "Scenario 2" and "Scenario 3") also drew inspiration from the feedback we received from different relevant stakeholders and policy practitioners. More specifically, our modelling framework, our scenarios, and respective assumptions, were initially co-created during two press conferences organised by the Peloponnese Regional Council in 2021 and 2022. As a next step, modelling results were presented, discussed, validated, and further refined, through a series of workshops and events held, during the period 2022-2024, in hybrid format (online and physically in different places in Peloponnese), involving a diverse group of relevant stakeholders at all the governance levels, as for example, representatives from the Greek Ministry of Environment and Energy, representatives from the Regional Authority of Peloponnese, representatives from Megalopolis (a local municipality in Peloponnese, which is currently undergoing a just transition process due to the phase out of lignite-fired power plants), etc.

These events were co-organised in the context of the EC-funded Horizon 2020 projects "TIPPING+²⁰" and "ENPOR", as well as the EC-funded LIFE project "RENOVERTY²¹". The revised scenario space

²⁰ <https://cordis.europa.eu/project/id/884565>.

²¹ <https://ieecp.org/projects/renoverty/>.

for the Peloponnese region's residential sector consists of three different transition pathways (**Table 3.7**). For the renovation rate, we keep the national target of 12-15%, as set in the Greek NECP, which in the case of Peloponnese is translated to 2,770 dwellings fully renovated on an annual basis. For all the three scenarios under study, and based on stakeholders' feedback, we assume that all the dwellings built before 2000, which have their heating technology substituted, are also renovated; in particular, the dwellings built before 1981 are renovated with exterior wall insulation and window upgrades, while the dwellings built during the period 1981-2000 are renovated with exterior wall insulation.

Table 3.7. Final scenario space to be simulated with the DREEM model to study the energy transition by 2050 in the Peloponnese region's residential sector.

a/a	Title	Milestone years	Description
1	<i>“The current strategy: Natural gas as a transition fuel”</i>	(2022-2030)	Annual natural gas penetration according to the NECP's 2030 targets (8-10% of total consumption).
		(2031-2035)	Annual heat pump penetration to achieve 300% increase in heat pump installations.
		(2036-2050)	Substitution of new natural gas installations with heat pumps.
2	<i>“A hybrid transition strategy: Investing in both electrification and natural gas”</i>	(2022-2030)	Phase out of the remaining natural gas installations, substituting them with heat pumps.
		(2031-2035)	Annual natural gas penetration at half of the NECP's 2030 targets (4-5% of total consumption). For the remaining households, it is assumed that they substitute oil boilers with heat pumps.
		(2036-2050)	Substitution of new natural gas installations with heat pumps.
3	<i>“An alternative transition strategy: Investing in electrification”</i>	(2022-2050)	Phase out of the remaining natural gas installations, substituting them with heat pumps.
		(2026-2050)	Substitution of oil boilers with heat pumps.

Furthermore, we supplement the scenario space with projections on the evolution of different useful exogenous variables to extract meaningful and policy-relevant conclusions on the socioeconomic and environmental implications of the transition scenarios under study. More specifically, in terms of energy prices, also considering the great uncertainty in their future evolution, we explored two different cases. As shown in **Table B2 Table B3(Appendix B)**, in the first case (i.e., “Low-price evolution”) the initial values are the ones prior to energy crisis (i.e., January 2021), while in the second case (i.e., “High-price evolution”), we consider values post energy crisis (i.e., September 2022 and beyond). In both cases, to extract the future evolution we followed the projection trends provided in the Greek “Long-Term Strategy towards 2050” (Hellenic Ministry of Environment and Energy 2019) and the latest NECP (2024) (Hellenic Republic- Ministry of Environment and Energy 2024a).

Our analysis also includes projections on the future evolution of technological costs by 2050, i.e., the costs to be paid by end-users for the implementation of the measures foreseen in the transition scenarios, e.g., natural gas/ heat pump installations, envelope upgrades, etc. (**Table B3 in Appendix B**). Finally, we quantify the ETS-relevant costs based on their expected evolution (€/tn) (**Table B4 in Appendix**

B), and the CO₂ emissions derived in each scenario. The latter is calculated using the emission factor projections from the Greek “Long-Term Strategy towards 2050” (Hellenic Ministry of Environment and Energy 2019) in the case of electricity, while in the case of heating oil, natural gas, and biomass the respective emission factors are kept constant by 2050 (**Table B5** in **Appendix B**).

C₉M₂: Matrix iteration

The overall time horizon of this application is 28 years, while the time interval is set to one year (i.e., annual energy demand calculation). The final transition matrix contains detailed results on the energy transition by 2050 in the Peloponnese region’s residential sector, based on the scenario space presented.

3.4. Results and Discussion

3.4.1. Final energy consumption and energy mix by 2050

When comparing simulation results between “Scenario 1” and “Scenario 2” (**Fig. 3.3**), we observe that investing in natural gas as a transition fuel (“Scenario 1”) leads to higher final energy consumption by 2050 (136.7 ktoe compared to 127.1 ktoe, respectively). We also see that investing in electrification from the beginning (“Scenario 3”) leads to the lowest final energy consumption by 2050 (119.2 ktoe); decreased by more than 38% compared to “Scenario 1”.

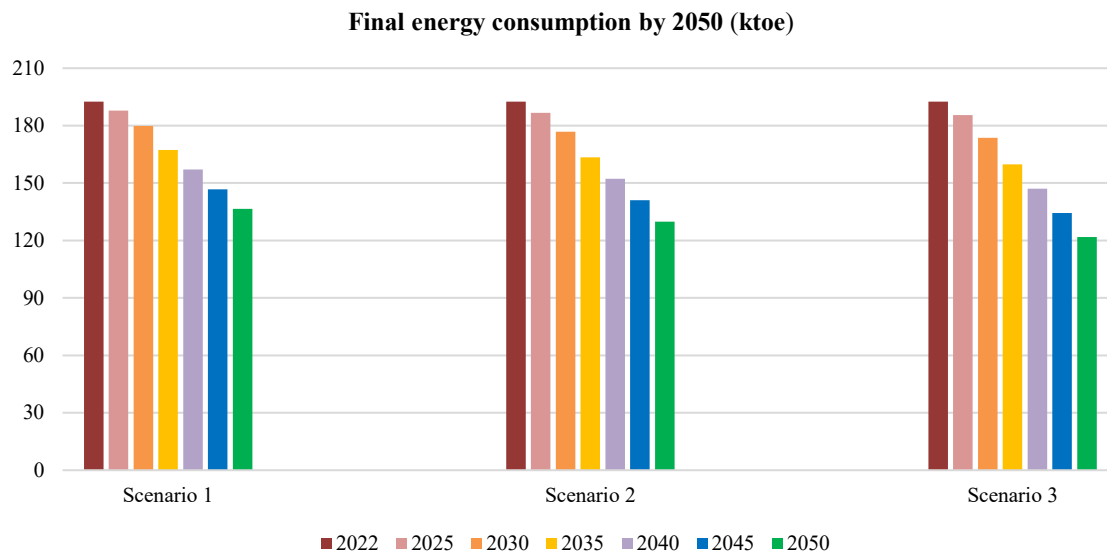


Fig. 3.3. Final energy consumption by 2050 in the Peloponnese region’s residential sector for the three scenarios under study.

Another important finding is that the national target of annual renovations (12-15%, ~2,770 dwellings in the case of Peloponnese) is not enough to result in decarbonisation in the Peloponnese region’s residential sector. As presented in **Fig. 3.4**, in none of the scenarios under study the consumption of fossil fuel-based products (i.e., heating oil and natural gas) is eliminated from the final energy mix by 2050.

More specifically, final consumption of fossil fuels in 2050 is, 23.3 ktoe under “Scenario 1”, 14.5 ktoe under “Scenario 2”, and 4.8 ktoe under “Scenario 3”. This difference is primarily due to how phasing out natural gas interacts with the allocation of heat pump installations under the renovation rates foreseen by the existing national planning. In “Scenario 1”, where natural gas is initially boosted and phased out at a later stage, a portion of the available heat pump installations must be used to replace gas boilers installed in the earlier phases of the transition, delaying the replacement of oil boilers. In contrast, “Scenario 3”, which prioritises electrification from the beginning, ensures that all heat pump installations directly replace oil boilers without an intermediate transition to gas.

The latter implies that, while investing in electrification in the residential sector as early as possible (“Scenario 3”) can result in the highest decarbonisation potential, the current renovation target in the residential sector is not ambitious enough to achieve complete decarbonisation in the Peloponnese region’s residential sector by 2050. This is not in line with the EU’s targets- set in the “Fit for 55” package- indicating that policymaking in Greece should intensify renovation efforts; increasing funds for programmes like “Energy Savings at Home” and prioritise energy efficiency measures, including electrification and building envelope upgrades, can be considered crucial to align Greece with sustainable and environmentally conscious policies, also contributing to meeting the EU’s relevant targets (Martin et al. 2024).

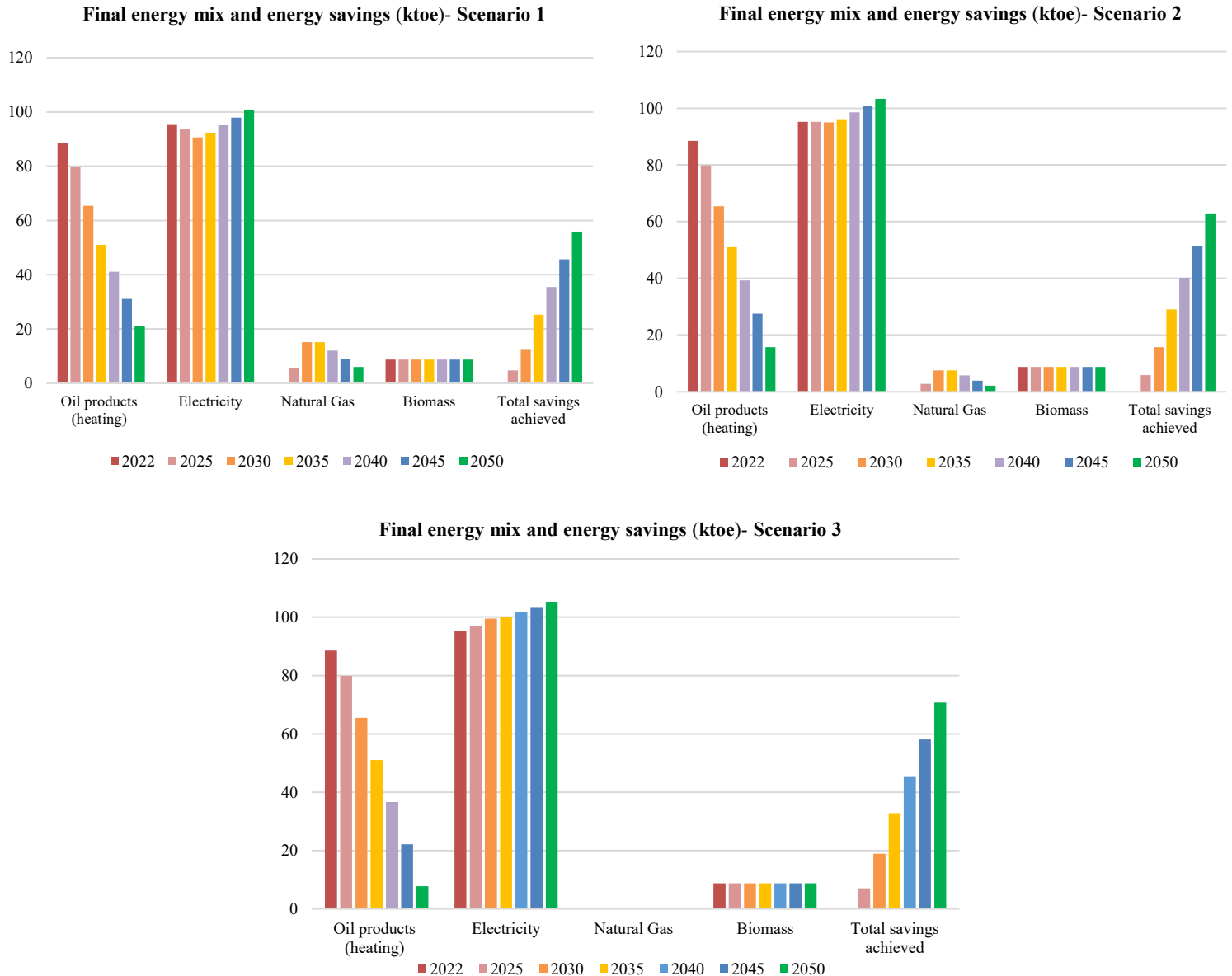


Fig. 3.4. Final energy mix and total energy savings achieved by 2050 in the Peloponnese region’s residential sector for the three scenarios under study.

3.4.2. Environmental impacts and CO₂ footprint

Simulation results also present the overall evolution of the expected CO₂ emissions in the Peloponnese region’s residential sector for each scenario under study. As expected, investing in electrification (“Scenario 3”) leads to lower levels of CO₂ emissions by 2050 (24,949 tnCO₂), compared to “Scenario

1” and “Scenario 2” (74,590 tnCO₂ and 51,339 tnCO₂, respectively), in which natural gas continues to have a dominant role in the final energy mix (**Fig. 3.5**). In addition, investing in electrification results in cumulative emissions of 7.95M. tnCO₂ by 2050, while the lower the penetration rate of natural gas (“Scenario 2” compared to “Scenario 1”), the lower the cumulative CO₂ emissions (8.34M. and 8.71M. tnCO₂, respectively).

Modelling outcomes showcase, thus, the positive impact of electrification on reducing CO₂ emissions. The observed emission reduction trends highlight an opportunity in the Peloponnese region to achieve greater environmental gains and foster a more sustainable environmental footprint, by adopting a strategy that increases the share of renewable energy sources (RES) in the electricity generation mix, thereby influencing the evolving landscape of electricity emission factors and resulting in lower values by 2050 (Lund 2014; Thellufsen et al. 2023). The latter is also related to the evident misalignment between the region’s environmental footprint and the EU’s decarbonisation vision towards 2050. This discrepancy emphasises the urgency of more intense mitigation efforts, the design of more ambitious policies, and the implementation of strategic interventions on both the demand and the supply sides, which will contribute effectively to harmonising regional strategies with broader decarbonisation and sustainability targets at both the national and the EU levels.

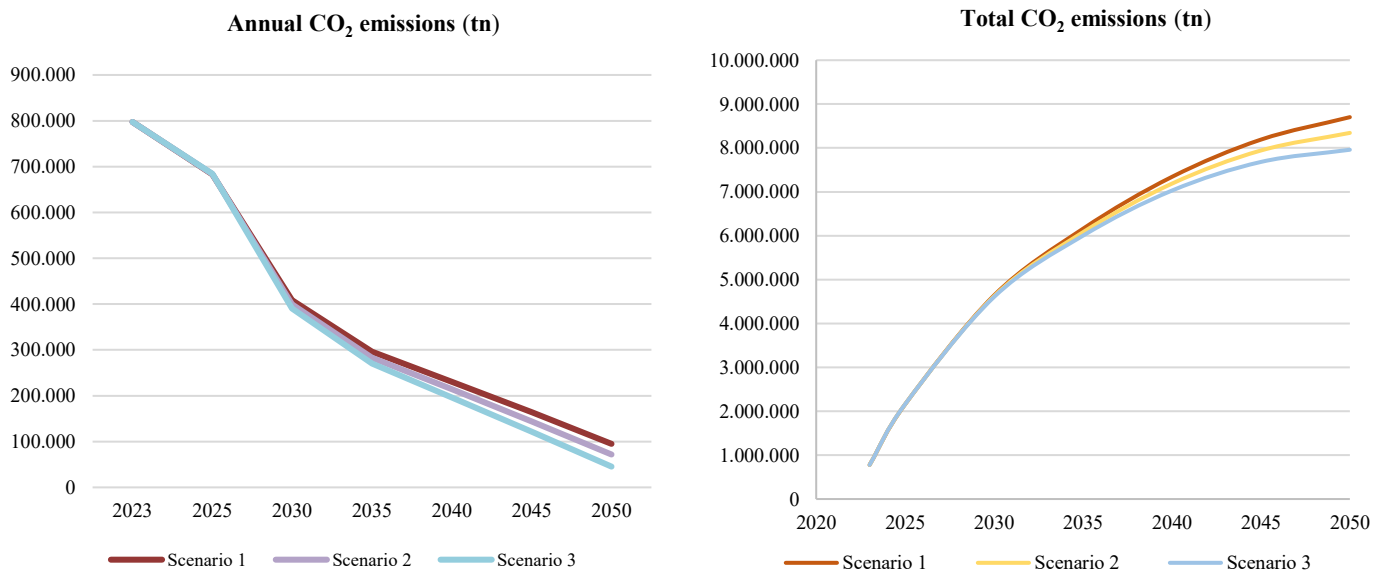


Fig. 3.5. Evolution of the CO₂ emissions by 2050 (annual and total) in the Peloponnese region’s residential sector for the three scenarios under study.

3.4.3. Economic implications at the regional and the household levels

Simulation results also offer insights into the economic implications of the energy transition in the Peloponnese region’s residential sector for each scenario under study. The analysis focuses on the costs associated with fuel consumption, renovations, and the inclusion of buildings under the ETS (**Fig. 3.6**).

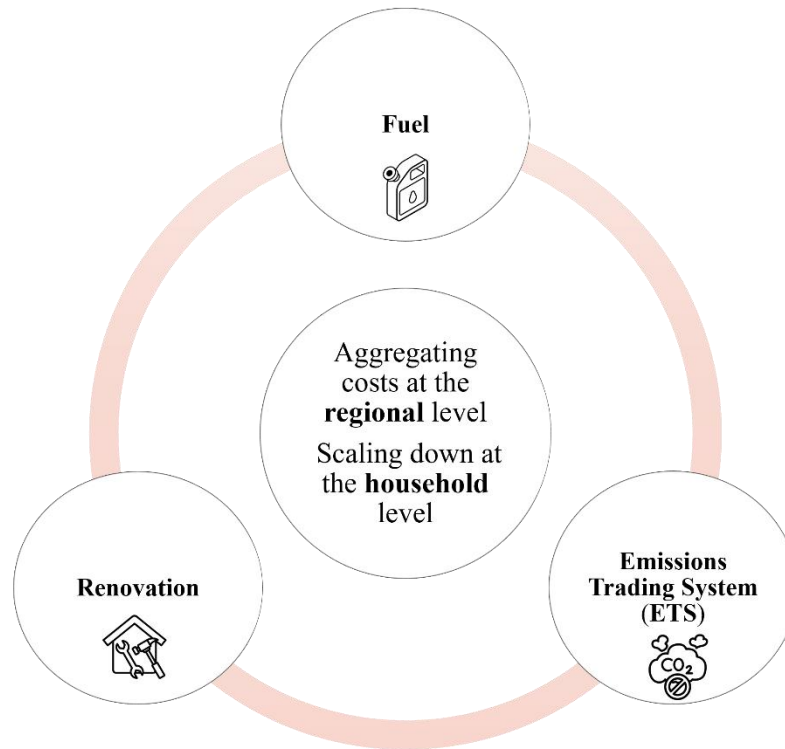


Fig. 3.6. Key cost components included in our modelling analysis at both the regional and the household levels.

Evolution of fuel costs

In this context, **Table 3.8** and **Table 3.9** present the evolution of the fuel costs by 2050, including the interim milestone years, also considering the two energy price cases specified, to account for potential uncertainties in future price projections. As expected, we see that investing in electrification (“Scenario 3”) leads to lower annual and cumulative fuel costs by 2050, also increasing the respective monetary savings when compared to investing in natural gas (“Scenario 1” and “Scenario 2”), in both the “High-price evolution” and the “Low-price evolution” cases.

More specifically, in the “High-price evolution” case, “Scenario 1” results in cumulative fuel costs of €12,347M. by 2050, “Scenario 2” results in cumulative fuel costs of €11,938M. by 2050, while “Scenario 3” results in cumulative fuel costs of €11,531M. by 2050. In addition, when compared to “Scenario 1” and “Scenario 2”, “Scenario 3” results in higher monetary savings, namely, €816.31M. and €407.41M., respectively.

Similarly, in the “Low-price evolution” case, “Scenario 1” results in cumulative fuel costs of €7,025M. by 2050, “Scenario 2” results in cumulative fuel costs of €7,013M. by 2050, while “Scenario 3” results in cumulative fuel costs of €6,977M. In this case, when compared to “Scenario 1” and “Scenario 2”, “Scenario 3” results in higher monetary savings too, namely, €48.43M. and €36.56M., respectively. These findings underscore the importance of prioritising electrification, also for its crucial role in addressing social justice concerns. By significantly reducing fuel costs, “Scenario 3” ensures a fairer energy transition, particularly for vulnerable households facing energy poverty, contributing to broader social well-being and inclusivity within the Peloponnese region.

Table 3.8. Evolution of fuel costs by 2050 in the Peloponnese region’s residential sector for the three scenarios under study: “High-price evolution” case.

Fuel costs (€)	2023	2025	2030	2035	2040	2045	2050
“Scenario 1”	460.1M.	467.3M.	483.6M.	462.3M.	434.0M.	401.9M.	366.0M.
“Scenario 2”	460.1M.	464.5M.	470.3M.	445.7M.	415.7M.	382.2M.	345.1M.

“Scenario 3”	460.1M.	461.7M.	458.6M.	429.1M.	397.5M.	362.7M.	324.5M.
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Table 3.9. Evolution of fuel costs by 2050 in the Peloponnese region’s residential sector for the three scenarios under study: “Low-price evolution” case.

Fuel costs (€)	2023	2025	2030	2035	2040	2045	2050
“Scenario 1”	278.9M.	277.5M.	270.8M.	256.1M.	243.1M.	228.3M.	211.7M.
“Scenario 2”	278.9M.	278.7M.	274.3M.	258.0M.	242.3M.	224.6M.	205.1M.
“Scenario 3”	278.9M.	279.9M.	277.9M.	260.0M.	240.4M.	219.0M.	195.4M.

Evolution of renovation costs

Different renovation costs characterise each scenario, based on the expected evolution of the technological costs of the different interventions, as detailed in **Table B3 (Appendix B)**. As illustrated in **Fig. 3.7**, prioritising electrification over natural gas (“Scenario 3”) results in higher renovation costs. However, it is important to remember that these costs represent just one facet of the total costs attributed to the energy transition. The latter speaks of the necessity to design and implement renovation programmes that focus on supporting wider citizen inclusion, especially of the most vulnerable groups, towards the implementation of measures that lead to increased overall benefits (e.g., enhanced comfort, reduced energy expenses, achievement of climate targets) (Mayer et al. 2024).

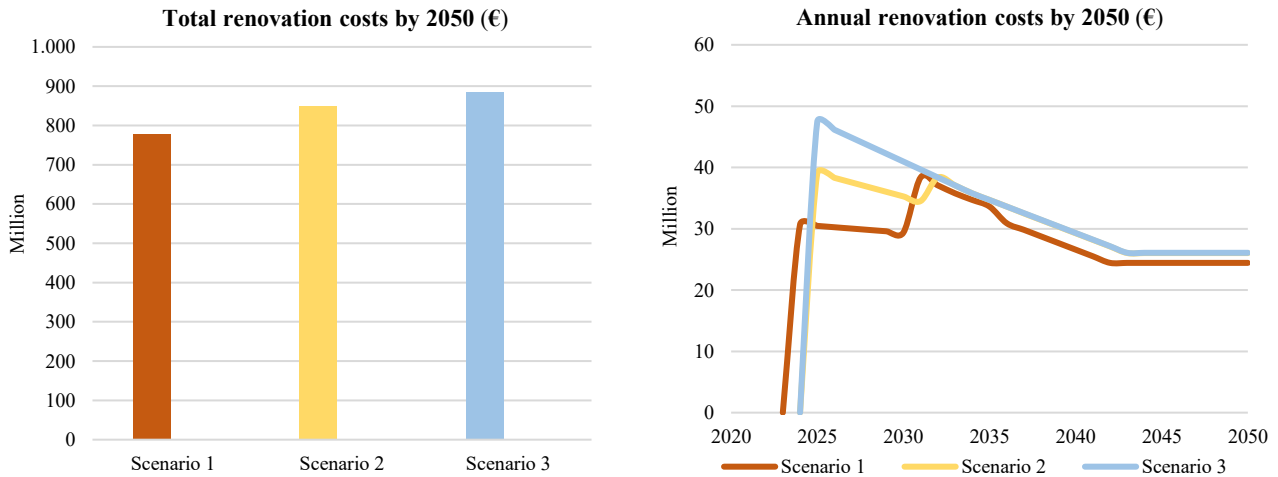


Fig. 3.7. Total and annual renovation costs by 2050 in the Peloponnese region’s residential sector for the three scenarios under study.

Evolution of Emissions Trading System costs

Finally, the expected introduction of a parallel ETS in the EU’s building and transport sectors is expected to begin in 2026, and, based on the latest announcements, the respective charges are expected to be passed on to households (IEECP 2022). Following the estimated evolution of the parallel ETS cost that is presented in **Table B4 (Appendix B)**, simulation results provide us with the annual and total ETS costs for each scenario under study (**Fig. 3.8**).

Results indicate that the current situation in the Peloponnese region (i.e., ongoing construction of a new natural gas distribution network- “Scenario 1”) results in a total of around €330.3M. of ETS costs by 2050. A hybrid strategy, with investments in both natural gas and electrification, results in a total of around €288.7M. of ETS costs by 2050, while investing in electrification as early as possible (“Scenario 3”) results in lower annual and cumulative ETS costs overall (**Fig. 3.8**), i.e., a total of around €244.6M. of ETS costs by 2050, reducing costs by 25.6% and 15.2% when compared to “Scenario 1” and “Scenario 2”, respectively.

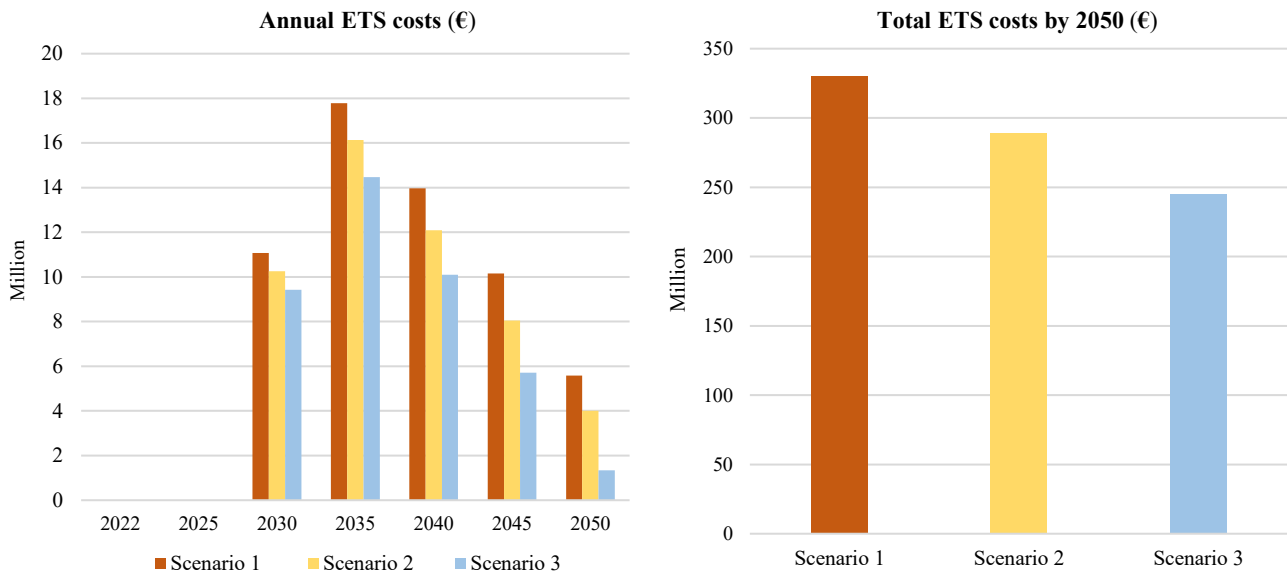


Fig. 3.8. Evolution of costs relevant to the expected introduction of an emission trading system in the Peloponnese region's residential sector by 2050, for the three scenarios under study.

Aggregating costs at the regional level and scaling down to the household level

Scaling down results from the regional to the household level, we present the expected annual charges of the energy transition for consumers. In this context, **Fig. 3.9** presents the expected annual charges at the household level, for the three scenarios under study and the “High-price evolution” case, if the total costs computed at the regional scale are equally divided among all the households in the Peloponnese region. We see that investing in electrification as early as possible (“Scenario 3”) results in lower annual charges at the household level by 2027, while, as presented in **Table 3.10**, it also results in lower total charges by 2050 and in lower total costs at the regional level.

More specifically, at the regional level, “Scenario 3” results in total costs of around €12,673M., while “Scenario 2” results in total costs of around €13,077M. and “Scenario 1”, which reflects the current national and regional strategy, results in total costs of around €13,456M. Therefore, when compared to the other two scenarios, “Scenario 3” results in total monetary savings of around €379.4M. and €783.6M., respectively.

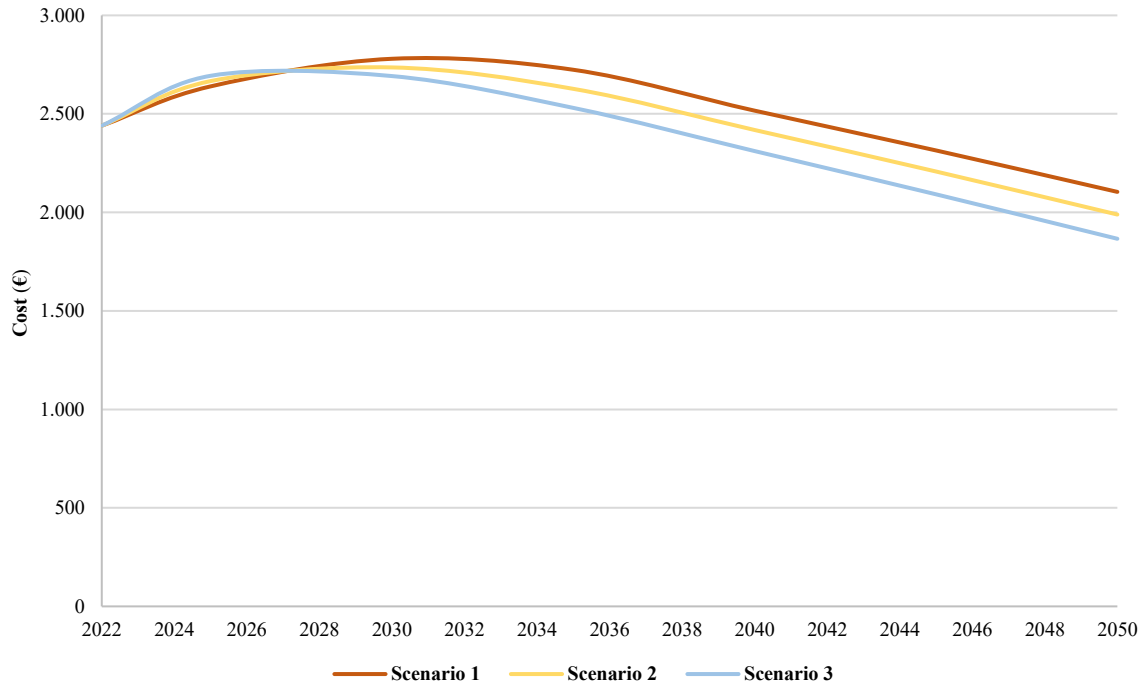


Fig. 3.9. Evolution of the total expected charges by 2050 at the household level in the Peloponnese region, for the three scenarios under study: “High-price evolution” case.

Table 3.10. Total charges at the household level and total costs at the regional level of Peloponnese, by 2050, for the three scenarios under study: “High-price evolution” case.

Scenarios	Household level	Regional level
“Scenario 1”	€71,357	€13,456M.
“Scenario 2”	€69,346	€13,077M.
“Scenario 3”	€67,206	€12,673M.

On the other hand, **Fig. 3.10** presents the expected annual charges at the household level, for the three scenarios under study and the “Low-price evolution” case, if the total costs computed at the regional level are equally divided among all the households in the Peloponnese region. In this case, we see that investing in electrification as early as possible (“Scenario 3”) results in lower annual charges by 2035, while, as presented in **Table 3.11**, it also results in lower total charges by 2050, and in lower total costs at the regional level.

More specifically, at the regional level, “Scenario 3” results in total costs of around €8,119M., while “Scenario 2” results in total costs of around €8,152M., and “Scenario 1” results in total costs of around €8,134M. When compared to the other two scenarios, “Scenario 3”, in this case, results in total monetary savings of around ~€15M. and ~€33M., respectively.

An interesting observation is that in the “Low-price evolution” case, “Scenario 2” results in higher costs compared to “Scenario 1”, which is not the case in the “High-price evolution” case. This is due to the future projections on lower natural gas prices by 2050; even in this case, though, investing in electrification as early as possible is, again, slightly a more attractive solution from an economic perspective.

Another interesting observation is that the higher the future projections on energy prices, the more economically attractive “Scenario 3” is, compared to the other two: in the “High-price evolution” case, it results in lower annual charges at the household level by 2027, while in the “Low-price evolution” case, it results in lower annual charges at the household level by 2035.

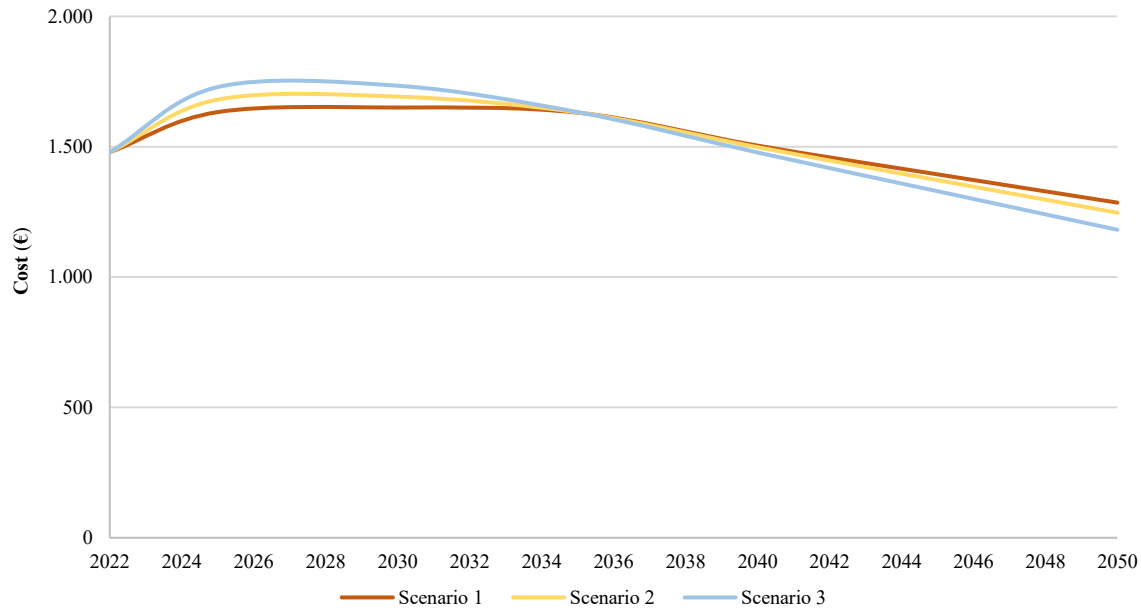


Fig. 3.10. Evolution of the total expected charges by 2050 at the household level in the Peloponnese region for the three scenarios under study: “Low-price evolution” case.

Table 3.11. Total charges at the household level and total costs at the regional level of Peloponnese by 2050 for the three scenarios under study: “Low-price evolution” case.

Scenarios	Household level	Regional level
“Scenario 1”	€43,135	€8,134M.
“Scenario 2”	€43,239	€8,152M.
“Scenario 3”	€43,057	€8,119M.

Furthermore, in the “High-price evolution” case, “Scenario 3” results in higher total monetary savings by 2050 at the regional level, compared to the other two scenarios, than in the “Low-price evolution” case. This highlights the importance of a “crisis resilient” policy planning, especially when considering the economic uncertainty and implications of the shock and extreme events of the recent past.

Overall, our results conclude that investing in electrification and energy efficiency as early as possible in the Peloponnese region’s residential sector, seems to result in greater benefits by 2050, especially in terms of energy savings achieved and CO₂ emissions avoided. In terms of the projected costs, while differences between the scenario focusing on natural gas as a transition fuel (“Scenario 1”) and the scenario focusing on early electrification (“Scenario 3”) remain relatively modest (especially under the “Low-price evolution case”), “Scenario 3” stands out as the transition pathway that is more aligned with the existing EU’s and national climate and energy targets. Notably, the earlier adoption of sustainable technologies, not only delivers clear environmental and energy-saving advantages, but can also lead to slightly lower end-user energy costs. In this context, the ongoing expansion of the natural gas network in the Peloponnese region risks becoming a missed opportunity of a more forward-looking and climate-resilient energy transition.

3.4.4. If decarbonisation is the real target

As presented above, an interesting finding of our study is that the current renovation rate in the Greek residential sector, as envisioned by the NECP and its latest draft amendment, is not enough to achieve decarbonisation by 2050 in the Peloponnese region’s residential sector. In alignment with the EU’s visions for the energy transition in the building sector, it becomes apparent that, if decarbonisation in the Greek residential sector by 2050 is the real target, national policymaking must set higher targets when it comes to the renovation rates required. In this context, we apply a “backcasting” modelling approach using the DREEM model in the three scenarios under study, to compute the necessary renovation rates, in order to achieve decarbonisation by 2050 in the Peloponnese region’s residential

sector. In terms of modelling configurations, the latter means that, in all three scenarios, we do not specify the renovation rate parameter, but we set an extra target in the model- this of complete decarbonisation by 2050- and we leave the model to solve and find the optimal solution to achieve the specified target. **Table 3.12** presents simulation results.

Table 3.12. Annual number of household renovations required at the regional level of Peloponnese to achieve decarbonisation by 2050 in the residential sector in each scenario under study. Comparison to the existing annual renovation rate envisioned by the National Energy and Climate Plan in Greece.

	Annual number of renovations required to achieve decarbonisation	Comparison to the envisioned annual renovation rate at the national level
“Scenario 1”	4,115	~1.50 times the existing renovation rate (a total of ~2.0% annually)
“Scenario 2”	3,700	~1.35 times the existing renovation rate (a total of ~1.8% annually)
“Scenario 3”	3,285	~1.20 times the existing renovation rate (a total of ~1.5% annually)

It becomes apparent, again, that, if decarbonisation in the Peloponnese region’s residential sector is the real target, investing in electrification right from the beginning (“Scenario 3”) is the most attractive scenario, as it requires the lowest renovation rate- much closer to the existing one suggested by the current version of the NECP, compared to “Scenario 1” and “Scenario 2”. On the other hand, “Scenario 2” requires that more than 700 more households are fully renovated on an annual basis (compared to the existing planning), to achieve the target of decarbonisation of the final energy mix in the Peloponnese region’s residential sector, while “Scenario 1”, which reflects the ongoing construction of a new natural gas distribution network, requires that more than 1,000 more households are fully renovated on an annual basis (compared to the existing renovation rate).

These conclusions are similar to other studies that have examined the cost-effectiveness of expanding the natural gas grid against more demand-side and renovation investments in Greece (through economic and social cost benefit analyses), such as Oikonomou et al. (2023) (Oikonomou et al. 2023) and Rogulj et al. (2023) (Rogulj et al. 2023). The cornerstone in the policy debate is that this comparison of supply- and demand-side options for heating decarbonisation is a prerequisite under the “Energy Efficiency First” principle (as has also been demonstrated in the EC-funded Horizon 2020 “ENEFIRST²²” project) (ENEFIRST 2022 2022).

3.4.5. Comparison with other cases across the European Union

The main outcomes of this study- indicating that expanding natural gas infrastructure could potentially result in a missed opportunity of a green, fair, and inclusive transition in the Peloponnese region, as investing in early electrification and decarbonisation could result in greater and strategic benefits- aligns with policies employed by other Member States. For example, Germany’s focus on electrification in the heating sector mirrors the dynamics observed in our study, where combining electrification with energy efficiency presents a viable alternative to fossil-based heating systems (Agora Energiewende 2024; German Federal Government 2024). Similar findings are also identified in the cases of the Netherlands and Sweden, where early phase out of fossil fuels and transition to renewable energy and electrification is pursued as part of their national energy strategy (Jacques Delors Energy Centre 2022; The Government of Netherlands 2019).

Conversely, our results can provide critical insights for countries like Italy and Poland, which continue to expand natural gas infrastructure as part of their strategy to reduce reliance on coal and oil. Both countries are investing in new gas infrastructure, positioning natural gas as an alternative fuel for residential heating (International Energy Agency 2023; Ministry of Climate and Environment -

²² <https://enefirst.eu>.

Republic of Poland 2021). This planning, though, risks a potential lock-in effect into long-term fossil fuel dependency in newly connected regions too, depriving these regions of the opportunity to benefit from alternative transition strategies, like electrification, achieving, eventually, earlier decarbonisation and net-zero targets. In a similar way, our findings could also inform the design of regional and national strategies in France and Spain, which have also invested in new natural gas infrastructure, particularly for residential heating, to reduce coal and oil dependency (International Energy Agency (IEA) 2021b, 2021a). While this approach could potentially offer short-term benefits, both countries may face challenges related to stranded assets and longer-term dependency on fossil fuels, especially as the EU's decarbonisation targets become increasingly strict.

3.5. Conclusions

While regional and local authorities are more involved in climate and energy transitions, their role in strategic policymaking is often overlooked and national legislation does not always support them. Such an example is the Peloponnese region in Greece, currently at the centre of an ambiguous policy debate regarding the construction of a new natural gas distribution network to support residential heating. While this decision reflects the national strategy, it raises significant concerns given recent geopolitical developments and their implications. In this context, our study employs high-resolution demand-side management modelling to evaluate different energy transition scenarios in the Peloponnese region's residential sector. Simulation results highlight that national decision-making about the expansion of the natural gas grid could result in a missed opportunity of a greener, fairer, and more inclusive energy transition. As a result, the current national strategy could increase the risk of a natural gas lock-in, establishing a new regime of energy dependence and socioeconomic inequalities, particularly in a region already struggling with energy poverty.

Our study emphasises that, compared to the ongoing planning, early investments in electrification and energy efficiency could result in lower energy consumption, decreased use of fossil fuels, and higher decarbonisation potential by 2050. Depending on the evolution of future prices, thus, a “*green rebranding*” in the Peloponnese region could be achieved, resulting in consumer charges slightly lower than the ones expected due to the ongoing construction of a new natural gas distribution network. This alternative transition could be achieved despite the currently high capital costs of heat pumps, as investing in electrification and energy efficiency actions is expected to result in a greener energy mix much earlier, with high levels of CO₂ emissions avoided, and, thus, lower ETS-related costs. Moreover, as indicated by the European Heat Pump Association, future capital costs of heat pumps are expected to decrease (European Heat Pump Association 2022), as a consequence of the supportive EU's policy environment (European Commission. Joint Research Centre. 2023) and the growing market size, which can reduce costs due to economies of scale, increased competition, and targeted focus on innovation and research funding opportunities (International Energy Agency (IEA) 2022a).

Furthermore, our results highlight that, if decarbonisation is the real target, national and regional policymaking should reevaluate current renovation targets in view of the upcoming NECP's amendment. In particular, modelling outcomes show that the current renovation rates are not sufficient for achieving complete decarbonisation by 2050, even in the case of investing in electrification. In this context, thus, national decision-making should assist the Regional Authority of Peloponnese in effectively utilising their share of the “National Strategic Reference Framework” and other national subsidy programmes (e.g., the “Exoikonomo-Autonomo” programme, “Photovoltaic in the Roof” programme) to finance the substitution of oil and gas boilers with heat pumps, and implement renewable-based and deep renovation actions, especially for the dwellings built before 2000.

At the same time, it is crucial to also ensure that energy policies remain socially inclusive throughout the entire process, not just at its outset. This includes safeguarding against a potential increase in

operational costs when shifting to more environmentally friendly solutions like heat pumps, particularly for vulnerable households, so that the transition is both green and fair in practice. In this context, if national and regional planning seek to promote sustainability and justice, they should not continue to invest in fossil-fuel infrastructure, also considering the specifications of the latest framework published by the EC for climate-proofing infrastructural projects during the period 2021-2027, and the adoption of the “Energy Efficiency First” principle as a guiding way of evaluating investments. These regulatory provisions could, in general, block investments targeting the further operation and maintenance of the existing gas infrastructure in Greece, along with the construction of new infrastructure (European Parliament and Council of The European Union 2021). However, Greece, and other Member States, benefit from the legislative “window” of financing new fossil-fuel infrastructure from public or EU funding, through the unspent amounts of the past “2014-2020 Operational Programmes”, like exactly in the case of Peloponnese. These decisions, though, could lead to stranded assets, since new construction projects will need to be re-financed again with public funding before their payback period (15-20 years), in order to move to cleaner fuels, according to the EU’s respective directives.

Overall, our study focuses on the implications of such planning decisions under the current policy landscape, following structured scenario development based on the most recent national and EU’s regulatory frameworks. However, considering that energy transitions are typically dynamic processes influenced by multiple factors and uncertainties, we acknowledge opportunities for further research, related with the assumptions used and the additional broader economic, social, and regulatory implications that require careful consideration.

In this respect, we intend to enhance our scenario design through better-structured participatory and deliberative processes and collect updated policy-relevant feedback and data from ground experts and other relevant actors in the Peloponnese region, also in collaboration with representatives from the Greek Ministry of Environment and Energy, the Regional Authority of Peloponnese, as well as different local citizen communities and associations. This approach will allow us to refine our scenarios and assumptions, eliciting, once more, knowledge from all relevant stakeholders. It will also allow us to envision technological breakthroughs that will significantly affect the way that energy is consumed in the residential sector and could further increase the expected benefits for consumers and other energy actors involved.

On this front, and considering the high RES potential in Greece, we envision future scenarios that include a wider range of technological innovations, such as small-scale photovoltaic systems for increased prosuming, smart energy management systems, electric vehicles, battery energy storage systems (Michas et al. 2019a), etc. Evaluating the impacts of such actions on self-consumed energy, transition costs, environmental footprint, and other relevant aspects, will provide a more nuanced understanding of the evolving energy landscape in the residential sector’s transition towards 2050.

We also envision future research to refine our modelling approach by incorporating broader financial, social, and regulatory inputs that will increase the robustness of our findings and yield more comprehensive insights for policymakers navigating the complexities of the energy transition. In this context, we intend to expand our current sensitivity analysis and perform more explorative approaches towards an in-depth analysis of future energy system structures and dynamics, entailing detailed examination of the electricity generation mix, the grid’s capacity to accommodate increased demand stemming from the electrification of the heating sector, etc. Relevant infrastructure developments and costs will be considered, along with the impact of utilising existing infrastructure to facilitate the adoption of alternative fuels, such as hydrogen and biogas.

Finally, building on the replicability potential of our study, we plan to expand our work by exploring similar energy transition scenarios in diverse geographic and socioeconomic contexts, at both the local and the regional levels across the EU, to specifically capture the perspectives of local actors and

authorities and address any inconsistencies between national strategies and their needs. These research efforts will be further supported in the context of the EC-funded LIFE Programme “LOCATEE²³”, focusing on how to align regional priorities with national energy strategies, reduce conflicts, and improve transition outcomes, while offering valuable guidelines for designing more effective energy policies at different governance levels across the EU.

²³<https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE23-CET-LOCATEE-101167621/local-authorities-to-tackle-energy-poverty-in-private-multi-apartment-buildings>.

Appendix B

Table B1. Classification of dwellings' construction period in the Peloponnese region (Greece).

Dwelling's construction period	Number of households
Before 1981	78,695
1981-2000	64,924
After 2000	44,234
Total	187,854

Table B2. Projections on the future evolution of prices by 2050 in the three scenarios under study.

Year	2022	2030	2050	Source(s)
“High-price evolution” case (<i>post energy crisis</i>)				
Heating oil (€/MWh)	123.2	166.5	199.0	(Hellenic Ministry of Development 2022b, 2022c, 2022a; Hellenic Ministry of Environment and Energy 2019)
Natural gas (€/MWh)	276.8	325.2	389.9	
Electricity* (€/MWh)	295.2	281.8	248.4	
“Low-price evolution” case (<i>prior to energy crisis</i>)				
Heating oil (€/MWh)	76.3	103.1	123.2	(Grigoriou, Mayer, and Pallicska 2022; Hellenic Ministry of Development 2021; Hellenic Ministry of Environment and Energy 2019)
Natural gas (€/MWh)	48.2	56.6	67.9	
Electricity* (€/MWh)	175.2	167.3	147.4	

* Note that the electricity price trajectories in both “price evolution” cases align with the latest official projections from the Greek government, as outlined in both the “Long-Term Strategy towards 2050” policy document and the latest version of the Greek NECP (2024). According to these sources, while medium-term capital investments in network expansion and storage systems are expected to rise, the increasing penetration of RES will significantly reduce the marginal cost of electricity generation. Furthermore, higher RES integration is projected to increase overall electricity throughout, thereby lowering the per-unit network cost over time. As it is specifically mentioned in the NECP 2024: “Overall, a continuous downward trend in electricity costs is expected in the medium-to-long term”, which is consistent with the downward trends displayed in the two price evolution pathways.

Table B3. Projections on the future evolution of technological costs by 2050 in the three scenarios under study.

Year	2022	2030	2050	Source(s)
Natural gas boilers (€)	5,000	4,904	4,713	(European Heat Pump Association 2021; De Vita, Kielichowska, Mandatowa, Capros, Dimopoulou,
Heat pumps (€)	12,000	7,680	4,086	
Building envelope insulations & window upgrades (€)	5,000	5,000	5,000	

Evangelopoulou,
Fotiou,
Kannavou,
Siskos, Zazias,
Vos, et al. 2018)

Table B4. Projections on the potential future evolution of ETS costs by 2050 in the European Union's building sector.

Period	(2022-2025)	(2026-2030)	(2031-2050)	Source(s)
Carbon price (€/tn)	0	50	100	(EU Carbon Permits - 2022 Data - 2005-2021 Historical - 2023 Forecast - Price - Quote n.d.)

Table B5. Projections on the future emission factors for electricity, heating oil, natural gas and biomass as derived from the Greek "Long-Term Strategy towards 2050" (Hellenic Ministry of Environment and Energy 2019).

Electricity	
Year	Emission factor (tnCO ₂ /ktoe)
2023	5,006
2025	4,476
2030	3,947
2035	3,418
2040	2,889
2050	2,360
Heating oil	
Year	Emission factor (tnCO ₂ /ktoe)
(2023-2050)	2,821
Natural gas	
Year	Emission factor (tnCO ₂ /ktoe)
(2023-2050)	2,332

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Nomenclature

Acronyms & abbreviations			
CCIR	Coal Carbon Intensive Region	GDP	Gross Domestic Product
CO ₂	Carbon Dioxide	HVAC	Heating, Ventilation, and Air Conditioning
DHW	Domestic Hot Water	HBS	Household Budget Survey
DREEM	Dynamic high-Resolution demand-side Management	NECPs	National Energy and Climate Plans
EC	European Commission	PMV	Predicted Mean Vote
ELSTAT	Hellenic Statistical Authority	PPD	Predicted Percentage of Dissatisfaction
EPBD	Energy Performance of Buildings Directive	PV	Photovoltaic
ELSTAT	Hellenic Statistical Authority	RC	Resistance-Capacity
EPBD	Energy Performance of Buildings Directive	TEESlab	Technoeconomics of Energy Systems laboratory
ETS	Emission Trading System	TEEM	Technoeconomics of Energy Systems laboratory Modelling
EU	European Union	TUS2013	Time of Use Survey 2013
Variables			
T _{air}	Mean indoor air temperature	T _o	Mean outdoor air temperature

4. Modelling in support of community-empowered energy transitions: Transforming a coal- and carbon-intensive region into a municipality of energy citizens

Abstract

As coal- and carbon-intensive regions across Europe undergo structural transformation, ensuring that these energy transitions are just and inclusive requires policies that also address cultural, identity, inequality, and perceptual dimensions. This study evaluates whether the current national strategy in Greece risks locking the municipality of Megalopolis- an illustrative case of historical lignite dependence- into continued reliance on natural gas, thereby missing the opportunity for a fully green and inclusive transition by 2050. To do so, we combine transformative scenario design, informed by publicly available data and expert insights, with high-resolution demand-side management modelling. Three alternative transition pathways are simulated, reflecting varying levels of citizen engagement and policy ambition. Results show that a community-empowered transition based on early electrification, energy efficiency, and behavioural change can accelerate decarbonisation and reduce costs at both municipal and household levels, while aligning with the European Union's climate objectives. Citizen participation emerges not only as a normative aspiration but as a practical lever for accelerating and democratising the energy transition. Supported by enabling policy frameworks and inclusive governance structures, stronger local engagement could guide post-carbon regions like Megalopolis toward more resilient and equitable energy futures.

Keywords: Natural gas; Just transition; Energy policy; Electrification; Local governance; Energy system modelling.

4.1. Introduction

Energy transformation processes at the local and the regional levels, supported by the European Union's (EU) strategic energy visions and corresponding national policies, have opened a window of opportunity to restructure coal- and carbon-intensive regions (CCIRs) (Brauers, Oei, and Walk 2020) in alignment with sustainable development goals (Markard, Rinscheid, and Widdel 2021). Over the past few decades, most of the EU CCIRs have experienced multiple negative trends, including job losses, population ageing, migration, insufficient services, and degraded environmental conditions (Rosenbloom 2018). In such socially complex contexts, systemic inertia and resistance to change often prevail (Chesmore et al. 2021). Overcoming these challenges requires acknowledging the multiple dimensions that influence deliberate and rapid transitions, not only through investments in structural funds and technological innovations, but also through intangible cultural and perceptual factors that shape how communities construct shared meaning and collective actions (McCauley and Heffron 2018). These considerations affect local actors' and relevant stakeholders' capacities and willingness to collaborate in transformative governance processes (Löhr, Chlebna, and Mattes 2022).

In this context, the EU's "Energy Union" strategy, places increasing emphasis on putting people at the centre of the energy system and envisions a future in which citizens take ownership of the energy transition, benefit from new technologies to reduce their bills, and actively participate in the energy market (European Commission 2015). Citizens are expected to drive changes within the energy system, either as prosumers or participants in energy communities, influencing both energy demand and supply. In this direction, future energy policies and decarbonisation strategies need to be socially just and inclusive, taking into consideration citizens' and local communities' perspectives, preferences, and acceptance (Cherp et al. 2018). Providing the appropriate regulatory environment and financial incentives, thus, is necessary to promote citizen participation, and should be a primary task for policymakers and other relevant end-users from the fields of policy and practice (Papantonis et al. 2022a). As a result, achieving the required energy transformations in CCIRs across Europe in a just and inclusive manner, requires policies and initiatives, which are not only predominantly centred on technical and economic considerations (often overlooking discussions on inclusive and democratic governance), but also address cultural, identity, inequality, and perceptual dimensions.

According to relevant research in the field, empowering local communities and citizens to drive systemic change on their own terms can foster more diverse, inclusive, and resilient transition pathways (Berka, MacArthur, and Gonnelli 2020; T. Hansen et al. 2024; Skoczowski et al. 2020). Because transition pathways depend on policy decisions made at multiple governance levels, breaking lock-ins is inherently a political process (Papantonis, Stavrakas, Oikonomou, et al. 2025). Most key decisions occur at the national level, yet, local and regional authorities are uniquely positioned to adapt broader policy frameworks into locally relevant actions (Fudge, Peters, and Woodman 2016), thereby integrating these critical dimensions (Dobracev et al. 2021; A. S. Hansen, Manniche, and Larsen 2024). This is particularly important given that regional and local authorities are increasingly tasked with implementing climate and energy transitions, yet their perspectives are not always adequately considered in strategic policymaking (Kleanthis et al. 2022), or consistently supported by legislation (Brandoni and Polonara 2012). This situation runs counter to Article 11 of the European Regulation on the Governance of the Energy Union and Climate Action 2018/1999, which requires Member States to establish a multilevel climate and energy dialogue aimed at achieving climate neutrality by 2050 (European Parliament and Council of the European Union 2018). Nevertheless, as indicated by the European Commission's (EC) assessment of National Energy and Climate Progress Reports, these multilevel governance structures are not yet functioning optimally (European Commission (EC) 2023). An illustrative case of a CCIR, which reflects the broader challenges and opportunities of the abovementioned energy transformations required and the complex interplay among different levels of

governance is the municipality of Megalopolis in Greece (Area: 722.6 km², Population (2021): 8,791) (Marinakis et al. 2020). Megalopolis has historically depended on lignite mining and lignite-fired power generation to sustain its economy and support a district heating system crucial for citizens' well-being. Following the first publication of the Greek National Energy and Climate Plan (NECP) in 2019, a gradual phase out of lignite was introduced, targeting the decommissioning of all the lignite-fired plants by 2023 (Greek Ministry of Environment and Energy 2019; Süsser, Ceglarz, et al. 2021). Megalopolis, as one of the most lignite-dependent regions in Greece, has been significantly impacted by this plan. Three power plants have been decommissioned, a fourth was initially scheduled for closure by 2023 (unofficially extended to 2025), and only one plant is expected to remain operational, transitioning to natural gas as its primary fuel source. These trends position Megalopolis as a compelling case study for examining pathways towards a just and inclusive energy transition.

According to the 2021 Megalopolis' "Integrated Territorial Investment Strategy", the municipality's dependence on lignite was exceptionally high in the years immediately preceding the phase-out decision. The Regional Unit of Arcadia, to which Megalopolis belongs, accounted for approximately 50% of all employment in the energy, mining, and water sector of the Peloponnese region, generating more than 1,600 direct jobs and around 3,000 jobs when indirect and induced effects were included. Within Megalopolis itself, the Public Power Corporation employed more than 1,000 workers (out of a total population of 8,784 in 2021) in its lignite units and associated operations. Although these figures reflect conditions prior to the major decommissioning steps, they illustrate the structural reliance of local households on lignite-related employment and contextualise the socioeconomic conditions during the transition (Municipality of Megalopolis and Regional Authority of Peloponnese 2021).

Under the current national strategy, lignite is phased out in favour of natural gas, backed by new infrastructure and subsidies for domestic heating. According to the national "Just Transition Development Plan", construction of a new natural gas distribution network is underway in Megalopolis, developed within Greece's regulated gas distribution framework and overseen by the Ministry of Environment and Energy. Within this scheme, households are exempt from connection fees, while the replacement of old heating boilers and related equipment with natural gas systems is subsidised through national and Just Transition funding mechanisms (Ministry of the Environment and Energy Hellenic Government 2020). While these measures aim to facilitate energy transition for the local community, they raise serious concerns about deepening its dependence on fossil fuels, as introducing natural gas as a transition fuel could delay essential investments in renewable energy infrastructure and energy efficiency (Rosenow, Lowes, and Kemfert 2024). Similarly, scientific literature has cautioned that expanding natural gas infrastructure and consumption can intensify both infrastructural and institutional lock-in effects, slowing a green transition and risking stranded assets, as well as adverse environmental and economic impacts (Kemfert et al. 2022).

However, recent insights of local stakeholders, gathered through a series of workshops and participatory events conducted under specific European Commission-funded Horizon 2020 and LIFE projects indicate that Megalopolis has substantial potential for a more inclusive and environmentally conscious transition, which could result in a "*green transformation*" (Frankowski et al. 2024; Horizon 2020 Tipping.plus project 2022). Over 40 stakeholders participated across multiple engagements between 2021 and 2024, including representatives from the municipal, regional and national authorities, civil society organisation, local businesses, energy cooperatives, and citizens. Stakeholders emphasised the importance of developing a robust legal and licensing framework that enables the deployment of renewable energy, advocating for a low-risk environment to attract relevant investments and create local employment, particularly through small-scale photovoltaic (PV) parks. Additional "rebranding" efforts were proposed, such as eco-friendly tourism, sustainable agriculture, the restoration of museums and educational facilities, and the development of a business park to attract new industries. Participants also

stressed the need to prioritise energy-efficiency upgrades in existing buildings- especially in the residential sector- as part of the “Just Transition Master Plan”, suggesting adjustments to the amended version of the Greek NECP. While some viewed natural gas as a transitional solution, many stakeholders expressed concerns about long-term fossil fuel dependence and highlighted the importance of supporting alternative, future-proof solutions, such as electrification and decentralised renewable energy systems, provided that adequate policy and financial support are in place.

The success of the above plan relies heavily on households’ willingness to invest in new technologies though, highlighting the need for innovative business models and a legal framework that demonstrates economic and environmental benefits. Considering the growing involvement of citizens and other relevant actors in combating the climate crisis and driving changes in the energy system, the overarching hypothesis of our study suggests that the current national planning, which emphasises the expansion of natural gas as a transitional fuel, may hinder a green transition in Megalopolis, while overlooking opportunities of a more sustainable and resilient energy future. To explore this hypothesis and identify whether the existing focus on expanding natural gas infrastructure aligns with the EU’s climate goals, or represents a missed opportunity of a green, inclusive, and just energy transition, we seek to provide answers to two main research questions:

- (a). *“Is the current shift to natural gas an effective transition strategy, or does it risk locking the municipality of Megalopolis into a continued fossil-fuel dependence, thereby missing the opportunity of a fully green and inclusive transition based on alternative pathways- like electrification- by 2050?”*
- (b). *“What are the potential benefits of a community-empowered energy transition that emphasises sustainable energy use through household investments in energy efficiency and the adoption of energy-saving behaviours?”*

To answer these questions, and with the premise that citizens must first recognise the benefits of investing in innovative green energy products and services to actively engage in the energy transition, we couple a dynamic high-resolution demand-side management model with a transformative scenario design framework. Informed by national and local experts’ perspectives, this framework explores alternative futures that go beyond the comfort zone of current scenario-based research and modelling practices and examine out-of-ordinary extremes. This allows us to simulate different transition pathways in the Megalopolis’ residential sector by 2050 and evaluate the current national strategy in Greece prioritising a transition based on natural gas, in the context of the most up-to-date regulatory developments at the EU level.

Our work responds to recent scientific studies calling for alternative scenario-based research and modelling approaches in support of interdisciplinary and inclusive just transition debates, considering that conventional energy modelling often falls short in addressing social complexity issues like active citizen participation and justice (Süsser et al. 2022, 2024; Süsser, Gaschnig, et al. 2021). In this context, we seek to capture, not only technological and economic aspects of different transition pathways, but also sociotechnical and governance dimensions that typically shape real-world transformations. Overall, the novel contribution of this study to the scientific literature is twofold:

- This paper has introduced a transformative scenario-based modelling approach to evaluate the impacts of different pathways in a CCIR under transition, providing insights for regions and cities with similar socioeconomic and infrastructural characteristics and energy transition trends. By comparing transition scenarios, it has identified pathways that balance decarbonisation goals with socioeconomic resilience, offering recommendations for policy adjustments.
- Focusing on the local level, the study has contributed to a deeper understanding of how tailored, community-empowered strategies can complement national and EU climate targets. The insights derived from Megalopolis have demonstrated broad implications, providing a replicable

framework for other European cases aiming to align socioeconomic priorities with ambitious sustainability objectives at the local level.

4.2. Methods

To explore the overarching hypothesis of this study and answer the individual research questions formulated, the Dynamic high-Resolution dEmAnd-sideE Management (DREEM) model, a fully-integrated energy demand and demand-side management simulation model, focusing on the building sector, is used. The model expands the computational capabilities of existing building energy system and demand-side models, by not only calculating energy demand, but also assessing the benefits and limitations of demand flexibility, primarily for main end-users (households/consumers) and, secondarily, for other energy system actors (suppliers, retailers, Distribution System Operators, etc.). To address the needs of the current study, the model's original architecture and capacities, as originally presented by Stavrakas and Flamos (2020) (Stavrakas and Flamos 2020), have been expanded, as part of the work undertaken in the context of specific EC-funded Horizon 2020 and LIFE projects. The updated modelling structure was further adjusted to the local scale based on the work presented by Papantonis et al. (2024) (Papantonis, Stavrakas, Tzani, et al. 2025), to analyse transition scenarios in local and socioeconomically complex settings (**Fig. 4.1**).

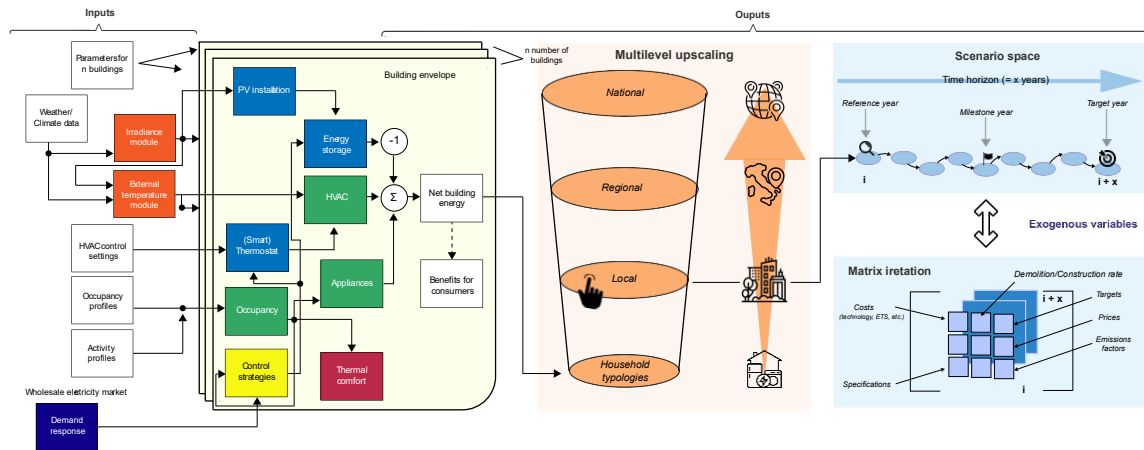


Fig. 4.1. Expanded architecture of the DREEM model as it currently stands, adjusted to the local level based on the work presented by Papantonis et al. (2024) (Papantonis, Stavrakas, Tzani, et al. 2025).

A short description of the model's components and respective modules used in the context of this study is provided in **Table 4.1**. All the model's components and individual modules have been developed using the "Buildings" library (Wetter 2011), an open-source, freely available Modelica library for building energy and control systems (Bünning, Sangi, and Müller 2017; Wetter, Bonvini, and Nouidui 2016; Zuo et al. 2016b). Alongside to the Modelica models, Python scripts have been developed to model parts of the model's components and to enable the interface with the "Dymola" simulation environment. DREEM is part of the Technoeconomics of Energy Systems laboratory (TEESlab) Modelling suite (TEEM); the model is open access²⁴ under the "GNU Affero General Public License". For more information about the model's components and modules, as well as the underlying modelling approaches and mathematical formulae, we refer to Stavrakas and Flamos (2020) (Stavrakas and Flamos 2020) and to Papantonis et al. (2024) (Papantonis, Stavrakas, Tzani, et al. 2025).

²⁴ <https://github.com/TEESlab-UPRC/DREEM>.

Table 4.1. Hierarchical structure of the DREEM model’s expanded version, used in this study: Short description of the main components and modules. Source: Papantonis et al. (2024) (Papantonis, Stavrakas, Tzani, et al. 2025).

Components	Modules	Description	Developed
C ₁ : Weather/ Climate data	-	This single-module component is responsible for generating climatic boundary conditions. It reads weather data from the respective files and then provides them to the other components, where and when necessary.	Modelica
C ₂ : Building envelope	-	This single-module component models different building typologies with the corresponding characteristics, properties, and heat conduction elements.	Modelica Python
C ₃ : Energy demand	<i>C₃M₁: Occupancy</i>	This module defines and sets the parameters for the behaviour and the activities of the occupants by generating and storing default patterns.	Modelica
	<i>C₃M₂: Appliances</i>	This module is responsible for generating energy demand profiles from appliances, using statistics describing their mean total daily energy demand and associated power use characteristics, including steady-state consumption, or typical use cycles, based on occupancy patterns.	
	<i>C₃M₃: Heating, ventilation, and air conditioning</i>	This module is responsible for heating, ventilation, and air conditioning inside the building.	
C ₈ : Multilevel upscaling	-	This new single-module component is responsible for applying an upscaling approach to compute cumulative energy consumption patterns in the building sector, at the scale of interest, using parameters and statistics obtained from survey and/ or census data. It receives inputs from the “C ₂ : Building envelope” and the “C ₃ : Energy demand” components.	Python
C ₉ : Transition matrix	<i>C₉M₁: Scenario space</i>	This module is responsible for designing the scenario space (in terms of the transition pathways and the respective exogenous variables) inside of which the transition matrix is initiated and updated, based on relevant policy documents’ specifications and practical experts’ feedback.	Python
	<i>C₉M₂: Matrix iteration</i>	This module is responsible for initialising the transition matrix and updating it at each time interval (i.e., iteration), following the scenario space’s specifications (i.e., targets and constraints) derived from the “C ₉ M ₁ : Scenario space” module.	

4.3. Model application to the residential sector

In this section we outline the parameterisation of the DREEM model’s individual components and modules required for the application under study, along with respective data inputs, scenario design, and assumptions, all tailored to the municipality of Megalopolis. This requires an accurate understanding of localised weather/ climate conditions, building envelope characteristics, energy

demand patterns, and community-level dynamics. By configuring the model's components and modules with data and scenarios at the local level, we aim to capture the critical factors driving energy transition trends, thus providing insights into potential post-lignite futures in Megalopolis.

4.3.1. C₁: Weather/ Climate data

Megalopolis is located in the regional unit of Arcadia ("Climate Zone C") in the Region of Peloponnese (Hellenic Ministry of Environment and Energy 2021), which is a large peninsula constituting the southernmost part of mainland in Greece. To ensure that weather/ climate data accurately reflects local conditions, we select nearest available data from the nearby city of Tripolis- approximately 40 km away- which provides a precise approximation of seasonal demand variations essential for understanding heating and cooling needs in the residential sector. We source such historical data from the database of the World Meteorological Organisation (WMO) (World Meteorological Organisation 2021). The data is formatted as Typical Meteorological Year (TMY) data (Cebecauer and Suri 2015)- and specifically the "TMY3" format- accumulating a 14-year period (2007-2021) of data values, and including information on latitude, longitude, and time zone in relation to Greenwich Mean Time, as well as temperature, relative humidity, wind speed and direction, sun direction and radiation values, on an hourly basis.

4.3.2. C₂: Building envelope

This component uses the concept of "reduced (low)-order" thermal network modelling, which represents a thermal zone by thermal resistances and capacities (RC-network), using the electrical circuit analogy, in which voltage is analogous to temperature and current is analogous to convective and radiative heat transfer (McKenna and Thomson 2016). The component represents all main thermal masses of the building under study as four elements, accompanied with supportive features for consideration of solar radiation (as visualised by Stavrakas and Flamos (2020) (Stavrakas and Flamos 2020)). For "Climate Zone C" in Greece, we use the different building typologies in the residential sector according to the "TABULA" webtool's database, which contains information on national residential building typologies in different European countries, classified per climate zone and construction period (European Union 2017). For Greece, and according to the transcription of the Energy Performance in Buildings Directive (EPBD) into the national law back in 2011, and its subsequent amendments in the following years (Daskalaki et al. 2011), the webtool distinguishes between four different construction periods, namely dwellings constructed: (i). before 1981, (ii). during the period 1981-2000, (iii). during the period 2001-2011, and (iv). after 2011.

4.3.3. C₃: Energy demand

The DREEM model generates accurate and realistic energy demand profiles, avoiding unnecessary computational complexity, by building on the concept of stochastic modelling and providing simulated data about households' energy demand, with statistics suitable for the task at hand (Stavrakas and Flamos 2020). This component uses a bottom-up approach to simulate energy consumption considering households' occupancy, use of appliances, and heating, cooling, and ventilation options. The component's individual modules use many simplified assumptions to simulate various aspects of energy demand (occupancy and occupants' activity/ behaviour profiles, sharing of appliances, etc.) and focuses on parameters and statistics obtained from survey and/ or census data. In this study, we use data for the regional unit of Arcadia and the municipality of Megalopolis obtained from the "2020 Household Budget Survey (HBS2020)", which, to the best of our knowledge, is the latest official survey conducted by the Hellenic Statistical Authority (ELSTAT) on households' energy consumption in Greece (Hellenic Statistical Authority ELSTAT 2020).

C₃M₁: Occupancy

We use household composition and occupancy patterns derived from historical and statistical data. The first key factor to properly configure is the number of members per household, while the second key factor concerns the time that occupants spend being active at their homes, which is strongly connected to their employment status and work schedules. To quantify these parameters, i.e., the number of members per household, according to the different dwelling typologies, as specified in the “C₂: Building envelope” component, and occupants’ activity levels when they are at home, we use the “HBS2020” data (Hellenic Statistical Authority ELSTAT 2020).

Furthermore, to quantify the parameter on time that occupants spend at, and away, from home, based on their work schedule, we use statistical data from the ELSTAT’s “Time of Use Survey 2013 (TUS2013)”, which again, to the best of our knowledge, is the most recent survey data collected (Hellenic Statistical Authority (ELSTAT) 2014). Note that this data concerns the entirety of Greece’s population, since there is no other such data, publicly available, especially at the regional or the local levels. The “HBS2020” and the “TUS2013” data allowed us to come up with three different household typologies, based on the most statistically significant data on dwelling typologies and occupancy and activity schedules (**Table C1** in **Appendix C** (Hellenic Statistical Authority ELSTAT 2020)), as summarised in **Table 4.2**.

Table 4.2. Three household typologies in the municipality of Megalopolis’ residential sector, based on dwellings’ climate zone and construction period, number of residents per dwelling, number of employed and non-economically active/ unemployed, and their overall occupancy profiles.

a/a	Climate zone	Construction period	Members	Employed members	Non-economically active/ Unemployed members	Overall occupancy profiles
1	C	Before 1981	4	1	3	1 employed person, 1 unemployed person & 2 children
2		1981-2000	2	1	1	1 employed & 1 unemployed person
3		After 2000	4	2	2	2 employed persons & 2 children

C₃M₂: Appliances

We use the “HBS2020” data to configure the final set of appliances in the model, specifically for the municipality of Megalopolis, based on information on appliances’ ownership rate, nominal power, and time of use (**Table 4.3**).

Table 4.3. Final set of appliances, included in the model, along with their ownership rates, nominal power capacities, and time of use schedules, as extracted from the “2020 Household Budget Survey (HBS2020)” data (Hellenic Statistical Authority ELSTAT 2020).

Appliances	Ownership rate (%)	Nominal power (W)	Time of Use (hours/day)
Cooking			
Hobs	91.67%	1,600	1.59

Oven	87.18%	2,150	1.00
Microwave oven	43.91%	1,150	1.15
Toaster	72.44%	1,300	1.38
Coffee maker	28.53%	1,100	0.94
Water boiler	41.03%	1,250	0.92
Cooker hoods	93.59%	108	1.56
Other appliances			
Fridge freezer	83.97%	150	24
Dishwasher	33.33%	1,350	1.75
Washer	97.44%	500	1.21
Iron	96.15%	1,000	0.85
Vacuum cleaner	82.69%	450	0.93
Television	99.68%	100	5.42
DVD or VCR	15.71%	40	0.59
Home cinema	1.92%	200	0.68
Stereo	21.47%	24	0.67
Computer	57.05%	300	2.67
Peripheral devices (printer, scanner, etc.)	3.85%	50	0.88
Internet devices (router, etc.)	55.13%	10	24.00
Video game console	7.37%	160	0.89
Domestic hot water electric boiler	56.41%	4,000	1.19

C₃M₃: Heating, ventilation and air-conditioning

For the configuration of the heating, the ventilation, and the air conditioning (HVAC) systems we also used the “HBS2020” data to acquire information on the systems’ ownership rates and coefficient factors (Hellenic Statistical Authority ELSTAT 2020). Given the specific heating and cooling needs associated with “Climate Zone C”, these parameters ensure that our model captures realistic demand variations driven by different appliance and HVAC configurations in households. **Table 4.4** presents the current ownership status of the main heating technologies in the municipality of Megalopolis’ residential sector, based on the “HBS 2020” data, while **Table 4.5** presents the respective ownership status of domestic hot water (DHW) technologies.

Table 4.4. Current ownership status of the main heating technologies in the municipality of Megalopolis’ residential sector based on the “2020 Household Budget Survey (HBS2020)” data (Hellenic Statistical Authority ELSTAT 2020).

Heating technology	Number of households	Percentage of households
Oil boiler	1,513	42.7%
District heating	432	12.2

Electric heating system	1,407	39.7%
Biomass	169	5.5%
Heat pump	23	0.6%
Natural gas boiler	0	0%
Total	3,545	100%

Table 4.5. Current ownership status of the main domestic hot water (DHW) technologies in the municipality of Megalopolis’ residential sector based on the “2020 Household Budget Survey (HBS2020)” data (Hellenic Statistical Authority ELSTAT 2020).

DHW technology	Number of households	Percentage of households
Solar water heater	2,099	59.2%
Electric heater	1,262	35.6%
Oil boiler	174	4.9%
Heat pump	10	0.3%
Total	3,545	100%

4.3.4. C4: Thermal comfort

The DREEM model addresses the- often overlooked by other models in the field- aspect of occupants’ thermal comfort, by utilising an individual component that aligns with international standards (DIN EN ISO 7730 (DIN EN ISO 7730 2005b), ASHRAE 55 (Taleghani, Tenpierik, Kurvers, and Van Den Dobbels 2013), EN 15251 (CEN Ce. CEN Standard EN15251. 2007)). Built upon the Fanger approach, the model employs the characteristic Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) indices (P.O. Fanger et al. 1970). To determine optimal indoor thermal conditions for occupants, DREEM calculates PMV and PPD, by considering weather and other parameters, such as dynamic metabolic rates and clothing insulation, adjusted based on seasonal variations (Luo et al. 2018). By doing so, the model offers a comprehensive approach to accurately model thermal comfort and fill existing modelling gaps. To configure the appropriate indoor temperature ranges and to define the proper indoor temperature setpoints for each simulation period in the municipality of Megalopolis, our analysis follows the approach outlined by Stavrakas and Flamos (2020) (Stavrakas and Flamos 2020), based on the correlation between the mean indoor air temperature (T_{air}) and the mean outdoor air temperature (T_o) in “Climate Zone C”, and during various weather conditions in three different periods of the year:

- Period 1 (mild weather): April, May, October, and November.
- Period 2 (warm weather): June-September.
- Period 3 (cold weather): December-March.

For Period 1, indoor temperature setpoints maintaining thermal comfort were determined using the de Dear and Brager adaptive model designed for HVAC applications (de Dear and Brager G.S. 1998), while for Periods 2 and 3, acceptable indoor temperature ranges were established by studying the correlation between PMV values and indoor temperatures as done in previous relevant studies (Alimohammadisagvand et al. 2017; Alimohammadisagvand, Jokisalo, and Sirén 2018; Peeters et al. 2009; Yang, Yan, and Lam 2014). Critical PMV values and indoor temperatures were simulated, leading to linear trendlines used to define acceptable temperature setpoints. The resulting ranges are presented in **Table 4.6**, categorised based on the minimum PMV values for heating and the maximum PMV values for cooling, aiming to ensure a comprehensive consideration of adaptive thermal comfort

for different weather condition periods. Acceptable ranges of the PMV and PPD indices are presented in **Table C2 (Appendix C)**.

Table 4.6. Acceptable indoor temperature ranges in the municipality of Megalopolis' residential sector ("Climate Zone C") for the three different weather periods of the year.

Climate Zone	Period 1								Period 2	Period 3
	April		May		October		November		<i>Min-Max T_{air} ($^{\circ}C$)</i>	<i>Min-Max T_{air} ($^{\circ}C$)</i>
	T_o	T_{air}	T_o	T_{air}	T_o	T_{air}	T_o	T_{air}		
"C"	14.9	22.4	19.4	22.9	18.4	22.8	14.2	22.4	21.1-25.5	19.8-23.4

4.3.5. C₅: Multilevel upscaling

This component uses an upscaling approach, building on parameters and statistics obtained from survey and/ or census data. After having specified the individual building typologies of interest under the "C₂: Building envelope" component and simulating their individual energy consumption patterns, based on the specifications and the parameterisation of the "C₃: Energy demand" component, this component computes cumulative energy consumption patterns at the scale under study as the product of each individual building typology's energy consumption and the number of the respective households per typology and number of occupants (as extracted by the available statistical data). In this study, after simulating energy consumption for each household typology presented in **Table 4.2**, we use the "HBS2020" data- which to the best of our knowledge is the most recent data available at the regional and the local levels in Greece- to compute the cumulative energy consumption patterns in the municipality of Megalopolis' residential sector for the reference year. According to the statistics used, the total number of households in the municipality of Megalopolis is 3,545, while the number of households per number of occupants used for upscaling each typology under **Table 4.2**, is presented in **Table 4.7**

Table 4.7. Number of households per number of occupants in the municipality of Megalopolis.

Number of occupants	Number of households
1-3 members	1,225
4 + members	2,320
Total	3,545

4.3.6. C₆: Transition matrix

Based on the thematic focus of our study, this component's individual modules are parameterised as follows.

C₉M₁: Scenario space

This module is responsible for designing the scenario space inside of which the transition matrix is initialised and updated. It starts with setting the modelling time horizon, i.e., reference year (simulation start year), interim milestone years (where and if necessary), and the target year (simulation end year), based, each time, on the specifications of the application under study. The initial scenario space is parameterised mainly based on the specifications of the most recent policy documents, in accordance with the emission caps of the updated mitigation targets for 2030 and 2050, also in the context of the "European Green Deal" strategy and the "Fit for 55" package. As a next step, relevant stakeholders' and policy practitioners' feedback is also considered to diversify and expand the initial scenario space and eventually account for possible uncertainties and different potential evolutions of the future energy

system. Finally, the scenario space is further populated with the evolution of different exogenous variables, e.g., emission factors, evolution of relevant energy prices and costs, technological costs and relevant updated configurations, demolition rate of old buildings and construction rate of new ones, benefits for occupants and/ or other power actors involved.

For the initial configuration of the scenario space in our study, 2023 is set as the reference year, 2050 as the target year, while as interim milestones, we select the years 2024, 2025, 2030, 2035, 2040, and 2045. In terms of scenario design, we develop three distinct scenarios, each offering a unique perspective on the municipality's transition possibilities, reflecting varying levels of citizen engagement and responses to policy frameworks. Inspired by the shock events and the geopolitical turbulences of the past years, such as the COVID-19 pandemic, Russia's invasion of Ukraine in early 2022 and the consequential energy crisis, the Middle East conflicts in late 2023, etc., our scenario design builds on the premise that transformative design in scenario-based research and climate and energy modelling should always account for potential challenges and vulnerabilities that humanity might face, in support of adaptive and resilient policymaking.

In this context, we exploit the transformative scenario design framework developed as part of the EC-funded H2020 "ENCLUDE" project, and presented by Tsopelas et al. (2022) (Tsopelas et al. 2023), while further adjusted to the local scale by Fotopoulos et al. (2024) (Fotopoulos et al. 2024). The suggested framework does not only consider regulatory influences and technological advancements, but also delves into the social, cultural, and behavioural manifestations of energy transition, envisioning futures that go beyond the comfort zone of current scenario-based research and modelling practices and examine out-of-ordinary extremes. This allows us to consider different potential evolutions of the future, encompassing a broad spectrum of uncertainties and embracing the depth of complexity of the energy landscape at the local level:

- Scenario 1 refers to a "*Familiar World*" narrative, a "baseline" ("business-as-usual") future, in which energy transition unfolds gradually, maintaining established patterns and limited disruption to the current status quo. In this scenario, the municipality of Megalopolis follows the national planning trajectory, shifting from lignite-based district heating and oil boilers to natural gas by around 2035. Citizens and households participate passively, adopting new technologies primarily in response to government incentives and regulatory requirements rather than through proactive engagement. The transition is coordinated through top-down policy mechanisms, reflecting moderate ambition and conventional implementation capacity. While local and national authorities ensure compliance with EU decarbonisation frameworks, citizen and household involvement remains limited to the uptake of subsidised technologies. This pathway portrays a policy-driven, centrally managed transition that achieves gradual emission reductions but lacks the transformative momentum of deeper, community-empowered approaches.
- Scenario 2 envisions a "*Unified World*" narrative, a future in which unity and inclusiveness drive systemic change. Institutions and organisations prioritise citizens as the main force behind the energy transition, placing human well-being above purely economic objectives. In this context, citizens and households in the municipality of Megalopolis are empowered to unite in the battle against the climate crisis through coordinated action supported by municipal initiatives, local energy cooperatives, and multilevel policy frameworks that connect local, regional, and national authorities. Their participation is facilitated by targeted financial mechanisms such as renovation subsidies, co-financing schemes, and incentives for heat pumps and renewable-based heating, which lower entry barriers and enable broad engagement, including among vulnerable groups. Following the phase-out of lignite and the decommissioning of the district-heating network, decentralised solutions- primarily heat pumps- become the default replacement technology, ensuring continued access to affordable and low-emission heating services. Both local and

national authorities play a proactive role in guiding this transition, implementing policy frameworks that promote shared ownership, inclusiveness, and affordability, while citizens adopt both technological solutions and sustainable lifestyle practices that exceed national policy targets. This coordinated and cooperative approach enables the municipality of Megalopolis to move swiftly and decisively away from fossil fuels, achieving a comprehensive and socially just transition towards renewable-based heating and cooling systems.

- On the contrary, Scenario 3 envisions a “*Fragmented World*” narrative- a potential future evolution of undesired societies- which increasingly resemble a “dystopia” in the sense of extreme or even exaggerated worst-case scenarios. Global dynamics take an unfavourable turn as nations prioritise domestic concerns and regional interests over global collaboration, while policymaking increasingly focuses on national and regional security, diverting attention and resources from broader sustainable development goals. Within this context, citizens in the municipality of Megalopolis display increasing scepticism towards the energy transition, prioritising immediate affordability and short-term stability over collective climate ambition. Financial constraints, policy uncertainty, and reduced public trust hinder investment in clean technologies, while conservative governance at the national level reinforces dependence on fossil fuels. Local authorities, constrained by limited funding and weak coordination mechanisms, struggle to mobilise meaningful action. As a result, natural gas remains the dominant energy source until around 2040, and cleaner technologies such as heat pumps are adopted slowly, primarily out of necessity rather than commitment to decarbonisation. This scenario reflects a slower, less coordinated energy transition, where emission reduction occurs gradually, and inconsistently as traditional energy sources are incrementally phased out.

It is important to note that the shift towards individualised heating systems is a structural feature common to all scenarios. This reflects not a scenario-specific preference but a practical consequence of the lignite phase-out and the permanent decommissioning of the district-heating network in Megalopolis. As a result, all the scenarios under study assume decentralised, building-level heating solutions- either natural gas boilers or electric heat pumps- depending on the degree of policy support, citizen engagement, and investment capacity envisioned in each scenario.

To ensure that this scenario design is also policy relevant and useful to potential end-users (especially “Scenario 2” and “Scenario 3”), we also elicited knowledge and perspectives embedded in stakeholders and other relevant actors to further refine and finalise our scenario space (**Table 4.8**). More specifically, our modelling framework, our scenarios, and respective assumptions, were co-created during two press conferences organised by the Peloponnese Regional Council in 2021 and 2022. Following this, between 2022 and 2024, a series of stakeholder workshops and events were organised in hybrid format (online and in-person), engaging over 40 participants. These included representatives from national ministries (e.g., the Greek Ministry of Environment and Energy), regional and municipal authorities (e.g., the Regional Authority of Peloponnese and the Municipality of Megalopolis), academics, local civil society organisations, and citizens. These sessions were aimed at discussing and validating the scenario space, and gathering feedback on the feasibility, urgency, and desirability of the transition pathways. In addition, specifically in the municipality of Megalopolis, several events were organised, including a field visit in February 2023, where discussions were held with the city mayor, representatives from the Greek Public Power Corporation, academics, and civil society organisations. The study findings were further refined following their presentation at events focused on energy poverty and just transition, co-organised by civil society organisations and local authorities in the context of EC-funded Horizon 2020 and LIFE projects. These activities, held in Tripoli- a neighbouring municipality- and in Kozani, another CCIR in Greece facing comparable transition challenges, ensured that the final scenarios were grounded in both local realities and broader regional experiences.

Insights from this co-creation process were directly translated into the scenario assumptions. For example, stakeholder concerns about long-term dependency on natural gas and the potential for stranded assets informed the early electrification and renovation trajectories in “Scenario 2”. Conversely, doubts regarding citizen engagement, affordability, and institutional inertia shaped the more fragmented and delayed transition dynamics of “Scenario 3”. This qualitative input was systematically incorporated into the model, guiding the definition of key parameters such as renovation rates, behavioural adoption patterns, and the timing of fuel replacement across scenarios.

Table 4.8. Final scenario space to study different energy transition scenarios by 2050 in the municipality of Megalopolis’ residential sector.

Title	Milestone years	Description of transition trends
“Scenario 1”: <i>A “Familiar World” narrative</i>	(2023-2025)	Substitution of oil boilers and district heating with natural gas.
	(2025-2036)	100% use of natural gas as a transition fuel.
	(2036-2050)	Phase-out of natural gas boilers and substitution with heat pumps (6.7% per year- current national strategy).
“Scenario 2”: <i>A “Unified World” narrative</i>	(2023-2025)	Substitution of oil boilers and district heating with heat pumps.
	(2026-2050)	100% use of heat pumps installations- instead of using natural gas as a transition fuel.
“Scenario 3”: <i>A “Fragmented World” narrative</i>	(2023-2025)	Substitution of oil boilers and district heating with natural gas.
	(2026-2040)	100% use of natural gas as a transition fuel.
	(2041-2050)	Phase-out of natural gas boilers and substitution with heat pumps (3.3% per year- half the substitution rate defined by the current national strategy).

In terms of renovation targets, we keep the national target of 12-15%, as set in the Greek NECP, which in the case of Megalopolis is translated to ~70 dwellings fully renovated on an annual basis. For all the three scenarios under study, and based on stakeholders’ feedback, we assume that all the dwellings built before 2000, having their heating system substituted, are also renovated through envelope/ window upgrades; the dwellings built before 1981 are renovated with exterior wall insulation and window upgrades, while the dwellings built during the period 1981-2000 are only renovated with exterior wall insulation.

Furthermore, our scenario space is further enhanced with projections on the evolution of different useful exogenous variables, which are affected by the different “future-world” evolutions, as perceived in each scenario, to extract meaningful and policy-relevant conclusions on the socioeconomic and environmental implications of energy transition trends. In terms of energy prices, **Table 4.9** provides projections on future price evolutions in Greece by 2050, as derived from the national “Long-Term Strategy towards 2050” (Greek Ministry of Environment and Energy 2020), along with the respective trends that are underlined by each scenario under study.

Table 4.9. Projections on the evolution of energy prices by 2050 in the municipality of Megalopolis, as envisioned by the different future trends at the national level, for the scenarios under study.

“Scenario 1”: <i>A “Familiar World” narrative</i>
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Energy carrier	2023 value	Sources
Heating oil (€/MWh)	114.6	(Country Economy n.d.; Energy Press n.d.)
Natural gas (€/MWh)	70.0	
Electricity (€/MWh)	232.5	
“Scenario 2”: A “Unified World” narrative		
Energy carrier	2023 value	Sources
Heating oil (€/MWh)	76.3	(Grigoriou, Mayer, and Pallicska 2022; Hellenic Ministry of Development 2021; Hellenic Ministry of Environment and Energy 2019)
Natural gas (€/MWh)	48.2	
Electricity (€/MWh)	175.2	
“Scenario 3”: A “Fragmented World” narrative		
Energy carrier	2023 value	Sources
Heating oil (€/MWh)	123.2	(Hellenic Ministry of Development 2022b, 2022c, 2022a; Hellenic Ministry of Environment and Energy 2019)
Natural gas (€/MWh)	276.8	
Electricity (€/MWh)	295.2	

Our analysis also includes projections on the future evolution of technological costs by 2050, i.e., the costs to be paid by end-users for the implementation of the measures foreseen in the transition scenarios, e.g., natural gas and heat pump installations, envelope upgrades (**Table C3** in **Appendix C**). Finally, we quantify costs relevant to the expected introduction of a parallel Emissions Trading System (ETS II) by 2026 in the EU’s building and transport sectors, based on their expected evolution (€/tn) and the trends that our scenarios underly (**Table C4** in **Appendix C**), along with the carbon dioxide (CO₂) emissions derived in each scenario. The latter is calculated using the emission factor projections from the Greek “Long-Term Strategy towards 2050” (Hellenic Ministry of Environment and Energy 2019) in the case of electricity, while in the case of heating oil, natural gas, and biomass the respective emission factors are kept constant by 2050 (**Table C5** in **Appendix C**).

C₉M₂: Matrix iteration

Finally, this module is responsible for initialising the transition matrix and updating it at each time interval (as specified by the user at the simulation start time), based on inputs of the cumulative energy consumption patterns (received from the “C₈: Multilevel upscaling” component) and the state of the scenario space (received from the “C₉M₁: Scenario space” module). At the simulation end time, this module derives the final transition matrix, containing detailed information on energy transition for the resolution and the time horizon specified by the user. The overall time horizon in our study is set to 27 years and the time interval is set to one year (i.e., annual energy demand calculation). The final transition matrix contains detailed results on the energy transition by 2050 in the municipality of Megalopolis’ residential sector, based on the scenario space presented.

4.4. Results and discussion

This section presents simulation results on the final energy consumption and the energy mix by 2050 in the municipality of Megalopolis’ residential sector, followed by an analysis of the CO₂ footprint and the respective economic implications, for the three different energy transition scenarios under study.

4.4.1. Final energy consumption and energy mix by 2050

Simulation results reveal that “Scenario 1” and “Scenario 2”, while representing different potential evolutions of a post-lignite era in the municipality of Megalopolis, achieve similar levels of final energy reduction by 2050 (**Fig. 4.2**), reaching approximately 65.5% of the initial consumption levels. This suggests that the scenario envisioning the current national strategy achieves comparable total energy reductions by 2050 with an alternative pathway, which envisions citizens coming together to jointly co-create and actively participate to the energy transition in their community.

However, the three pathways under study differ significantly in their decarbonisation trajectories and the timing of the relevant targets’ achievement, which in turn lead to distinct environmental and socioeconomic implications. More specifically, while “Scenario 1” follows a gradual reduction in energy demand, aligned with the existing national planning, reaching lower consumption levels only after 2040, “Scenario 2” achieves a notably faster reduction in energy consumption levels, reaching approximately 50% of the baseline energy consumption levels by 2030, in comparison to “Scenario 1”, which only achieves around 80% of the baseline energy consumption levels by the same period. On the other hand, “Scenario 3”, which represents a “fragmented” evolution of the future, characterised by heavy reliance on fossil fuels and limited citizen engagement and participation, achieves a total energy consumption reduction of only 48.5% by 2050, compared to the baseline levels.

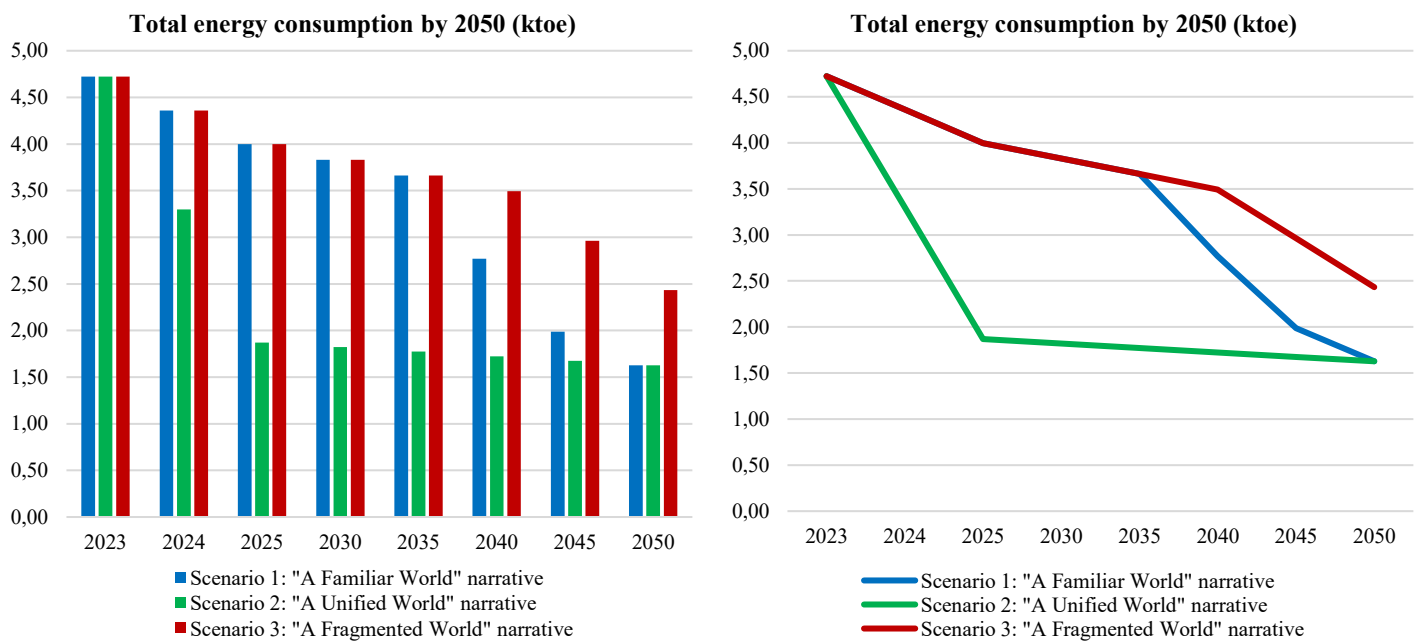


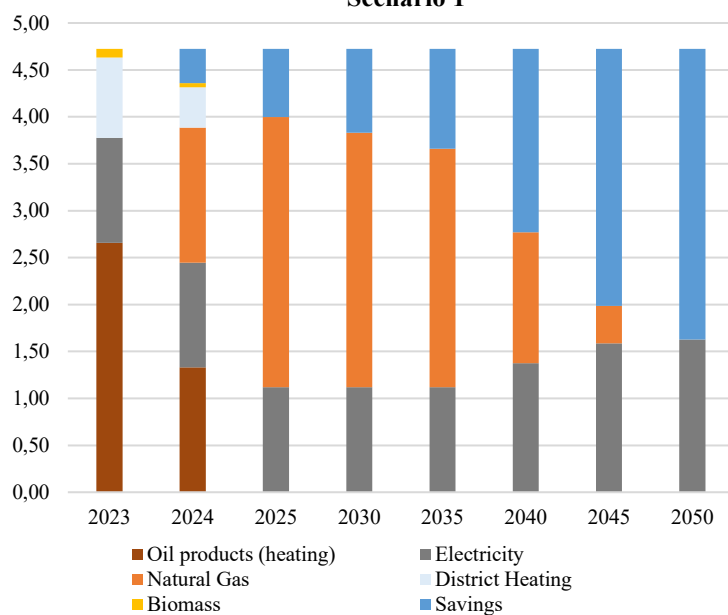
Fig. 4.2. Total energy consumption (ktoe) in the municipality of Megalopolis’ residential sector by 2050 for the three energy transition scenarios under study.

In addition, **Fig. 4.3** depicts the energy mix evolution for each scenario under study. Our results clearly demonstrate that a future transition pathway where citizens unite in the fight against climate change—investing as early as possible in green solutions, like energy efficiency and electrification, while also adopting climate-friendly lifestyle and behavioural changes to manage their energy consumption (“Scenario 2”: A “*Unified World*” narrative)—could result in a swift and complete phase out of fossil fuels by 2030. These results underscore the significance of empowering collective actions and a unified approach between citizens and local and national authorities, along with the importance of early investments in sustainable and green solutions in achieving total decarbonisation, towards a robust, low-carbon community model.

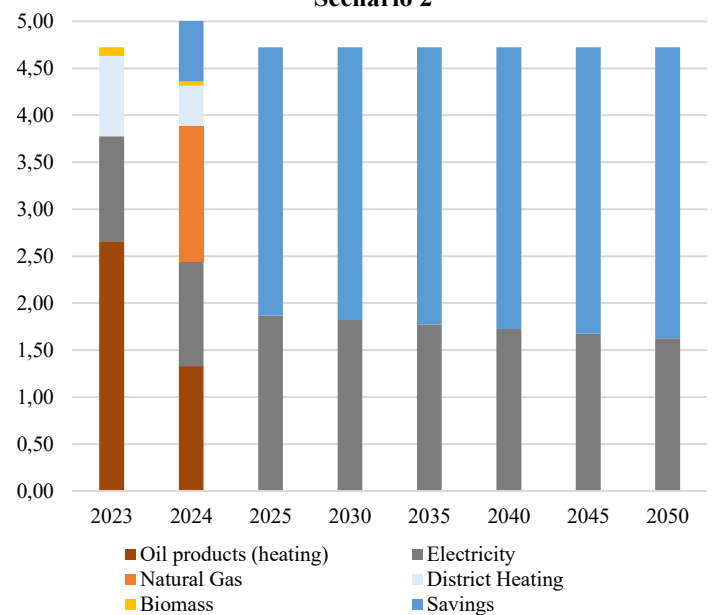
Furthermore, under a transition pathway where citizens follow the current decarbonisation trajectory investing in technological solutions as foreseen each time by current policymaking at the EU and the national levels (“Scenario 1”: A “*Familiar World*” narrative), decarbonisation in the residential sector can also be achieved by 2050. However, the pace of transition is considerably slower; the gradual reduction in fossil fuels only begins post 2035, reflecting the limitations of the current policy-driven transitions, which also do not fully leverage citizen engagement and active participation.

On the other hand, in a future characterised by distrust and scepticism, and in which individuals prioritise traditional perceptions of short-term energy security and cost savings (“Scenario 3”: A “*Fragmented World*” narrative), the use of fossil fuels remains entrenched in the energy mix until 2050. In this case, the vision of decarbonisation remains out-of-reach as the persistence of fossil fuels in the energy mix undermines efforts towards a sustainable and resilient green future. The latter underscores the pitfalls of “fragmented” centralised governance and limited public and citizen involvement.

Final energy mix and energy savings (ktoe)
"Scenario 1"



Final energy mix and energy savings (ktoe)
"Scenario 2"



Final energy mix and energy savings (ktoe)
"Scenario 3"

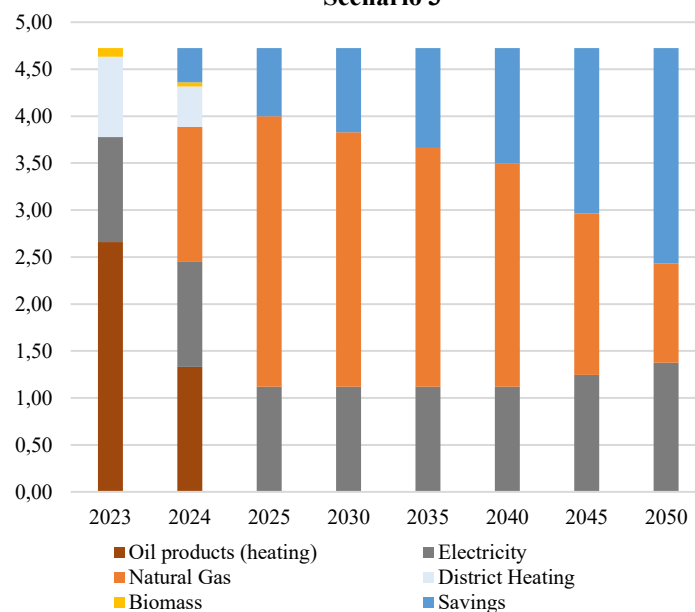


Fig. 4.3. Evolution of the final energy mix and total energy savings (ktoe) by 2050 in the municipality of Megalopolis' residential sector for the three energy transition scenarios under study.

4.4.2. Environmental impacts and carbon footprint

The environmental impact of the three scenarios is assessed through projected CO₂ emissions, serving as a crucial metric for accounting decarbonisation progress. As illustrated in **Fig. 4.4**, both “Scenario 1” and “Scenario 2” achieve total decarbonisation by 2050; however, the pathways diverge significantly in terms of the timing and the pace of emission reduction.

In particular, “Scenario 2” achieves a much faster reduction in CO₂ emissions compared to “Scenario 1”. By 2030, “Scenario 2” attains the CO₂ emission reduction levels that “Scenario 1” only reaches over a decade later (post 2040). This accelerated decarbonisation trajectory underscores the effectiveness of a strategy that integrates proactive community-empowered actions with ambitious policy support, leading to significant environmental benefits as early as possible, also highlighting the importance of an engaged, well-informed and well-trained citizen base, and how robust policy frameworks, co-created with local communities, can expedite progress towards climate neutrality.

Results on total emissions further highlight the comparative advantage of “Scenario 2”; by 2035, total emissions under “Scenario 2” are approximately 80,000 tonnes CO₂, whereas “Scenario 1” records nearly double that amount, at around 160,000 tonnes CO₂. This difference- almost a 50%- emphasises the long-term environmental value of early action and collective commitment to sustainable practices. This rapid reduction in total emissions showcases the substantial benefits of unifying local authorities and citizens under a common goal towards a greener future, enabled through coordinated mechanisms such as municipal programmes, citizen energy cooperatives, and national/ EU policy incentives that reduce financial barriers to participation moving decisively towards achieving climate targets at the local level.

In contrast, “Scenario 3” fails to achieve full decarbonisation by 2050; total emissions in this case are projected to reach nearly 200,000 tonnes CO₂ by 2050- almost equal to the emissions achieved in both “Scenario 1” and “Scenario 2” together. The latter highlights that the persistent reliance on fossil fuels, coupled with limited community engagement and participation, demonstrates how fragmented governance and reluctance to commit to ambitious climate actions can stall progress towards decarbonisation. This approach not only limits immediate environmental gains but also creates a significant risk of non-compliance with the EU’s climate goals, prolonging dependence on non-renewable resources and facing potential economic penalties and carbon-related costs.

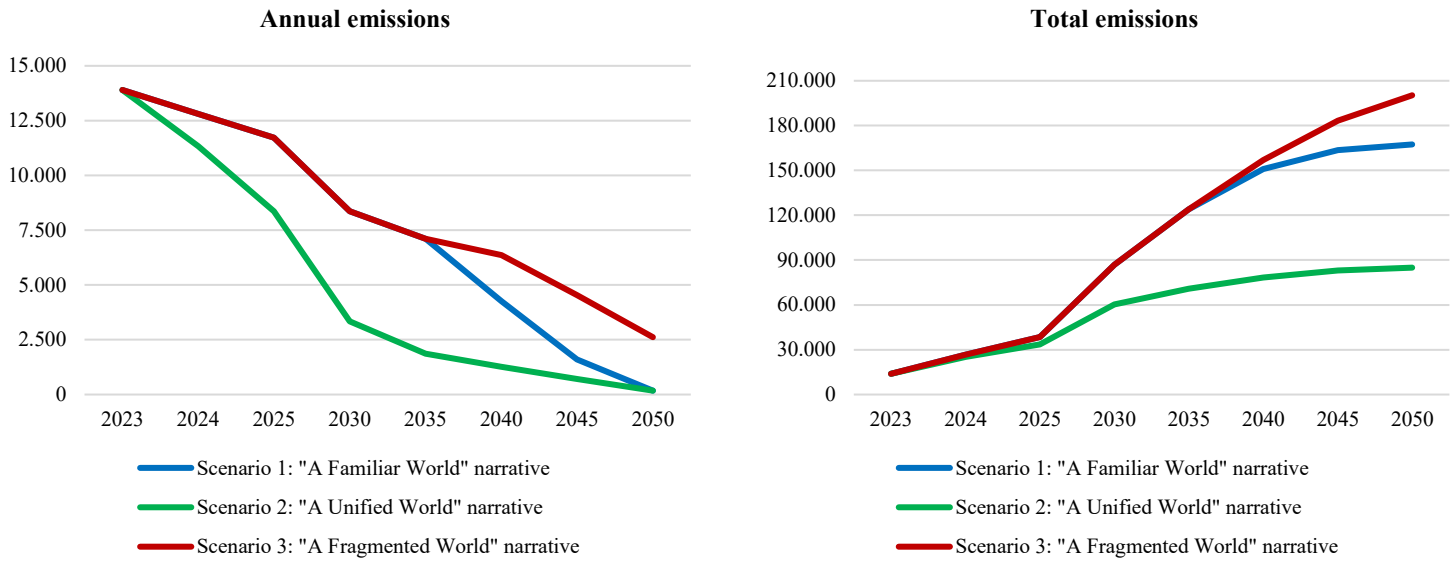


Fig. 4.4. Evolution of (a). annual emissions (tonnes CO₂) and (b). total emissions (tonnes CO₂) by 2050 in the municipality of Megalopolis' residential sector, for the three scenarios under study.

Finally, emphasis on electrification could also pave the way to achieve broader decarbonisations goals in the supply side. As the municipality of Megalopolis and the Peloponnese region shift away from fossil fuels, the reliance on electric heating and energy-efficient technologies makes it easier to integrate renewable energy sources, such as residential photovoltaic (PV) systems and battery energy storage systems, to boost local renewable energy generation. This shift supports a more resilient, sufficient, and self-sustaining energy system that aligns well with innovative solutions. By encouraging such investments thus, "Scenario 2" creates a foundation that not only reduces demand-side emissions but also facilitates the use of cleaner energy sources on the supply side, amplifying decarbonisation effects, which could enable a "green transformation" in Megalopolis and could establish the municipality as a leading force in adopting local and community-based sustainable governance models.

4.4.3. Economic implications at the local and the household levels

Assessing the economic implications of the three scenarios under study, our analysis focuses on end-use costs and charges by 2050. These include costs related to the costs of energy use, the costs of renovations, and the costs associated with the anticipated introduction of a parallel ETS in the EU's building sector.

Fuel costs

The analysis of fuel costs provides insights into the financial sustainability of the energy transition scenarios. As shown in **Fig. 4.5**, "Scenario 2" amounts to €89.74 million of fuel costs by 2050. In contrast, "Scenario 3", reaches the amount of €336.24 million- nearly three times higher- underscoring the potential financial burden of delayed transitions and reliance on fossil fuels. "Scenario 1", aligned with current national policies and a moderate pace of a green transition, results in total fuel costs of €126.06 million by 2050. While this figure is considerably lower than that of "Scenario 3", it is still over 40% higher than the fuel costs under "Scenario 2".

Except for the cumulative values, the annual evolution of fuel costs also reveals notable trends: "Scenario 3" exhibits the highest annual costs throughout the transition period, peaking at €13.75 million in 2030 and gradually declining to €8.75 million by 2050. In contrast, "Scenario 2" maintains a steady decline in annual fuel costs, starting at €4.78 million in 2023 and reaching a low of €2.81 million by 2050, reflecting the financial benefits of early electrification and zero dependence on fossil

fuels. Finally, “Scenario 1”, while showing a gradual decline to €3.75 million by 2050, remains consistently higher than “Scenario 2” throughout the entire transition period.

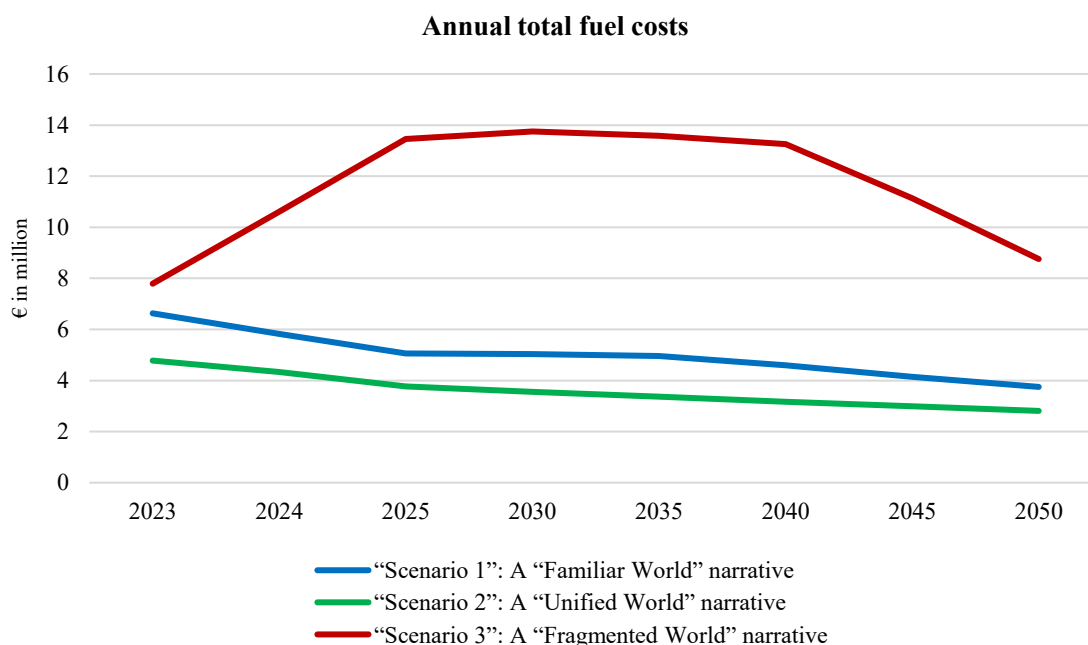


Fig. 4.5. Evolution of total fuel costs (€ in million) by 2050 in the Megalopolis’ residential sector for the three scenarios under study.

Renovation costs

Renovation costs, as illustrated in **Fig. 4.6**, are higher in “Scenario 2” due to the proactive adoption of heat pumps and energy-efficiency upgrades. In this case, transition under “Scenario 2” proves considerably more expensive than the transition under both “Scenario 1” and “Scenario 3”, especially during the early stages, which is marked by drastic changes in the energy mix. Nevertheless, renovation costs represent just one facet of the household-related charges attributed to the energy transition in the residential sector. The latter speaks of the necessity to design and implement renovation programmes that focus on supporting wider citizen inclusion, especially of the most vulnerable groups, towards the implementation of measures that lead to increased overall benefits (e.g., enhanced comfort, reduced energy expenses, achievement of climate targets).

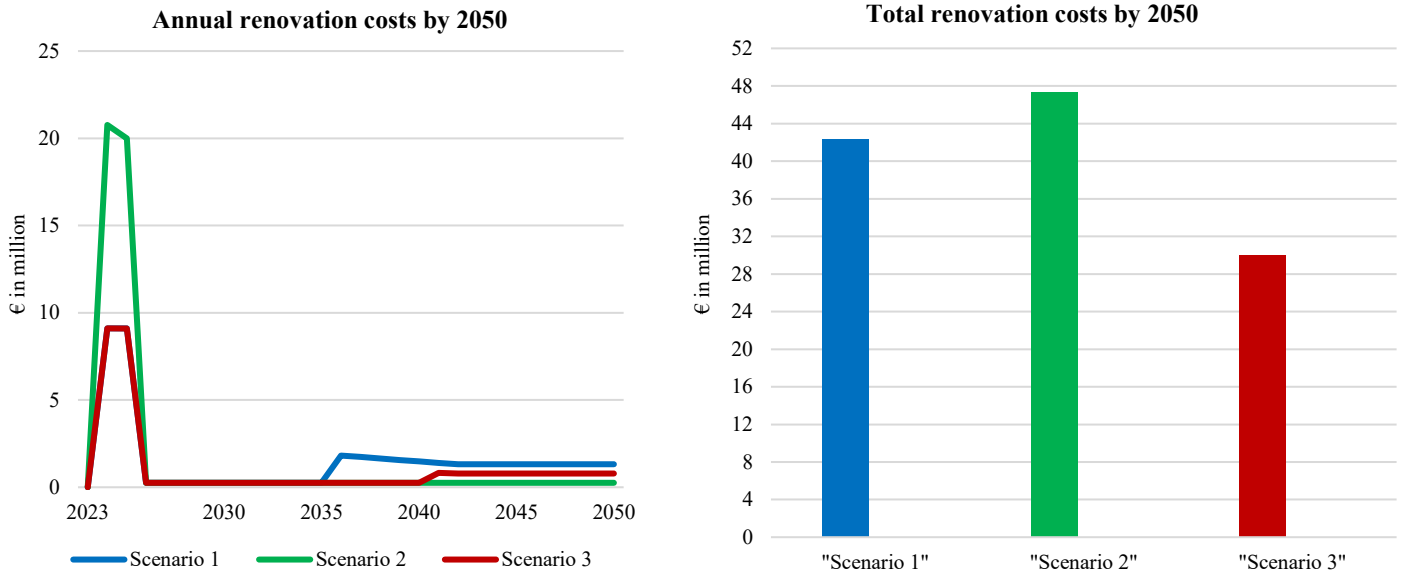


Fig. 4.6. (a). Evolution of the annual renovation costs and (b). Total renovation costs by 2050 in the Megalopolis' residential sector for the three scenarios under study.

In addition, it should also be noted that infrastructure and other indirect costs due for the expansion of the natural gas network are not included in the renovation costs; only costs to be paid by households are included. The latter implies that renovation costs under both “Scenario 1” and “Scenario 3”, which focus on keeping reliance on natural gas as a transition fuel (with different trajectories, of course) and expanding natural gas infrastructure will be higher than the ones projected. The latter should also be considered in the context of expected decrease in the currently high capital costs of heat pumps due to the “learning curve” effect. As indicated by the European Heat Pump Association (European Heat Pump Association 2022), costs are also expected to decrease in the near future due to the expected supportive regulatory context at the EU level (European Commission. Joint Research Centre. 2023), and the consequent growing market size, which can reduce costs due to the impacts of economies of scale, heightened competition, and increased focus on innovation and research (International Energy Agency (IEA) 2022b).

Costs related to the introduction of a new Emissions Trading System (ETS II) in the building sector

The evolution of ETS-related charges, as depicted in **Fig. 4.7**, highlights significant differences across the three scenarios: Under “Scenario 2”, households incur zero ETS-related costs by 2050; this is due to the structure of the new ETS framework, which excludes household electricity consumption from additional ETS charges, as these costs are integrated at the electricity generation level of the supply side. Furthermore, this scenario opens the possibility for a reduction in electricity prices in the long term, as the national electricity generation mix in Greece becomes greener. As renewable energy sources progressively dominate the generation mix, ETS-related charges associated with fossil fuel-based electricity generation are expected to decline, potentially reducing the indirect cost burden on households. This highlights how early investments in electrification and renewable infrastructure under “Scenario 2” can mitigate long-term financial impacts towards the energy transition process.

In contrast, “Scenario 1”, which aligns with existing national policies and moderate citizen engagement, incurs ETS costs of approximately €7.5 million by 2050; a 32% reduction compared to “Scenario 3”, which shows that households are expected to bear the highest ETS-related charges at nearly €11 million. The latter underscores the financial pitfalls of delayed actions and prolonged reliance on fossil fuels and highlights the economic inefficiencies of scenarios reliant on fossil fuels, reinforcing the

importance of proactive and collaborative strategies to minimise long-term costs in alignment with climate goals.

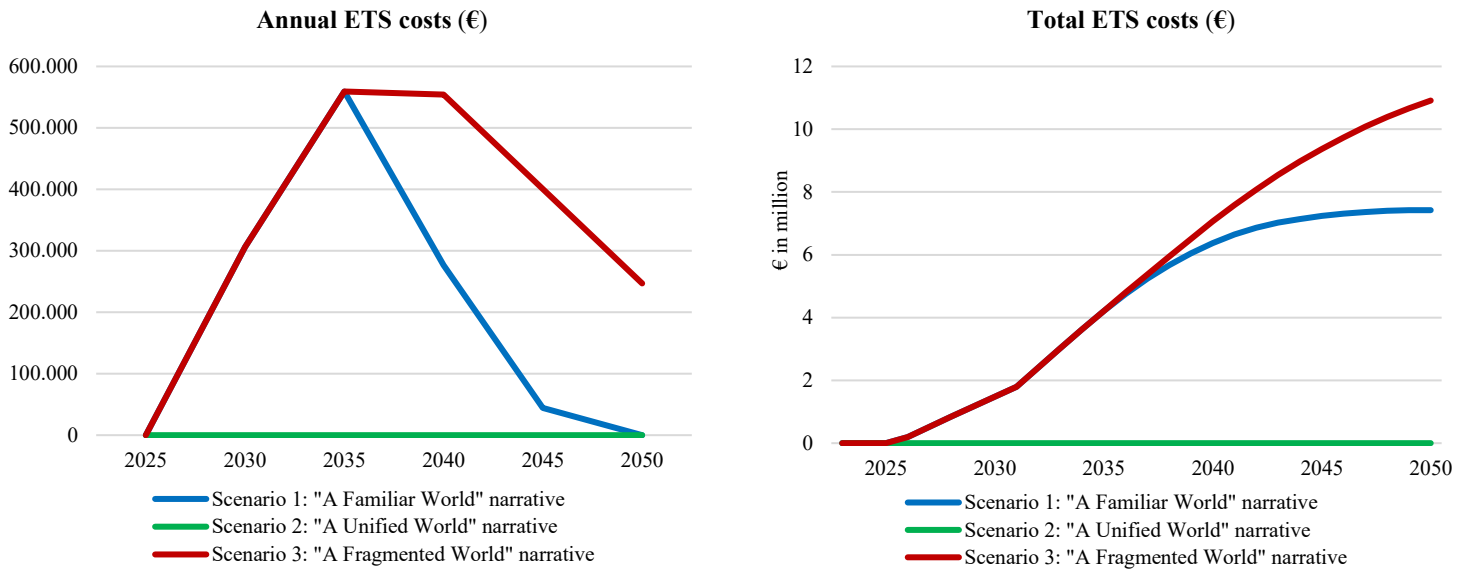


Fig. 4.7. (a). Evolution of the annual ETS costs at the municipality level and (b). total costs from the expected introduction of an Emissions Trading System (ETS II) in 2026 in the European Union’s building sector for the three scenarios under study.

Aggregating at the municipality level and scaling down to the household level

Lastly, to comprehensively assess the economic viability of each transition pathway under study, we aggregate costs at the municipality level, while also scaling down to the household level by assuming equal cost distribution among households.

At the municipality level, **Fig. 4.8** illustrates clear distinctions in the evolution of both annual and total costs across the three transition scenarios under study, demonstrating that “Scenario 3” is economically unsustainable in the long term. Without robust citizen engagement and a decisive shift away from fossil fuels, potential adverse developments drive costs progressively higher, emphasising the necessity of cohesive, proactive strategies that align local actions with the EU’s climate objectives. The inability of “Scenario 3” to achieve cost-efficiency demonstrates that a short-term focus on low-cost fossil fuel replacements ultimately leads to the highest total costs, challenging the validity of this approach. This scenario reaffirms that fostering citizen empowerment, promoting collaboration, and prioritising green investments are essential to achieving an affordable and resilient energy future.

Moreover, by comparing “Scenario 1” with “Scenario 2” we see that the existing national strategy in Megalopolis appears to represent a missed opportunity, as “Scenario 2” clearly demonstrates that a decisive shift towards electrification and energy efficiency yields economic benefits by lowering costs at the municipality level and avoiding prolonged reliance on natural gas infrastructure. This finding highlights the importance of re-evaluating current plans to focus on sustainable practices that provide a more cost-effective and resilient energy future, especially considering that Megalopolis is a CCIR under transition.

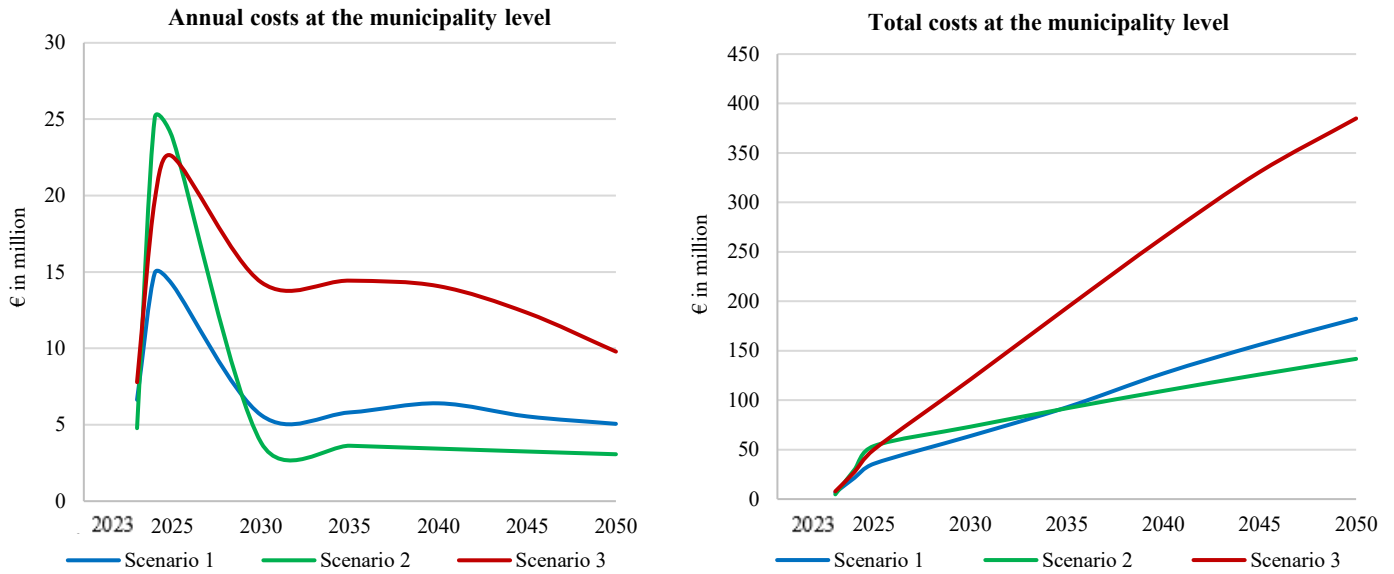


Fig. 4.8. Evolution of the (a). annual and (b). total costs by 2050 at the municipality level of Megalopolis for the three scenarios under study.

In addition, at the household level, **Fig. 4.9** showcases similar patterns. Although it is assumed that under “Scenario 3” households keep relying to fossil fuels as a means to energy security and lower bills, it is actually “Scenario 2”- characterised by early investments in electrification and energy efficiency- that achieves the lowest annual costs at the household level; falling below the threshold of €1,000 per household by 2030 and continuing to decline steadily thereafter, reaching approximately a total cost of €850 per household by 2050. Total costs per household under this scenario amount to just under €40,000 (around two times the current gross domestic product (GDP) per capita in Greece) by 2050, reflecting the significant long-term savings enabled by proactive policies, energy-efficiency measures, and the adoption of energy-saving behaviours.

In contrast, “Scenario 3 results in the highest financial burden for households. Annual costs peak sharply at over €6,500 per household in 2025, driven by reliance on costly fossil fuels, and only gradually decrease to around €2,500 per household by 2050. The total costs per household under this scenario exceed €108,000, by 2050, which is more than double the total cost per household under “Scenario 2”. The latter underscores once more the economic inefficiency of delayed actions and prolonged dependence on fossil fuels. Finally, “Scenario 1”, aligned with the current national strategy, represents a more moderate evolution; while annual costs decline more gradually compared to “Scenario 2”, reaching approximately €1,200 per household by 2050, total costs per household amount to around €51,500- almost 30% higher than those under “Scenario 2”.

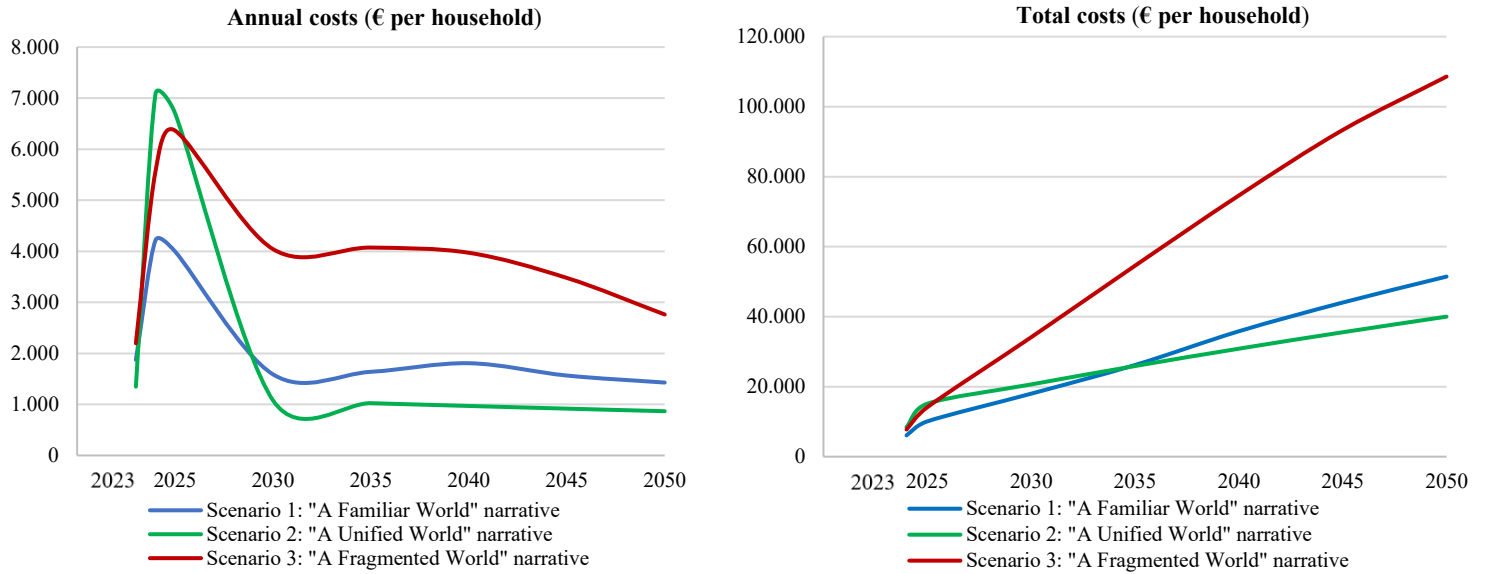


Fig. 4.9. Evolution of the (a). annual and (b). total costs per household by 2050 in the municipality of Megalopolis for the three scenarios under study.

Overall, considering that the local economy in Megalopolis, which is currently mainly dependent on the energy and the mining sectors, will undergo an abrupt pathway towards the phase out of lignite, and that by 2027 (when lignite-fired units are expected to close), employment and income levels could be significantly reduced, a community-empowered transition focusing on early electrification and investments in energy efficiency, could significantly decrease households' energy costs, limiting the effect of wage decreases, providing, thus, a significant helping hand to the most vulnerable citizen groups. Considering the respective energy, environmental, and economic benefits of a "Unified World" narrative, our results showcase that the current national planning appears to represent a missed opportunity of a "green transformation" with significant benefits at both the municipality and the household levels.

4.4.4. Comparison of findings to similar cases around the European Union

Our findings align with evidence from other European coal-intensive regions, particularly Silesia in Poland, where household-level interventions and participatory governance have proven pivotal for just and inclusive transitions. Analyses linked to the "Just Transition Fund" programme show that investments in building renovations, rooftop photovoltaics, and heat-pump systems are among the most effective measures for reducing household energy costs and improving air quality, while reinforcing regional resilience. These actions are embedded in a multi-level governance framework connecting municipal, regional, and civil-society actors, ensuring that transition planning addresses both technical and social dimensions (Tarasova 2024; Żuk, Żuk, and Pluciński 2021). Studies about the Polish residential sector further confirm that replacing outdated fossil boilers with cleaner technologies and retrofitting buildings yields large emission reductions but continues to face financial and institutional barriers requiring coordinated policy support (Sokołowski and Bouzarovski 2022). Recent assessments in Silesia and Western Macedonia (Greece) likewise show that cooperative frameworks and citizen participation accelerate decarbonisation while strengthening procedural justice, mirroring results from our "Scenario 2", where early citizen engagement and aligned policy frameworks drive greener and more affordable energy transitions (Topaloglou et al. 2024).

Germany's experience similarly demonstrates that technical progress must coincide with social legitimacy. Modelling studies at national and regional levels highlight deployment of heat pumps and renovation programmes as the most cost-efficient and resilient decarbonisation measures (Bernath,

Deac, and Sensfuß 2019; Maruf 2021). Yet, empirical studies on the coal-intensive regions of Lusatia and North Rhine-Westphalia reveal that technical and financial feasibility alone cannot ensure success; multi-level coordination among regional agencies, municipal utilities, labour unions, and civil-society organisations has been critical to redirect investments, reskill workers, and sustain public acceptance (Oei et al. 2020; Oei, Brauers, and Herpich 2020). Complementary modelling research on Germany's energy transition confirms (Brandes et al. 2024) that electrifying heating enhances flexibility and renewable integration- an outcome consistent with our findings for Megalopolis, where early household electrification and behavioural engagement reduce emissions and costs. On the other hand, the case of Asturias in Spain provides a governance analogue to these modelling insights. The region's 2023 "Territorial Just Transition Plan" and "Energy Poverty Alleviation Plan" identify local participation, energy communities, and citizen-led renovations as key tools for managing decarbonisation's social impacts (Asturias Energy Foundation (FAEN) n.d.; OECD 2025; Subdirección General de Gestión del FEDER 2025). Evaluations of Spain's "Just Transition Agreements" show that multi-level consultation and co-creation frameworks- linking authorities, trade unions, and civil-society actors- build trust and accelerate implementation. Together, experiences among CCIR across Europe show that embedding participation, coordination, and household-scale action into transition design is not a normative aspiration but a practical condition for fair and cost-effective decarbonisation.

However, across these contexts, a consistent pattern emerges; while the technical potential of electrification and renovation is well established, outcomes depend on how governance, behavioural change, and institutional capacity interact. Yet even in well-studied CCIRs such as the regions of Silesia, Western Macedonia, Lusatia, North Rhine-Westphalia, and Asturias, there remains a notable lack of modelling efforts at the regional or local scale capable of capturing the sociotechnical and socioeconomic dynamics at play. Most existing studies continue to optimise technologies using top-down frameworks at either the national or the European level, which, although valuable for high-level insights, lack the granularity needed to represent demand-side dynamics, citizen behaviour, policy coordination, and justice considerations (Kleanthis, Stavrakas, and Flamos 2025; Vlachou and Pantelias 2022). Modelling of residential energy systems within coal- and carbon-intensive regional transitions- particularly where district heating infrastructures depend on local energy sources such as lignite - remains uncommon. However, it constitutes a critical yet often neglected aspect of the energy transformation, playing a key role in safeguarding household living conditions and maintaining indirect socioeconomic linkages with the mining sector.

Our study addresses this gap by setting boundaries for intervention and point out trade-offs through the local-scale modelling framework that links household energy dynamics with participatory scenario design. This approach offers an initial demonstration of how varying levels of citizen participation and policy coherence could shape both the pace and fairness of decarbonisation outcomes. Technical pathways, such as heat pumps and renovation measures, acquire different meanings depending on the degree of collective mobilisation and institutional support. This highlights the analytical value of coupling bottom-up high-resolution (demand-side) modelling with governance and behavioural dimensions, revealing not only which transition pathways are technically feasible but also which are socially sustainable. Taken together, these insights underscore the need for interdisciplinary, context-specific modelling frameworks that integrate engineering precision with institutional and behavioural realism. Embedding participation, governance, and affordability within model design is therefore not merely an analytical refinement but a prerequisite for credible and just transition planning. The Megalopolis case, when viewed alongside other European experiences, illustrates how integrating technical and social dimensions can yield more accurate, policy-relevant, and inclusive strategies for achieving decarbonisation targets in coal-dependent regions.

4.5. Conclusions and policy implications

Empowering local communities across Europe to drive systemic change on their own terms can foster more diverse, inclusive, and resilient energy transitions, especially in socially complex contexts like CCIRs, which are experiencing multiple negative effects in the post-carbon era, including job losses, migration, insufficient services, and degraded environmental conditions. Achieving the required energy transformations in a just and inclusive manner in these regions, requires policies and initiatives, which are not only predominantly centred on technical and economic considerations (often overlooking discussions on inclusive and democratic governance), but also address cultural, identity, inequality, and perceptual dimensions. An illustrative case of a CCIR, which reflects these broader challenges of the energy transformations required and the complex interplay among different levels of governance, is the municipality of Megalopolis in Greece, which is currently at the heart of a contested policy debate. National planning, prioritising the expansion of the natural gas infrastructure and the use of public funding from the “Just Transition Fund” to fully subsidise the installation of gas boilers in the residential sector, raises concerns about a potential lock-in effect and a long-term dependence on fossil fuels, envisioning a transformation of decreased decarbonisation potential, which, overall, undermines the principles of just transitions.

Responding to recent scientific literature calling for alternative scenario-based research and modelling approaches in support of interdisciplinary and inclusive transition debates to address social complexity issues like citizen participation and justice, in this article, we evaluate if the current national strategy risk locking the municipality of Megalopolis into a continued natural gas dependence, thereby missing the opportunity of a fully green and inclusive transition based on alternative pathways by 2050. To do so, we couple a dynamic high-resolution demand-side management model (DREEM) with a transformative scenario design framework to assess the potential benefits of a community-empowered energy transition, which emphasises sustainable energy use through investments in heat pumps and energy-efficiency solutions, along with energy-saving behaviours. Informed by national and local experts’ perspectives, our scenario design framework explores alternative futures that go beyond the comfort zone of current scenario-based research and examine out-of-ordinary extremes.

Each scenario offers a unique perspective on a post-lignite future by 2050, envisioning varying levels of citizen participation and responses to policy frameworks, to also address the often-overlooked social, cultural, and behavioural dimensions that typically encompass real-world transformations and shape citizen participation and local responses. Simulation results indicate that prioritising an alternative community-empowered strategy, focusing on electrification and energy efficiency, emerges as the most effective transition pathway in terms of reducing energy consumption, improving environmental performance, and minimising costs. This scenario envisions a socially cohesive and proactive model of transition, where citizens are not passive recipients of policy, but agents of change, jointly shaping a sustainable energy future alongside local and national authorities. The effectiveness of this approach is not merely technological, but fundamentally sociotechnical, illustrating the tangible benefits of embedding collective ownership and behavioural change into transition planning. This pathway also aligns with the “REPowerEU” plan, which promotes a citizen-centred approach to electrification, including doubling the deployment rates of heat pumps and achieving ten million installations within the next five years (European Commission 2022c).

Notably, our results show that such an alternative transition strategy delivers significant advantages, not only achieving decarbonisation targets, but also reducing total costs at both the municipality and the household levels, through early sustainable investments and well-coordinated, bottom-up collective action. In contrast, alternative transition pathways closely aligned with current national policies, or envisioning a “dystopian” future evolution where citizens keep relying on centralised fossil-fuel-based planning, both reflecting typical or even limited community and citizen engagement trends, result in

higher total costs and slower progress towards decarbonisation. These outcomes underscore the economic and environmental value of participatory and community-empowered transition pathways that embrace co-creation and social innovations as essential drivers of systemic change.

More specifically, approximately €250 million could be saved by 2050 if local authorities and households collectively decide to directly invest in heat pumps instead of natural gas. Downscaling from the municipality to the household level, this is translated to total monetary savings of more than €60,000 per household, which amount to approximately three times the current GDP per capita in Greece (Trading Economics 2025). It should also be noted that monetary savings could even be higher due to expanding infrastructure costs, which are not attributed to households and could increase the total investment costs of using natural gas as a transition fuel. Beyond economic benefits, our findings also show that a community-empowered transition based on electrification, energy efficiency, and behavioural shifts, can significantly accelerate decarbonisation in Megalopolis; “Scenario 2” showcases emission reductions that are not only faster but also deeper. Specifically, when comparing the environmental footprints of “Scenario 2” and “Scenario 3”, approximately 115,000 tonnes CO₂ emissions can be avoided- approximately 30,000 tonnes more than the total footprint of “Scenario 2”.

These forms of engagement, centred around local agency, civic participation, and collective action, highlight the need for a broader shift in policy and research towards the exploration and implementation of innovative concepts like “energy citizenship” (Laakso, Eranti, and Lukkarinen 2023; Silvast and Valkenburg 2023). By recognising the role of individuals and communities as active agents of systemic change, such approaches challenge the prevailing narrative that green transitions impose unbearable economic burdens on citizens. Instead, they demonstrate that although such citizen-centred transitions might require higher upfront investments, they can deliver significant long-term economic, environmental, and social returns. By fostering energy citizenship and enabling local actors to participate in decision-making processes, Megalopolis could pave the way for a more inclusive, just, and resilient post-lignite future.

At the same time, our findings raise concerns about the current national plan. Fully subsidising a shift to new natural gas infrastructure, using public resources from the “Just Transition Fund”, risks deepening dependency on fossil fuels in the region, increasing households’ energy costs over time, and creating stranded assets that will need to be decommissioned prematurely, especially as the EU’s climate regulations tighten. This approach conflicts with the “Energy Efficiency First” principle and with recent guidance from the EC on climate-proofing infrastructure projects under the “2021-2027 Funding Framework” (European Parliament and Council of The European Union 2021). To avoid these pitfalls, national and local authorities should focus on alternative transition strategies, where existing financial, institutional, and social resources are allocated more effectively- shifting from subsidising fossil-based infrastructures towards electrification and community-empowered green investments. Although such approaches may appear more demanding in the short term, they can yield substantially greater socioeconomic and environmental benefits in the long run, ensuring that public resources genuinely serve the objectives of a just and sustainable transition. In this regard, expanding national programmes like “Exoikonomo-Autonomo” (or “Energy Savings at Home”) to include stronger incentives for heat pumps, and supporting energy communities through targeted funding, training, and capacity-building programmes, would enhance local resilience and accelerate alignment with the EU’s climate targets. Tailored and well-targeted campaigns, increasing awareness and promoting behavioural change and community ownership, will also play a catalytic role, reduce energy vulnerability, and create new employment opportunities in green construction, maintenance, and services.

Given the socioeconomic challenges that Megalopolis is expected to face by 2027 due to the complete phase out of the in-house lignite- including GDP decline and income loss- a green and community-empowered transition model like the one studied also offers a viable pathway for cushioning these

impacts through energy cost reductions and stimulation of the local economy. The current national planning appears to represent a missed opportunity of accelerating decarbonisation, strengthening social inclusion, and unlocking long-term economic and environmental benefits through clean energy investments and local job creation. A proactive shift towards electrification and energy efficiency could not only mitigate immediate economic shocks but also lay the foundations for a long-term “*green transformation*”, establishing Megalopolis as a pioneer in climate-forward, community-empowered municipal models of governance. This, in turn, may attract more sustainable investments, improve public health, and redefine the municipality’s identity around resilience, equity, and environmental leadership.

Acknowledging limitations of our work, it is important to note that our modelling framework does not explicitly capture all socioeconomic dynamics typically associated with coal region transitions. Factors such as employment shifts, outmigration, or changes in income distribution, are particularly relevant in the context of CCIRs like Megalopolis, where the local economy is strongly dependent on lignite-related activities. In addition, community heterogeneity, such as differences between renters and homeowners (Papantonis, Stavrakas, Burbidge, et al. 2025), or between elders and younger families, also plays an important role in shaping energy transition patterns and the fairness of its outcomes.

Regarding input data, we ensured data transparency, consistency, and accuracy despite existing limitations in municipal-level statistics. The “TUS2013” dataset- the latest dataset offering detailed time-of-use activity profiles in Greek households- was used selectively, only where newer alternatives such as the more recent “HBS2020” dataset lacked sufficient coverage. Similarly, using three representative household typologies to model 3,775 dwellings, reflects a typical- according to the most recent scientific literature- balance between representativeness, data availability, and generalisability. While this simplification may not capture all household-level diversity, the resulting ratio aligns with established modelling practices (Nayak et al. 2023) and ensures methodological rigour and transparency within the constraints of available data.

As future research, we aim to refine the scenarios through an inclusive approach that integrates sociotechnical and socioeconomic dimensions in more detail. In particular, coupling high-resolution demand-side modelling with macroeconomic and demographic models would allow for the explicit consideration of employment effects, income distribution, and potential outmigration, which are highly relevant for planning inclusive energy transitions. Equally important will be expanding the framework to reflect citizen heterogeneity- for example, by differentiating between tenure status, income groups, and demographic profiles- to capture how diverse needs and capacities influence both the pace and equity of transitions. Expanding the framework to include supply-side dynamics (Stavrakas, Kleanthis, and Flamos 2020a) and innovative technologies such as renewable generation and advanced storage solutions (Michas et al. 2019b) is expected to also provide a more holistic understanding of transition outcomes (Tzani et al. 2023). Finally, the replicability potential of our study offers opportunities for application across diverse geographic and socioeconomic contexts. As such, we call for future research to explore similar modelling studies at the regional or the local level in other cases across Europe, also addressing the often-overlooked input from local authorities. Such studies could support aligning local and regional priorities with national strategies, reduce policy conflicts, and improve transition outcomes, offering insights towards effective and adaptive policymaking across multiple governance levels in the EU.

Appendix C

Table C1. Classification of dwellings' construction period in the municipality of Megalopolis (Peloponnese region, Greece).

Dwelling's construction period	Number of households
Before 1981	1,485
1981-2000	1,225
After 2000	835
Total	3,545

Table C2. Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) value ranges and respective expectation levels according to the EN 15251 standard (de Normalisation and EN15251 2007).

PPD (%)	PMV	Description
< 6	- 0.2 < PMV < + 0.2	Increased expectation level: recommended for spaces inhabited by highly vulnerable individuals with specific needs, like sick children, elderly persons, etc.
< 10	- 0.5 < PMV < + 0.5	Standard expectation level: new and renovated buildings.
< 15	- 0.7 < PMV < + 0.7	Moderate expectation level (acceptable range): existing buildings.
< 20	- 1 < PMV < + 1	Minimum expectation levels: values acceptable only for limited parts of the day.
> 20	PMV < -1 or PMV > + 1	Unacceptable expectation levels: values deviating acceptable criteria, deemed tolerable only for a very limited part of the year.

Table C3. Projections of the future evolution of technological costs by 2050 in the three scenarios under study.

Year	2023	2030	2050	Source(s)
Natural gas boilers (€)	5,000	4,904	4,713	(European Heat Pump Association 2022; De Vita, Kielichowska, Mandatowa, Capros, Dimopoulou, Evangelopoulou, Fotiou, Kannavou, Siskos, Zazias, De Vos, et al. 2018)
Heat pumps (€)	12,000	7,680	4,086	
Building envelope insulations & window upgrades (€)	5,000	5,000	5,000	

Table C4. Projections of the future evolution of the costs relevant to the introduction of a parallel Emissions Trading System (ETS II) by 2050 in the EU's building sector.

Period	(2022-2025)	(2026-2030)	(2031-2050)	Source
Carbon price (€/tn)	0	50	100	(EU Carbon Permits - 2022 Data - 2005-2021 Historical - 2023 Forecast - Price - Quote n.d.)

Table C5. Projections on the future emission factors for electricity, heating oil, natural gas, and biomass as derived from the Greek “Long-Term Strategy towards 2050” (Hellenic Ministry of Environment and Energy 2019).

Electricity	
Year	Emission factor (tnCO₂/ktoe)
2023	5,006
2025	4,476
2030	3,947
2035	3,418
2040	2,889
2050	2,360
Heating oil	
Year	Emission factor (tnCO₂/ktoe)
(2023-2050)	2,821
Natural gas	
Year	Emission factor (tnCO₂/ktoe)
(2023-2050)	2,332
Biomass	
Year	Emission factor (tnCO₂/ktoe)
(2023-2050)	2,337

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Chapter 5 - Discussion and conclusions

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Nomenclature

Acronyms & abbreviations			
DREEM	Dynamic high-Resolution dEmand-side Management	GHG	Green House Gas
EED	Energy Efficiency Directive	NBRP	National Building Renovation Plan
EPBD	Energy Performance of Buildings Directive	NECP	National Energy and Climate Plan
ETS2	Emissions Trading System 2	PV	Photovoltaics
EU	European Union	RED	Renewable Energy Directive

5. Discussion and conclusions

This chapter synthesises the results of the dissertation and discusses the key findings, with particular attention to their implications for policymakers and practitioners. It also outlines the thesis's contributions to academic research and the field of energy system modelling. Finally, the chapter acknowledges the limitations of the study, while presenting directions for future research.

5.1 Introduction

Buildings occupy a central position in the European Union's (EU's) climate and energy transition, as they simultaneously represent a major source of final energy consumption and greenhouse gas (GHG) emissions, and a primary interface between climate and energy policy and citizens' everyday lives. Buildings account for around 40% of the EU's final energy consumption and approximately 36% of energy-related GHG emissions, while their long lifetimes, current low rates of energy renovations, and strong links to social and economic outcomes make their decarbonisation both technically complex and socially sensitive (European Commission 2020c; European Energy Agency 2024).

Within the broader buildings sector, the residential segment occupies a particularly critical position, as it accounts for the largest share of building-related final energy consumption and GHG emissions. Residential buildings dominate energy demand for space heating and hot water, making them central to achieving emissions reductions in the buildings sector and to meeting the EU's climate neutrality objectives (European Commission 2019a; International Energy Agency (IEA) 2025). Beyond their quantitative importance, residential energy transitions directly shape household living conditions and well-being, as decarbonisation outcomes are closely intertwined with affordability, energy poverty, behavioural responses, and social acceptance, while exposure to energy resilience challenges can directly affect households' ability to maintain adequate thermal comfort and basic living standards (Levell, Connell, and Smith 2024).

Over the past decade, the EU has developed an increasingly ambitious policy framework for building decarbonisation, combining regulatory instruments such as the Energy Performance of Buildings Directive, the Energy Efficiency Directive, and the Renewable Energy Directive with strategic and financial instruments such as the Renovation Wave, REPowerEU, cohesion policy funds, the Recovery and Resilience Facility, and the Social Climate Fund (European Commission 2025; Official Journal of the European Union 2023b). At the national level, these objectives are translated mainly through National Energy and Climate Plans and National Building Renovation Plans. Together, these instruments aim to accelerate renovation, improve energy efficiency, promote electrification, and reduce the role of fossil fuels in buildings (European Commission 2022c, 2023a; European Union 2024)..

However, recent events, such as the COVID-19 pandemic and the energy crisis triggered by geopolitical developments over the past decade, have highlighted significant vulnerabilities in the planning and implementation of residential energy transitions. These crises exposed the risks inherent in relying on static assumptions about fuel availability, price stability, and geopolitical conditions, revealing the need for more adaptable and resilient approaches to energy policy (Emter, Gunnella, and Schuler 2023).

The latter highlights that residential decarbonisation pathways are not only about achieving long-term emissions reduction goals but also about addressing short- to long-term energy resilience. Energy resilience, in this context, refers to the reliable access to energy resources. This includes mitigating risks related to the volatility of fuel prices, the availability of energy resources, and geopolitical events that may impact supply chains (Brodny and Tutak 2023; Maduta et al. 2023; Schmitz et al. 2025; Wejnert-Depue et al. 2025).

Another critical aspect of the ongoing decarbonisation and energy transition efforts is the introduction of emissions trading for buildings and road transport under the revised EU Emissions Trading System 2 (ETS2). ETS2, which forms part of the EU's broader climate and energy framework, aims to accelerate the transition towards electrification, energy efficiency, and fuel switching in the residential sector, with the goal of reducing emissions by 42% by 2030 compared to 2005 levels (Official Journal of the European Union 2023a). Set to fully operate in 2028, ETS2 will impose emissions caps on fossil fuel suppliers, requiring them to purchase allowances at auctions to cover their emissions. While suppliers are directly regulated, the costs of purchasing these allowances are expected to be passed on to end users, including households, in the form of higher fossil fuel prices (Leonardi 2025).

When embedded within a comprehensive and well-coordinated policy package, ETS2 can enhance the decarbonisation potential of the residential sector by strengthening incentives for energy efficiency improvements, electrification, and the uptake of low-carbon heating solutions. However, if introduced in isolation, carbon pricing in the residential sector risks increasing short-term vulnerability by disproportionately affecting low-income and energy-poor households, who face limited capacity to absorb higher energy costs or invest in transition technologies (Perdana and Vielle 2026). A balanced and integrated policy framework, combining carbon pricing with targeted financial support, regulatory measures, and social protection instruments, is therefore essential to mitigate adverse distributional impacts and to ensure that the transition towards a low-carbon residential sector is both resilient and socially inclusive.

In this context, energy justice emerges as a central aspect of residential decarbonisation, shaping both the effectiveness and the social legitimacy of transition policies. Energy justice concerns the fair distribution of the costs and benefits of decarbonisation across social groups, with particular attention to low-income and energy-poor households that are least able to absorb higher energy prices or invest in low-carbon technologies. Without explicit energy justice considerations, decarbonisation efforts risk reinforcing existing social inequalities and increasing exposure to energy poverty, especially in the presence of carbon pricing and rising energy costs (Bartiaux et al. 2019; Kime et al. 2023; De Simone, Arcaya, and Reinhart 2025). Embedding energy justice in policy design is therefore essential to ensure that the transition to a low-carbon residential sector supports social inclusion, protects vulnerable households, and ensures that no one is left behind.

This dissertation contributes to this context by applying a bottom-up modelling framework for the decarbonisation of the residential sector, with particular attention to energy resilience and energy justice implications. By leveraging and extending the DREEM modelling framework, the dissertation provides evidence to support the design of residential energy transition strategies that are not only effective in reducing emissions, but also robust, socially inclusive, and sensitive to the risks faced by vulnerable households.

The dissertation investigates residential energy transitions across different spatial scales, including the national, regional, and local levels. At the national level, the analysis examines how policy priorities, renovation rates, and heating technology choices affect the feasibility of achieving long-term residential decarbonisation objectives. At the regional level, it examines how nationally driven energy planning interacts with regional conditions, focusing specifically on the implications of expanding natural gas infrastructure in the Peloponnese residential sector. At the local level, the dissertation focuses on a coal- and carbon-intensive municipality undergoing a Just Transition process, assessing how alternative heating technology and renovation pathways can support or hinder a greener and fairer residential energy transition.

The modelling framework adopts a bottom-up approach to simulate residential energy demand and assess transition pathways across multiple spatial scales, namely local, regional, and national levels. It provides a basis for analysing residential transitions through the three pillars of the dissertation: decarbonisation, energy resilience, and energy justice.

To operationalise these pillars, this dissertation expands the computational capabilities of the **Dynamic high-Resolution demand-side Management (DREEM) model** (Stavrakas and Flamos 2020) by developing two new components: “*C₈: Multilevel Upscaling*” and “*C₉: Transition Matrix*”, along with its two subcomponents, namely “*C₉M₁: Scenario space*” and “*C₉M₂: Matrix iteration*”. The “*C₈: Multilevel Upscaling*” component enables the model to estimate cumulative residential energy consumption across different spatial scales by using relevant data to upscale household-level energy demand profiles to the selected level of analysis. This allows residential transition outcomes to be assessed in local, regional, and national contexts.

The “*C₉: Transition Matrix*” component enables the simulation of residential energy transitions over time. It defines a scenario space that combines policy-driven assumptions with exogenous variables and updates them to reflect evolving conditions across the selected time horizon. This allows the model to examine how alternative transition pathways unfold, providing outputs on final energy demand, emissions, and costs. Together, these components enhance the ability of the DREEM model to evaluate residential transition pathways across different governance scales and to assess how decarbonisation objectives interact with resilience-related concerns and energy justice implications.

The entire work of this dissertation is presented as a series of research chapters, each contributing to the development of a comprehensive framework for assessing residential energy transitions through the lens of **decarbonisation**, **energy resilience**, and **energy justice**. The structure is as follows:

- **Chapter 1:** Introduces the overarching challenges and objectives of residential energy decarbonisation, focusing on the need for analytical and policy frameworks that can address emissions reduction, resilience, and justice in an integrated manner. The chapter discusses challenges and limitations of existing modelling approaches, identifies the main research gaps, and outlines the rationale, objectives, and research questions of the dissertation.
- **Chapter 2:** Develops and applies the modelling framework at the national level to assess residential decarbonisation pathways towards 2050. The chapter explores how long-term EU and national climate targets can be translated into transition pathways by examining alternative renovation rates, heating technology choices, and policy priorities. By assessing implications for energy consumption, emissions, and household-level costs, the chapter provides evidence on the conditions required for achieving climate neutrality in the residential sector.
- **Chapter 3:** This chapter applies the developed framework at the regional level to examine how national energy planning priorities and policy pathways interact with regional decarbonisation potential, place-specific socio-economic and infrastructural conditions, and residential energy needs. The analysis compares scenarios that prioritise the continued expansion of natural gas with pathways that accelerate electrification and the deployment of alternative low-carbon solutions.
- **Chapter 4:** Shifts the analysis to the local level by examining the conditions under which residential energy transitions in carbon-dependent regions can evolve into green, inclusive and just pathways towards 2050. Focusing on a structurally vulnerable post-lignite municipality, the chapter integrates participatory scenario design within the dissertation’s modelling framework to explore alternative transition pathways that differ in technology choices, household engagement, and local development orientations.

Considered together, these research chapters form a sequential application of the dissertation's methodological framework (as outlined in **Chapter 1.3**) across national, regional, and local scales. This multi-scale structure illustrates how residential energy transition pathways can be assessed from complementary perspectives, linking national decarbonisation planning with regional resilience implications and local energy justice concerns. In doing so, the dissertation provides a basis for analysing how residential decarbonisation strategies can be designed to remain effective, context-sensitive, and socially inclusive.

The remainder of this chapter summarises the key findings of the dissertation and discusses its main conclusions. In particular, it outlines the implications for practitioners in the fields of policy and practice and highlights the contributions the dissertation makes to the scientific community and the field of energy modelling. Additionally, it addresses the limitations of the research and offers recommendations for future studies.

5.2 Summary of results and key findings

The primary focus of this doctoral dissertation is model-informed policy assessment applied to the residential energy transition. Its main goal is to support decision-making by assessing residential decarbonisation pathways and exploring their implications for energy resilience and energy justice across different governance scales.

The overarching research question (RQ) is:

How can advancements in bottom-up demand-side modelling support the design of energy transition strategies for the residential sector, addressing decarbonisation targets alongside energy resilience, and energy justice implications, while informing policymaking across multiple governance levels?

To address the overarching RQ, the dissertation is structured around three thematic pillars: **(i) decarbonisation**, focusing on the translation of long-term targets into actionable policy pathways; **(ii) energy resilience**, examining the robustness of alternative transition pathways and implications of fossil-fuel dependence and; and **(iii) energy justice**, considering how residential energy transitions can become more inclusive and fair for vulnerable households and communities.

The respective thematic RQs formulated to address these pillars are as follows:

RQ₁: *How can the residential energy transition by 2050 be shaped to meet national and EU decarbonisation targets, and what are the key considerations for achieving these goals?*

RQ₂: *How do nationally defined residential energy transition strategies interact with regional decarbonisation objectives, and what are the implications of this interaction for long-term energy resilience and fossil-fuel dependence?*

RQ₃: *Under what conditions can residential energy transitions in carbon-dependent regions evolve into green, inclusive, and just transition pathways towards 2050?*

The responses to these RQs are provided in **Chapters 2, 3 and 4**. The following sub-chapters present a summary of the results and key findings in relation to the three thematic RQs and the overarching research question that guides them.

5.2.1 Summary per thematic research question

Greece has been selected as the testbed for the application of the modelling framework developed in this dissertation. Greece constitutes a relevant case, as it combines ambitious climate and energy targets with a structurally energy-intensive and ageing residential building stock, as well as a historically high dependence on imported fossil fuels. The revised NECP, adopted in December 2024, places the building

sector at the core of the national decarbonisation strategy, recognising its critical role in achieving energy efficiency improvements, emissions reductions, and long-term climate neutrality objectives (Hellenic Republic- Ministry of Environment and Energy 2024b). In particular, the NECP establishes binding targets for reducing primary energy consumption in residential buildings, scaling up deep renovation rates, and accelerating the replacement of oil and natural gas boilers with low-carbon technologies such as heat pumps.

However, recent developments have demonstrated that residential energy transitions cannot be assessed solely through long-term decarbonisation pathways. Sharp increases in energy prices and supply-related reassessments at the EU level following recent geopolitical developments exposed the vulnerabilities associated with continued reliance on imported fossil fuels, particularly natural gas, thereby highlighting the importance of energy resilience and system robustness in the design of transition strategies (European Commission 2022c; International Energy Agency (IEA) 2023). In this context, policies that promote large-scale building renovations, the electrification of heating, and on-site renewable energy generation are increasingly recognised not only as climate mitigation measures, but also as instruments to strengthen the system's resilience.

At the same time, the implementation of ambitious renovation and electrification targets faces substantial uncertainty related to renovation rates, technology uptake, household heterogeneity, and financing constraints. While the NECP sets quantitative targets and indicative renovation trajectories, these are largely derived from aggregate planning assumptions and do not fully capture the differentiated impacts of policy measures across regions, building typologies, and socio-economic groups. This creates a risk of policy lock-in and uneven outcomes, particularly in a context where past energy policy interventions have led to market distortions and distributional challenges.

Against this backdrop, the thematic research questions addressed in this dissertation aim to support evidence-based, resilient and inclusive energy planning for the residential sector.

RQ1: *How can the residential energy transition by 2050 be shaped to meet national and EU decarbonisation targets, and what are the key considerations for achieving these goals?*

The results indicate that a residential transition pathway centred on natural gas as a transition fuel, combined with relatively modest renovation rates, is not sufficient to achieve full decarbonisation by 2050. Under this pathway, emissions reductions remain constrained, primarily due to the slow pace of renovation and the continued presence of fossil-fuel-based heating technologies in the residential energy mix. As a result, such a pathway risks delaying alignment with national and EU decarbonisation objectives.

Simulation outcomes show that achieving decarbonisation by 2050 requires acceleration of renovation activity. Specifically, the annual renovation rate must increase to approximately 2.5% of the housing stock, corresponding to around 100,000 dwellings undergoing energy renovations per year. If the decarbonisation target is advanced to 2040, the required annual renovation rate increases further to approximately 3.5% of the housing stock, or around 145,000 dwellings per year.

In parallel, the results highlight that pathways prioritising electrification combined with energy efficiency outperform scenarios that rely on an expanded role for natural gas as a transition fuel. Electrification of dwelling heating, supported by building envelope upgrades, emerges as a critical condition for achieving sustained emissions reductions. In contrast, scenarios that maintain or expand gas-based heating systems exhibit higher cumulative emissions and reduced long-term flexibility, increasing the risk of transition lock-ins.

From an economic perspective, the analysis shows that earlier and more ambitious decarbonisation pathways result in lower cumulative expected energy-related costs at the household level over the transition horizon, despite higher upfront investment requirements. This holds even when accounting

for anticipated policy instruments, such as the extension of emissions trading to the building sector. Delayed action, by contrast, leads to higher long-term household expenditures and increased exposure to future policy and price-related uncertainties.

Overall, the analysis demonstrates that meeting national and EU decarbonisation targets in the residential sector is technically feasible but conditional on significantly higher renovation rates, a strategic shift towards electrification, and early implementation of deep efficiency measures. The results underline that pathways relying on incremental renovation progress and transitional fossil-fuel use are insufficient, and that a decisive scaling-up of ambition and implementation is required to align residential energy transitions with long-term climate objectives.

RQ2: *How do nationally defined residential energy transition strategies interact with regional decarbonisation objectives, and what are the implications of this interaction for long-term energy resilience and fossil-fuel dependence?*

The analysis shows that the regional implications of residential energy transition strategies depend not only on national decarbonisation targets, but also on the infrastructure and technology pathways through which these targets are implemented. In the case of the Peloponnese region, this is particularly evident in nationally driven decisions to extend the natural gas distribution network to support residential heating.

Modelling results show that continued investment in natural gas infrastructure limits the region's decarbonisation potential and establishes a new regime of dependence on imported fuels. This pathway increases exposure to external price volatility and geopolitical risks, while constraining the region's ability to transition towards a more resilient and flexible energy system. By contrast, scenarios prioritising early investments in electrification and energy efficiency demonstrate improved outcomes in terms of final energy consumption, fossil fuel use, and emissions reductions by 2050. Despite higher upfront capital costs- particularly for heat pump deployment- electrification-oriented scenarios achieve comparable or lower consumer energy charges over time, largely due to reduced energy consumption and lower cumulative emissions-related costs.

The analysis also highlights the critical role of renovation rates in shaping regional transition outcomes. Even under electrification-focused pathways, the current renovation targets embedded in national planning prove insufficient to deliver full decarbonisation by 2050. This finding underscores the need for closer alignment between national policy objectives and regional implementation capacities. In this context, national decision-making can play a key enabling role by supporting regional authorities in effectively deploying available funding instruments to accelerate deep renovations and the replacement of oil and gas boilers, particularly in older residential buildings.

Overall, the findings challenge the perception that the green energy transition is more expensive than short-term solutions linked to fossil fuels. They show that continued investment in natural gas infrastructure may represent a missed opportunity for the region, as it risks undermining long-term resilience and creating stranded assets.

RQ3: *Under what conditions can residential energy transitions in carbon-dependent regions evolve into green, inclusive, and just transition pathways towards 2050?*

The analysis indicates that residential energy transitions in carbon-dependent regions can evolve into greener, more inclusive, and more beneficial pathways when technology adoption and renovation efforts are directed towards electrification and energy efficiency rather than fossil-fuel-based heating solutions. The case of the coal- and carbon-intensive municipality of Megalopolis illustrates how locally adapted transition pathways can produce differentiated outcomes depending on the assumed evolution of heating technologies and renovation progress.

When transition pathways centred on gas-based heating substitution are simulated, the results indicate higher long-term costs for both households and the municipality, slower progress towards emissions reduction, and continued exposure to fossil-fuel dependence. This is particularly important in the case of Megalopolis, where district heating historically constituted one of the main heating sources for households due to the operation of local lignite power plants. The replacement of this district heating system with fully subsidised gas boilers risks transferring fossil-fuel dependence into the post-lignite period, rather than using the phase-out of lignite as an opportunity to accelerate cleaner residential heating solutions. In this sense, the allocation of Just Transition resources towards gas-based heating substitution can be understood as a missed opportunity to support more transformative alternatives based on electrification and energy efficiency.

By contrast, transition pathways prioritising electrification and energy efficiency measures demonstrate improved outcomes across economic and environmental dimensions. The results show that these pathways reduce final energy consumption, accelerate emissions reductions, and lower total costs at both the municipal and household levels. In particular, the electrification and efficiency pathway deliver cumulative savings of approximately €250 million at the municipal level by 2050 compared to the gas-based transition pathway. At the household level, the same pathway results in savings of more than €60,000 per household by 2050, highlighting the scale of the long-term economic benefits associated with avoiding fossil-fuel-based heating lock-in.

5.2.2. Synthesis addressing the overarching research question

After consolidating the key findings from the three thematic research questions, this section synthesises how the dissertation addresses the overarching research question:

How can advancements in dynamic bottom-up demand-side modelling support the design of energy transition strategies for the residential sector, addressing decarbonisation, energy resilience, and energy justice, while informing policymaking across multiple governance scales?

The findings of this dissertation demonstrate that the applied bottom-up demand-side modelling framework can support residential energy transition policymaking by translating high-level climate and energy objectives into context-sensitive transition pathways. Unlike modelling approaches that represent residential energy demand in an aggregated or “black-box” manner, the framework preserves household- and building-level heterogeneity while enabling the assessment of transition outcomes across multiple spatial scales. In doing so, it strengthens the link between detailed demand-side modelling and the policy levels at which residential energy transition decisions are designed, and implemented.

Residential energy transition pathways are more effectively assessed when decarbonisation, energy resilience, and energy justice are considered together. Meeting emissions reduction targets remains a central objective, while modelling results show that the way this objective is pursued matters significantly. Transition pathways centred on gradual renovation progress and fossil-fuel-based short-term solutions may slow emissions reductions, reinforce dependence on imported fuels, create lock-in risks, and increase long-term affordability pressures for households and communities. By contrast, strategies that combine early electrification, ambitious renovation activity, reduced fossil-fuel dependence, and sensitivity to local conditions can create synergies across these dimensions, supporting transition pathways that are not only lower-carbon, but also more resilient and socially beneficial.

Therefore, residential decarbonisation should not be understood only as a long-term emissions reduction target, but as a transition process whose outcomes depend on the assumed pace of renovation, the

evolution of heating technology uptake, and the way these changes affect energy consumption, emissions, and costs over time.

The three applications demonstrate that residential energy transition strategies need to be assessed as multi-level processes, rather than as pathways defined only through EU or national targets. While national-level analysis is necessary for translating long-term decarbonisation objectives into implementation requirements, such as renovation rates, heating technology substitution trajectories, and policy priorities, it cannot fully capture how these strategies unfold across territories and households. The regional and local analyses show that transition outcomes are shaped by the interaction between national planning specifications and place-specific conditions, including geography, climate, building-stock characteristics, existing heating systems, infrastructure availability, and socio-economic vulnerabilities. This multi-level perspective makes visible potential mismatches between centrally defined strategies and regional or local needs, while clarifying the conditions under which residential decarbonisation pathways can become more resilient, affordable, and context-sensitive.

The policy relevance of the developed framework was further strengthened through its use in structured stakeholder engagement and policy-facing activities carried out in the context of **Horizon 2020** and **LIFE Programme** projects **SENTINEL**¹, **TIPPINGPLUS**², **ENCLUDE**³, **ENPOR**⁴, and **RENOVERTY**⁵. The framework also contributed to the development of the latest Greek Long-Term Renovation Strategy⁶ (2026), while findings from the Peloponnese regional analysis were discussed with regional policy actors, including in the context of the Peloponnese Regional Council. These applications provided opportunities to discuss modelling assumptions, scenario narratives, and transition pathways with policy practitioners, local authorities, civil society actors, and citizens. They therefore demonstrate that the framework can support not only analytical assessment, but also co-produced and policy-relevant decision-making under real-world governance conditions.

5.3. Contribution of the dissertation

In this section, the overall contribution of this Dissertation is summarised across three key fields: energy modelling, policymaking, and the research community.

5.3.1 Contributions to the field of energy modelling

Energy system models play an important role in supporting the assessment of long-term energy transition pathways. In the residential sector, however, modelling approaches often face a trade-off between detail and policy relevance. Highly aggregated models can support national target-setting and system-level analysis, but they often provide limited insight into how transition pathways unfold within the building stock (Chatterjee et al. 2022b; Trutnevyte et al. 2019). Conversely, detailed building-level models can represent household and dwelling characteristics more explicitly, but their outputs are not

¹ [SUSTAINABLE ENERGY TRANSITIONS LABORATORY | SENTINEL](#)

² [Enabling Positive Tipping Points towards clean-energy transitions in Coal and Carbon Intensive Regions | TIPPING.plus](#)

³ [Energy Citizens for Inclusive Decarbonization | ENCLUDE](#)

⁴ [Actions to Mitigate Energy Poverty in the Private Rented Sector | ENPOR](#)

⁵ [Home Renovation Roadmaps to Address Energy Poverty in Vulnerable Rural Districts | RENOVERTY](#)

⁶ <https://ypen.gov.gr/dimosia-ilektroniki-diavoulefsi-gia-to-schedio-ypourgikis-apofasis-tou-ypourgeiou-perivallontos-kai-energeias-ekthesi-makroprothesmis-stratigikis-anakainisis-tou-dimosiou-kai-idiotikou-ktiria/>

always translated into indicators that are directly useful for policy assessment across national, regional, and local scales (Mastrucci et al. 2023; Pfenninger, Hawkes, and Keirstead 2014).

This dissertation contributes to demand-side energy modelling by developing additional capabilities within the DREEM framework that enable the assessment of residential energy transition pathways over time and across spatial scales, while building on its existing high-resolution representation of residential energy demand. This contribution is realised through two main methodological developments: first, the development of a multilevel upscaling approach that links household- and building-level demand simulations with local, regional, and national residential building stocks; and second, the development of a transition matrix that allows alternative transition scenarios to be represented and adjusted over time.

The first contribution concerns the scale-bridging representation of residential energy demand. Through the newly developed “C₈: Multilevel Upscaling” component, the dissertation modelling frameworks can aggregate simulated household-level energy demand to higher spatial levels using datasets and census-based information on household numbers, building typologies, occupancy characteristics, and existing heating technologies. This allows the same modelling logic to be applied at different scales: the Greek residential sector in **Chapter 2**, the Peloponnese region in **Chapter 3**, and the municipality of Megalopolis in **Chapter 4**. The contribution lies in maintaining the connection between detailed residential demand simulations and aggregate policy-relevant outcomes, rather than treating national, regional, or local residential demand as a single homogeneous block.

The second contribution concerns the representation of residential transition pathways over time. Through the “C₉: Transition Matrix” component, the dissertation operationalises the unfolding of different transition pathways by linking scenario assumptions on renovation rates and heating technology substitution with the evolution of key parameters, including energy prices, technology costs, emission factors, population trends, construction and demolition rates, and policy-related costs such as ETS2-related costs. The component supports both forecasting and backcasting approaches, allowing the analysis to explore the implications of predefined policy and technology assumptions up to a specified target year, as well as to identify the transition effort required to meet a specific decarbonisation target within a defined time period.

These methodological developments are applied across the three applications of the dissertation. At the national level, the framework is used to identify combinations of renovation rates and heating technology substitution pathways that can deliver residential decarbonisation in Greece by 2050 or, under a more ambitious pathway, by 2040. At the regional level, it is used to assess how natural gas expansion and electrification-oriented alternatives affect energy consumption, emissions, fossil-fuel dependence, and household costs. At the local level, it is used to compare the gas-based replacement of lignite-linked district heating with electrification- and efficiency-oriented alternatives in a CCIR, quantifying their implications for municipal and household costs and emissions, while supporting the interpretation of long-term fossil-fuel dependence and place-based rebranding.

Overall, the dissertation contributes to the field of energy modelling by strengthening the link between residential demand-side modelling and the assessment of long-term energy transition strategies. The developed framework supports transition pathway assessment across multiple governance levels. Its added value lies in its ability to connect detailed assumptions about buildings, households, heating systems, and energy efficiency measures with policy-relevant indicators such as decarbonisation feasibility, renovation requirements, cumulative costs and household-level affordability impacts.

5.3.2. Contribution to the field of policymaking

Beyond its technical contributions to the field of energy modelling, this dissertation provides policy-relevant insights for decision-makers and practitioners involved in the design and implementation of residential energy transition strategies. Its policy relevance is grounded in the modelling outcomes of the three applications, as well as in the use of the developed framework in policy-facing contexts, including its contribution to the development of the latest Greek Long-Term Renovation Strategy and the discussion of the Peloponnese regional analysis with regional policy actors, in the context of the Peloponnese Regional Council.

The insights presented in this section are synthesised with a focus on the Greek context across the three governance levels under study, national, regional, and local.

Implications for Greece

National level

- i. **National residential energy transition planning should recalibrate renovation ambition in line with climate-neutrality objectives.** Modelling results indicate that, if climate neutrality by 2050 is the objective, the annual renovation rate should increase to approximately 2.5% of the housing stock, corresponding to around 100,000 dwellings per year. A more ambitious pathway aiming for climate neutrality by 2040 would require renovation rates of approximately 3.5%, or around 145,000 dwellings per year. These requirements should be operationalised through the NBRP and reflected in the scale, sequencing, and eligibility criteria of national renovation support schemes.
- ii. **Electrification and energy-efficiency-first strategies in the residential sector should be prioritised over the expansion of fossil fuel use and infrastructure.** National and regional planning that continues to support gas-based heating or new gas networks risks creating long-term fossil-fuel lock-ins, increased import dependency, and potential stranded assets, particularly under tightening EU climate policy, building-sector carbon pricing, and the application of the Energy Efficiency First principle in investment decisions. The modelling evidence shows that early electrification combined with energy efficiency delivers decarbonisation, reduced fossil-fuel use, and lower cumulative household costs over time.
- iii. **Public funding frameworks should be redirected towards integrated electrification and deep renovation packages.** National and EU funding instruments, including programmes such as “Exoikonomo” and “Anakainizo”, should prioritise comprehensive packages that combine building envelope upgrades, heat pumps, and, where appropriate, renewable self-consumption, rather than fragmented measures or investments that prolong fossil-fuel use. Priority should be given to dwellings constructed before 2000, worst-performing buildings, and households with limited capacity to finance upfront investments. Allocations from the Social Climate Fund should be directed towards these structural measures, so that public support reduces long-term energy costs rather than mainly compensating households after affordability pressures have already emerged.
- iv. **ETS2 should be anticipated as a structural driver of residential energy policy, not only as a compliance obligation.** The modelling results indicate that, under building-sector carbon-pricing trajectories, pathways prioritising early electrification and deep renovation lead to lower cumulative household energy-related charges than delayed or gas-based transition strategies. National policy should therefore use the introduction of ETS2 to accelerate demand-side transformation in the residential sector. ETS2 revenues, together with Social Climate Fund resources, should be leveraged to finance electrification and deep renovation measures, with targeted support for vulnerable households. This should be accompanied by advisory services and awareness campaigns that

communicate the long-term cost risks of fossil-fuel heating and the comparative benefits of early action.

v. **The implementation of the recast EPBD should be used to strengthen regulatory coherence and delivery capacity.** Greece should use its NBRP as a central instrument for strengthening regulatory coherence and delivery capacity in the residential sector, provide a clear roadmap for residential decarbonisation, renovation targets and requirements, investment needs, and financing instruments consistent with long-term climate-neutrality objectives. The roadmaps and associated regulatory implications should be closely aligned with financial support schemes, ensuring that programmes such as “Exoikonomo” reduce compliance costs and incentivise early, standards-consistent renovations. This would help avoid incremental upgrades that improve performance only partially while leaving households exposed to future regulatory and cost pressures.

vi. **A robust national building-stock data infrastructure should be established to support targeted and equitable implementation.** Achieving higher renovation rates and directing support where it is most needed requires a more integrated evidence base on the residential building stock. Energy Performance Certificates, renovation histories, heating system information, and future renovation passports should be integrated into a unified national database. Such an infrastructure would support the identification of worst-performing buildings, improve the targeting of public funding, facilitate the enforcement of Minimum Energy Performance Standards, and strengthen the design of energy-efficiency obligation schemes. It would also allow policy support to be directed more effectively towards high-impact dwellings and vulnerable households.

vii. **Energy-poverty policy should progressively shift from short-term compensation toward structural solutions.** While consumer-protection measures such as social tariffs and regulatory safeguards remain essential, national policy should increasingly prioritise deep renovation, electrification, and renewable self-consumption for energy-poor households. Existing instruments, including “Exoikonomo”, “Photovoltaics on the Roof”, and Energy Efficiency Obligation Schemes, should be adapted to target worst-performing dwellings and vulnerable households, enabling combined photovoltaic (PV)- heat pump solutions, and reducing long-term exposure to energy price volatility.

viii. **Awareness campaigns and advisory services should support households in making forward-looking heating and renovation decisions.** Residential transition outcomes depend not only on policy targets and funding availability, but also on household decisions regarding heating technologies and renovation investments. National authorities should develop targeted awareness campaigns and advisory services that clearly communicate the long-term cost risks of fossil-fuel heating under ETS2, the possibility of stranded household heating investments, and quantified comparative benefits of electrification and energy-efficiency upgrades. These initiatives should be linked to existing support schemes, so that households, especially those with limited economic capacity, are not only informed about future risks but also supported in taking timely action.

Regional and Local levels

i. **Use territorial evidence to advocate for national schemes that fit regional and local transition needs.** Although the main residential energy policy framework is largely defined at the national level, regional and local authorities are better positioned to identify the specific conditions that shape implementation within their territories. They should therefore assess building-stock characteristics, heating needs, existing infrastructure, climate conditions, and socio-economic vulnerabilities, and use this evidence to advocate for national and EU support schemes that are adapted to their context. This

would help avoid uniform policy measures that may appear coherent at the national level but produce less effective or less affordable outcomes when applied in regions with different needs and constraints.

ii. Assess proposed energy infrastructure investments against decarbonisation, affordability, and fossil-fuel dependence risks. Before supporting or facilitating new energy infrastructure, regional and local authorities should assess whether such investments are consistent with long-term decarbonisation objectives and with the needs of their territories. The analysis of the Peloponnese region shows that extending natural gas distribution networks for residential heating can lead to higher cumulative household costs, weaker decarbonisation outcomes and continued fossil-fuel dependence, compared to electrification- and efficiency-oriented alternatives. Regional and local authorities should therefore evaluate infrastructure proposals not only in terms of short-term feasibility or access to heating options, but also in terms of their long-term implications for household affordability, exposure to imported fuels, carbon-pricing risks, and potential lock-in effects.

iii. Target renovation and heating support towards worst-performing dwellings and vulnerable households. Regional and local authorities can add value to national support schemes by helping identify where intervention is most urgent and where public funding can deliver the greatest benefits. In practice, this means prioritising dwellings with poor energy performance, households exposed to high heating costs, and areas where socio-economic vulnerabilities increase the risk of energy poverty. By supporting the targeting of renovation and heating replacement measures towards these groups, regional and local authorities can help ensure that national funding is used to reduce long-term affordability pressures rather than mainly benefiting households already able to invest. This is particularly important in structurally vulnerable and post-lignite territories, where residential energy transition policies need to address both decarbonisation and household affordability issues.

iv. Use awareness campaigns and quantified evidence to support informed household decision-making. Awareness efforts should go beyond general communication about the benefits of renovation and electrification. Regional and local authorities should use scientifically validated quantified evidence to help households understand the expected long-term implications of different heating and renovation choices. This includes communicating potential energy-cost savings, renovation and technology costs, emissions reductions, exposure to fossil-fuel price volatility, and future carbon-pricing costs under ETS2. Presenting this information in locally relevant and accessible formats can help households compare fossil-based and electrification-oriented options more clearly. Such awareness campaigns are particularly important for preventing short-term decisions, such as investment in gas-based heating systems, that may appear affordable today but expose households to higher costs and transition risks over time.

v. Act as implementation intermediaries between national support schemes and households. Even when national renovation and electrification schemes are available, their effectiveness depends on whether households can access and use them in practice. Regional and local authorities can help translate national policy instruments into territorial implementation by supporting households with application procedures, coordinating with engineers, installers, energy communities, and financial institutions, and identifying local barriers that prevent uptake. This role is particularly important in areas where limited administrative capacity, low incomes, fragmented ownership structures, or lack of technical support may delay renovation and heating replacement decisions. By reducing the gap between national scheme design and household-level implementation, regional and local authorities can improve the actual delivery of residential transition measures.

vi. Monitor implementation barriers and feed evidence back into national policy design. Regional and local authorities are well positioned to observe how residential transition policies

operate in practice. They should systematically monitor uptake of renovation and heating replacement schemes, identify administrative, financial, technical, and social barriers, and assess whether support reaches worst-performing dwellings and vulnerable households. This evidence should be communicated back to national authorities to improve the design of future programmes, eligibility criteria, funding levels, and advisory services. In this way, regional and local authorities can help create a feedback loop between policy implementation and policy revision, ensuring that national residential energy transition schemes remain responsive to territorial realities.

vii. Align residential heating transitions with broader territorial transformation strategies.

Residential heating transitions should not be treated only as technical substitutions of one heating system with another. At the regional and local levels, the direction of heating decarbonisation can support broader territorial transformation by contributing to a cleaner local identity, the development of green skills and services, the uptake of complementary technologies such as rooftop PVs, storage, and electric vehicles, and the positioning of regions and municipalities around sustainability-oriented development. Electrification and energy efficiency can therefore become part of a wider strategy for regional rebranding and local development, including in areas seeking to attract new economic activities, strengthen sustainable tourism, or reduce dependence on legacy fossil-fuel infrastructures. Regional and local authorities should use residential transition planning to connect household-level decarbonisation with these wider development priorities, ensuring that heating choices support long-term territorial resilience and a more sustainable economic profile.

Building on the national, regional, and local applications in Greece, the dissertation identifies broader lessons/ implications at the EU level. The Greek cases provide a useful basis for this reflection because residential decarbonisation in Greece is shaped by the same EU-level objectives, funding mechanisms, and regulatory pressures that influence building-sector transitions across Member States.

EU level

i. Strengthen the implementation credibility of NBRPs and NECPs through transparent, quantified pathway assessments. EU planning instruments should not only define long-term targets, but also demonstrate how these targets can be delivered in practice. Member States should be encouraged to support their NBRPs and NECPs with assessments that quantify the renovation effort, heating technology substitution pathways, investment needs, emissions reductions, household cost implications, and exposure to carbon-pricing risks. This would improve the transparency of national planning assumptions and help ensure that building-sector strategies are credible from an implementation, affordability, and long-term decarbonisation perspective.

ii. EU building and heating policy should close remaining funding and legislative windows that allow fossil-based transitional lock-ins. Although EU policy increasingly limits support for fossil-fuel heating, residual flexibility in funding and implementation frameworks can still allow public resources to support gas infrastructure or gas-based heating replacement. The dissertation shows that such choices, including the use of Just Transition resources to replace lignite-linked district heating with subsidised gas boilers, may reduce short-term implementation pressures but create adverse long-term effects. These include higher cumulative costs, prolonged fossil-fuel dependence, and delayed deployment of alternatives based on electrification and energy efficiency. EU funding rules and implementation guidance should therefore more clearly ensure that transitional support does not finance solutions that are likely to become inconsistent with long-term decarbonisation, resilience, and affordability objectives.

iii. EU guidance for Social Climate Plans should prioritise structural measures that reduce long-term household exposure to ETS2 costs. At EU level, the key role is to ensure that Social Climate Plans do not rely predominantly on temporary compensation, but support measures that reduce households' future exposure to fossil-fuel and carbon-pricing costs. EU guidance and assessment criteria should therefore encourage Member States to prioritise investment-based measures, such as renovation, heat pumps, and renewable generation and self-consumption, especially for vulnerable households and worst-performing dwellings. Temporary income support may be necessary to address immediate affordability pressures, but EU-level monitoring should ensure that it complements rather than substitutes structural demand-side measures that reduce energy demand, fossil-fuel dependence, and long-term vulnerability.

iv. Strengthen the territorial and social targeting of EU building renovation policy. EU building renovation policy already recognises the importance of supporting vulnerable households and worst-performing buildings. The next step is to ensure that funding allocation and programme assessment are more clearly linked to expected outcomes, including emissions reduction, long-term affordability improvements, fossil-fuel phase-out, and support for households with limited capacity to invest. EU funding instruments should therefore incentivise Member States to design renovation and heating programmes that demonstrate where public support can deliver the highest combined social and climate value, rather than relying mainly on broad eligibility criteria or demand-driven applications.

v. Improve civic and stakeholder engagement in residential transition planning. Existing EU instruments require consultation with regional and local authorities, social partners, civil society, and other stakeholders. The priority should therefore be to ensure that this engagement is not only procedural, but also substantively informs the design of residential transition pathways, funding priorities, and implementation measures. EU guidance could encourage Member States to use quantified evidence, territorial assessments, and locally grounded scenario discussions in consultation processes, so that stakeholders can evaluate the long-term cost, emissions, affordability, and fossil-fuel dependence implications of alternative heating and renovation pathways. This would help make residential transition planning more transparent, socially credible, and locally implementable.

5.3.3. Contribution of the dissertation thesis to the fields of research and academia

Contributing to the research community, this dissertation concludes with the publication of:

1. Six (6) scientific articles in peer-reviewed journals with impact factor (IF), as presented in **Table 5.1**.
2. Twenty-two (22) announcements in international peer-reviewed conferences,
3. Fifteen (15) technical reports and other studies.

Table 5.1. List of peer-reviewed journals in which the PhD candidate has published scientific articles during the dissertation.

Journal	Publisher	IF*	Number of published articles
Energy Conversion and Management	Elsevier	10.9	1
Energy	Elsevier	9.4	1
Energy Research and Social Science	Elsevier	7.4	1
Environmental Innovation and Societal Transitions	Elsevier	6.1	1
Sustainability	MDPI	3.3	1

*As accessed on the 22nd of December 2025

Finally, the methodological and modelling frameworks presented in this dissertation have laid the groundwork for new researchers that pursue their PhD thesis.

Until the time of the defense of this dissertation, the PhD candidate has an overall of 67 citations and an h-index of 3 according to the “Scopus”⁷ database, and an overall of 103 citations and an h-index of 4, based on the “Google Scholar”⁸ database. A detailed overview of the scientific publications and technical reports that the PhD candidate has published and contributed to is presented in **Appendix 2**.

5.4. Limitations and potential for further research

This section discusses the main limitations of the framework introduced in this dissertation and outlines directions for future research. The dissertation developed additional capabilities within the DREEM modelling framework, notably the “C₈: Multilevel Upscaling” and “C₉: Transition Matrix” components, to support the assessment of residential energy transition pathways across time horizons and spatial scales. As with any modelling framework, these developments involve methodological choices regarding the level of detail represented, the treatment of heterogeneity, the use of exogenous assumptions, and the balance between transparency, scalability, and policy relevance.

A key methodological consideration relates to the “C₈: Multilevel upscaling” component, which enables the aggregation of residential energy demand from the household level to regional and national levels. By building on detailed bottom-up information, such as building characteristics, occupancy patterns, working schedules, thermal comfort levels, this component allows higher-level analyses to reflect household-level transition dynamics. This scale-bridging approach ensures that insights derived at regional and national levels remain grounded in micro-level realities, addressing a key limitation of purely top-down modelling approaches that rely on highly aggregated assumptions.

However, the current methodology of the dissertation’s framework preserves heterogeneity only to the extent allowed by the selected typologies and the available statistical data. While this supports transparent and computationally manageable multilevel analysis, it may abstract from intra-typology variation, locally specific heating practices, and other contextual factors that can influence transition outcomes. Future research could address this limitation by developing more adaptive typology structures, in which representative household and building categories can be further differentiated when local data indicate meaningful variation. This would allow the upscaling process to remain transparent and scalable, while improving its sensitivity to local implementation conditions.

Another methodological consideration concerns the “C₉: Transition Matrix” component, which provides a time-explicit representation of residential energy transition pathways. By describing how households move between different heating technologies, fuels, and renovation states over successive periods, under alternative policy contexts, this component allows the analysis to examine how transition outcomes evolve over time. In this way, it supports the assessment of the pace of renovation, heating technology substitution, fossil-fuel phase-out, emissions reductions, and cost evolution across different residential transition scenarios.

Under the current formulation, transition pathways are driven by exogenous assumptions and policy signals, with transition rates calibrated using empirical evidence, expert and stakeholder input, and alignment with relevant targets. While this supports transparent exploration of policy-conditioned transition trajectories, it abstracts from several real-world constraints that shape how transitions unfold

⁷ [Papantonis, Dimitris - Author details - Scopus Preview](#)

⁸ [Dimitris Papantonis - Google Scholar](#)

in practice. These include limitations in funding availability, household investment capacity, skilled labour for renovations and heating system replacement, supply-chain constraints, administrative bottlenecks, rebound effects, and regulatory delays. Future methodological extensions could allow transition dynamics to respond more explicitly to cumulative uptake, technology learning, market development, and capacity constraints. This would make it possible to distinguish more clearly between pathways that are technically sufficient to meet decarbonisation targets and pathways that are feasible within specific institutional, market, and implementation conditions.

A broader area for methodological development concerns the integration of residential demand-side transition pathways with wider system, macroeconomic, and socioeconomic dynamics. The current framework represents residential demand, heating technology substitution, renovation pathways, emissions, and household-level costs in detail. However, electricity generation expansion, grid reinforcement, system flexibility requirements, infrastructure investment needs, macroeconomic conditions, and socioeconomic change are treated mainly as external assumptions rather than as endogenous processes that co-evolve with residential transition pathways. This modelling choice reflects the dissertation's focus on demand-side implementation, but it may limit the ability to fully assess how residential electrification, renovation, and fossil-fuel phase-out interact with system readiness, regional economies, household vulnerability, and the distribution of transition costs and benefits over time.

Future research could address this limitation by soft-linking the developed framework with supply-side, power system, macroeconomic, and socioeconomic models. Coupling with power system models would allow residential electrification pathways to be assessed jointly with generation expansion, network constraints, flexibility requirements, infrastructure adequacy, investment needs, and cost allocation. This would make it possible to identify potential bottlenecks, timing mismatches between demand growth and system readiness, and system-level trade-offs, for example under deep electrification scenarios. In parallel, linking the framework with macroeconomic and socioeconomic modelling would allow employment effects, income evolution, regional economic impacts, and household investment capacity to be examined alongside energy demand, emissions, and cost outcomes.

Such integration would strengthen the framework's ability to assess decarbonisation, energy resilience, and energy justice in a more connected way. It would allow future applications to examine whether electrification pathways are compatible with power system development, how reduced fossil-fuel dependence interacts with infrastructure adequacy and price exposure, and how transition costs and benefits are distributed across households, regions, and socio-economic groups over time. This would move the framework beyond demand-side pathway assessment towards an integrated analysis of residential energy transitions within broader energy system and territorial transformation processes.

A further promising direction for future development concerns the use of artificial intelligence (AI)-based techniques to complement the developed framework. AI methods could be trained on a large number of simulation runs produced by the dissertation's framework, covering different combinations of renovation rates, heating technology substitution pathways, energy prices, technology costs, emission factors, policy assumptions, and household typologies. Surrogate models or machine learning emulators could then provide selected model outputs, such as final energy consumption, emissions, renovation costs, fuel costs, ETS2-related costs, and household-level charges, with significantly lower computational time.

Such AI-supported tools could also improve the usability of the framework for policymakers by enabling interactive scenario exploration. For example, decision-makers could adjust key assumptions, such as renovation rates, heat pump uptake, fossil-fuel phase-out timing, or energy price trajectories, and rapidly observe the expected implications for emissions, costs, and household affordability. In this way, AI-based techniques could support faster policy screening, more accessible communication of

modelling results, and more iterative engagement with stakeholders, while preserving the detailed bottom-up simulations as the basis for training and validation.

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Appendix D. Contribution of the PhD candidate to academic material

Scientific articles published in peer-reviewed journals

1. **Papantonis, D.**, Stavrakas, V. and Flamos, A. (2026) ‘Modelling in support of community-empowered energy transitions: Transforming a coal- and carbon-intensive region into a municipality of energy citizens’, *Environmental Innovation and Societal Transitions*, 59, p. 101079. Available at: <https://doi.org/10.1016/j.eist.2025.101079>
2. **Papantonis, D.**, Stavrakas, V., Burbidge, M., Bouzarovski, S., & Flamos, A. (2025). Addressing energy poverty in the private rented sector across Europe: A comprehensive analysis of over 100 policies through the lens of energy justice. *Energy Sources, Part B: Economics, Planning, and Policy*, 20(1). <https://doi.org/10.1080/15567249.2025.2558542>
3. **Papantonis, D.**, Stavrakas V., Oikonomou V., and Flamos, A. (2025). “Expanding Natural Gas Infrastructure in Greece: Good Practice or Missed Opportunity of a Green and Inclusive Transition?” *Energy* 326:136314. <https://doi.org/10.1016/j.energy.2025.136314>
4. **Papantonis, D.**, Stavrakas V., Tzani D., and Flamos, A. (2025). “Towards Decarbonisation or Lock-in to Natural Gas? A Bottom-up Modelling Analysis of the Energy Transition Ambiguity in the Residential Sector by 2050.” *Energy Conversion and Management* 324:119235. <https://doi.org/10.1016/j.enconman.2024.119235>
5. **Papantonis, D.**, Tzani D., Burbidge M., Stavrakas V., Bouzarovski S., and Flamos A. (2022), “How to improve energy efficiency policies to address energy poverty ? Literature and stakeholder insights for private rented housing in Europe,” *Energy Res. Soc. Sci.*, vol. 93, no. September, p. 102832, doi: <https://doi.org/10.1016/j.erss.2022.102832>
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Scientific articles currently under revision in peer-reviewed journals

Kleanthis N., Stavrakas, V., **Papantonis D.**, Flamos A., Green transition reforms in Greece: Evaluating the effectiveness of the National Recovery and Resilience Plan in boosting employment and investments towards carbon neutrality, under review in *Energy Policy* (Elsevier).

Working scientific articles to be soon submitted in peer-reviewed journals

1. **Papantonis D.**, Tourkolias C., Oikonomou V., Stavrakas V, Flamos A., Towards better energy-efficiency policy implementation and alleviation of energy poverty: Introducing the “ENPOR” tool to quantify implications of the split incentive barrier in the European Union’s Private Rented Sector to be submitted in *Energy Research and Social Science* (Elsevier).
2. Apostoliotis A., **Papantonis D.**, Peretto M. Bouzarovski S., Flamos A., Updating the Energy Poverty and Energy Efficiency Framework in Rural Areas Across the EU- Literature review and stakeholder insights, to be submitted in *Energy Research and Social Science* (Elsevier).
3. Stavrakas V., **Papantonis D.**, Apostoliotis A., Flamos A., Advancing integrated renovation packages for efficient, sustainable, and inclusive energy use: A European perspective to be submitted in *Smart Energy* (Elsevier).
4. Apostoliotis A., **Papantonis D.**, Stavrakas V., Flamos A., Energy efficiency policy to alleviate rural energy poverty across the EU: Insights from demand-side modelling addressing the needs of rural households, to be submitted in *Energy Conversion and Management* (Elsevier).

Announcements in conferences

1. Anagnostopoulou, C., **Papantonis, D.**, Tzani, D., Stavrakas, V., & Flamos, A. (2026), Support of real-world building renovation planning at the national level: Bottom-up demand-side modelling of decarbonisation pathways by 2050 in the residential sector, 44th International Energy Workshop (IEW), 22-24 June 2026, Cape Town, South Africa.
2. Anagnostopoulou, C., **Papantonis, D.**, Tzani, D., Stavrakas, V., & Flamos, A. (2025), Towards deep cuts in emissions in the residential sector by 2050: Bottom-up demand-side modelling in support of real-world policymaking at the national level, 18th Integrated Assessment Modelling Consortium (IAMC) Annual Meeting, 11-13 November 2025, Armação dos Búzios, state of Rio de Janeiro, Brazil.
3. Stavrakas, V., Kleanthis, N., Fragkos, P., Zamanipour, B., Johannsen, R.M., Zisarou, E., **Papantonis, D.**, Yuan, M., Maheshwari, J., Ahmadi, F., Thellufsen, J.Z., Keppo, I., Vishwanathan, S.S., & Flamos, A. (2025), Top-down and bottom-up modelling of current and future decarbonisation trends in the buildings sector

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4. Stavrakas, V., Kleanthis, N., Fragkos, P., Zamanipour, B., Johannsen, R.M., Zisarou, E., **Papantonis, D.**, Yuan, M., Maheshwari, J., Ahmadi, F., Thellufsen, J.Z., Keppo, I., Vishwanathan, S.S., & Flamos, A. (2025), Top-down and bottom-up modelling of current and future decarbonisation trends in the buildings sector across different scales and contexts, *European Climate and Energy Modelling Platform (ECEMP) Annual Conference*, 16-17 October 2025, Brussels, Belgium.
 5. Apostoliotis, A., **Papantonis, D.**, Flamos, A. (2025), A modelling-based approach to rural energy poverty: evaluating energy efficiency solutions in seven EU countries, *European Conference of the EC4RURAL project - Rural energy communities: Bridging local action and clean energy transition*, 01 October 2025, Vigo, Spain
 6. **Papantonis, D.**, Apostoliotis, A., Flamos, A. (2025), Promoting evidence-based energy transition policies in rural EU regions: a bottom-up demand-side modelling analysis of real-life residential pilots, *European Climate & Energy Modelling Platform (ECEMP) Annual Conference 2025*, 16-17 October 2025, Brussels
 7. Apostoliotis, A., **Papantonis, D.**, Flamos, A. (2025), Energy efficiency policy to alleviate rural energy poverty across the EU: Insights from demand-side modelling addressing the needs of rural households, *World Sustainable Energy Days 2025- Young researchers conference* 05-07 March 2025, Wels/Austria
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 9. **Papantonis, D.**, Stavrakas, V., Flamos, A., Data-driven bottom-up demand-side management modelling towards integrated and smart renovation packages for efficient, sustainable, and inclusive energy use in real-life residential pilots across the European Union, *European Climate & Energy Modelling Platform (ECEMP) Conference 2024*, 16-17 October 2024, Brussels
 10. Stavrakas, V., **Papantonis, D.**, Oikonomou, V., & Flamos, A. (2024), Advancing integrated and smart renovation packages for efficient, sustainable, and inclusive energy use: Modelling of real-life residential buildings, *10th International Conference on Smart Energy Systems (SESAAU 2024)*, 10-12 September 2024, Aalborg, Denmark.
 11. **Papantonis, D.**, Apostoliotis, A., Peretto, M., Bouzarovski, S., Flamos, A. (2024), Towards the improvement of the energy poverty and energy efficiency policy implementation framework in rural and suburban areas across Europe, *European Council for an Energy Efficient Economy (ECEEE) Annual Conference*, 10-15 June 2024, Center Parcs Lac d'Ailette, France.
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