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"Exploratory assessment of adaptive pathways toward renewable energy systems: A modelling framework facilitating decision making under deep uncertainty"

Doctoral dissertation

by

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Athens, April 2024
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Περίληψη

Η συχνότητα αναθεώρησης της Ευρωπαϊκής ενεργειακής και κλιματικής πολιτικής, είναι αποτέλεσμα της προσπάθειας εναρμονισμού της με αβέβαιες εξελίξεις, όπως η επίδραση της ανθρώπινης δραστηριότητας στην κλιματική αλλαγή, οι γεωπολιτικές εντάσεις ή οι χρηματιστηριακές τιμές ενέργειας. Εν μέσω τέτοιων αβεβαιοτήτων, τα κράτη μέλη συναντούν δυσκολίες ως προς τον σχεδιασμό των εθνικών τους συνεισφορών μέσω των Εθνικών Σχεδίων για την Ενέργεια και το Κλίμα, διότι εκτός από εντατικοποίηση των στόχων καθαρής ενέργειας, οι αναθεωρήσεις των Ευρωπαϊκών στρατηγικών και κανονισμών μπορεί να περιέχουν διαρθρωτικές αλλαγές, όπως η μείωση της χρήσης φυσικού αερίου ως ενδιάμεσο καύσιμο κατά την ενεργειακή μετάβαση. Κατά συνέπεια, τα κράτη μέλη, όχι μόνο πρέπει να επιλέξουν ένα νέο τεχνολογικό μονοπάτι, αλλά πρέπει να πάρουν και αποφάσεις για επενδύσεις που έχουν ήδη ξεκινήσει και ενδέχεται να έρχονται σε αντίθεση με την επικαιροποιημένη στρατηγική της Ευρωπαϊκής Ένωσης.

Λαμβάνοντας υπόψη σημαντικές αβεβαιότητες που αντιμετώπισε η Ευρωπαϊκή Ένωση τα τελευταία χρόνια (όπως η οικονομική κρίση, η πανδημία COVID-19 και η ενεργειακή κρίση του 2022), γίνεται εμφανές ότι ο ενεργειακή πολιτική/στρατηγική και τα αντίστοιχα ενεργειακά μοντέλα που την υποστηρίζουν, πρέπει να απομακρυνθούν από προβλέψεις που βασίζονται σε βελτιστοποιήσεις υπό γραμμικές υποθέσεις. Αντίθετα, τόσο τα μοντέλα όσο και οι ενεργειακές στρατηγικές/πολιτικές, θα πρέπει να χαρακτηρίζονται από ικανότητα προσαρμογής σε περιπτώσεις πραγματοποίησης μη-γραμμικών εξελίξεων. Αυτή είναι η περίπτωση της **διερευνητικής αξιολόγησης προσαρμοστικών μονοπατιών για την μετάβαση σε συστήματα ανανεώσιμων πηγών ενέργειας (ΑΠΕ) υπό συνθήκες μεγάλης αβεβαιότητας**.

Σκοπός της παρούσας διδακτορικής διατριβής είναι η ανάπτυξη ενός πλαισίου μοντελοποίησης το οποίο:

- Πραγματοποιεί διερευνητική αξιολόγηση διαφόρων πολιτικών/στρατηγικών προς ενεργειακά συστήματα πλούσια σε ΑΠΕ, για τον εντοπισμό εκείνων που αποδίδουν καλύτερα, καθορίζοντας παράλληλα εναλλακτικές πολιτικές/στρατηγικές για την αντιμετώπιση συνθηκών αβεβαιότητας.
- Υποστηρίζει τον προσαρμοστικό σχεδιασμό μονοπατιών ενεργειακής μετάβασης, καθορίζοντας γιατί και πότε πρέπει να γίνει αλλαγή πολιτικής/στρατηγικής, καθώς και ποιες πολιτικές/στρατηγικές είναι ευάλωτες σε συγκεκριμένες αβεβαιότητες. Με αυτό τον τρόπο γίνεται εμφανές τι πρέπει να παρακολουθείται κατά την υλοποίηση των ενεργειακών στρατηγικών/πολιτικών, δίνοντας την δυνατότητα στους υπευθύνους χάραξης πολιτικής και στρατηγικής να παρακολουθούν συστηματικά την απόδοση των επιλογών τους, και να ενσωματώνουν διορθωτικές κινήσεις σε μελλοντικές αποφάσεις.

- Υποστηρίζει την σταδιακή εφαρμογή πολιτικών/στρατηγικών και την αξιολόγηση των αποτελεσμάτων τους πριν την λήψη μακροπρόθεσμων αποφάσεων. Με αυτό τον τρόπο, η χάραξη μονοπατιών πολιτικής είναι διαδραστική, και επιτυγχάνεται στενή συνεργασία μεταξύ μοντέλου και υπεύθυνου χάραξης πολιτικής/στρατηγικής.

Με βάση τα παραπάνω, η διδακτορική διατριβή απαντάει στο εξής κύριο ερευνητικό ερώτημα: ***«Πως μπορούν τα ενεργειακά μοντέλα να υποστηρίξουν την διερευνητική αξιολόγηση προσαρμοστικών μονοπατιών για την μετάβαση σε συστήματα ανανεώσιμων πηγών ενέργειας υπό συνθήκες μεγάλης αβεβαιότητας;»***

Συγκεκριμένα, αναλύονται τρία καίρια ζητήματα για την μετάβαση προς ενεργειακά συστήματα πλούσια σε ΑΠΕ:

- Ενεργός συμμετοχή των πολιτών στην ενεργειακή μετάβαση.
- Ελαχιστοποίηση περικοπών ανανεώσιμης ενέργειας.
- Βιωσιμότητα του ενεργειακού συστήματος υπό συνθήκες αβεβαιότητας.

Η εφαρμογή του πλαισίου μοντελοποίησης στην μελέτη περίπτωσης της μετάβασης του συστήματος παραγωγής ηλεκτρικής ενέργειας της Ελλάδας, επέτρεψε την αξιολόγηση της πληρότητας και της αξιοπιστίας των αποτελεσμάτων που παρέχει. Συγκεκριμένα, αρχικά αξιολογήθηκαν πολιτικές για την εμπλοκή των πολιτών σε επενδύσεις ΑΠΕ μικρής κλίμακας. Στην συνέχεια αναλύθηκαν μίγματα ΑΠΕ και αποθήκευσης τα οποία ελαχιστοποιούν τις περικοπές ενέργειας, εντοπίζοντας εκείνα που πετυχαίνουν ελάχιστο κόστος ενσωμάτωσης της ενέργειας ΑΠΕ στο μίγμα ηλεκτροπαραγωγής. Τέλος, μελετήθηκαν ενεργειακά μίγματα τα οποία αποσυνδέουν την ηλεκτροπαραγωγής της Ελλάδας από το φυσικό αέριο, ενώ ταυτόχρονα πετυχαίνουν τους στόχους εκπομπών άνθρακα και ανανεώσιμης ενέργειας, με οικονομικά αποδοτικό τρόπο. Συνολικά, οι προσεγγίσεις μοντελοποίησης που αναπτύχθηκαν βελτιώνουν τα υφιστάμενα υπολογιστικά εργαλεία προσομοίωσης, αναδεικνύοντας ενεργειακές στρατηγικές και πολιτικές οι οποίες αποδίδουν καλά υπό πολλά σενάρια αβεβαιότητας του μέλλοντος. Με αυτό τον τρόπο, οι υπεύθυνοι χάραξης πολιτικής και στρατηγικής μπορούν να βοηθηθούν τόσο κατά τον βραχυπρόθεσμο όσο και κατά τον μακροπρόθεσμο ενεργειακό σχεδιασμό.

Λέξεις-Κλειδιά: Ανανεώσιμες πηγές ενέργειας; Μοντελοποίηση και προσομοίωση ενεργειακών συστημάτων; Διερευνητική αξιολόγηση ενεργειακού σχεδιασμού; Προσαρμοστικά μονοπάτια ενεργειακής μετάβασης; Φωτοβολταϊκά στέγης; Συστήματα αποθήκευσης ενέργειας; Μίγματα ανανεώσιμων πηγών ενέργειας; Ενεργειακή και κλιματική πολιτική; Ενεργειακή μετάβαση; Κόστος από-ανθρακοποίησης; Περικοπές ενέργειας.

Summary

The European energy and climate policy is frequently revised in order to be aligned with uncertain factors, such as the influence of human activity on climate change, geopolitical tendencies, and energy market dynamics. Given such uncertainties, member states encounter difficulties in formulating their national contributions via the National Energy and Climate Plans, since, in addition to strengthening clean energy objectives, modifications to European energy and climate policy may entail structural adjustments, such as the minimization of natural gas use as an intermediate fuel during the energy transition. Hence, member states must not only select new technological trajectories, but also make decisions for implemented expenditures that may contradict with the revised European policy.

Given the notable uncertainties that the European Union has encountered in recent years, including the economic crisis, the COVID-19 pandemic, and the energy crisis of 2022, energy policy and the energy models supporting it must shift away from optimized projections made under linear assumptions. Instead, modelling simulations and the consequent energy policy formulation, should be characterized by adaptability to non-linear trends. This is the case of exploratory assessment of adaptive pathways toward renewable energy systems.

The purpose of this doctoral dissertation is the development of a modeling framework that:

- Performs exploratory analysis of policy/strategy options, to identify those that perform well under deep uncertainty, while specifying coping strategies that can be implemented in the case of realization of unlikely uncertainties.
- Supports adaptive policy making, by specifying why and when a policy change should be sought, which policies/strategies are prone to specific uncertainties, and therefore making explicit what should be monitored to trigger adaptation during actual implementation.
- Supports stepwise implementation of policies. This means that a policy or strategy may be chosen for implementation for a specific period of time by a stakeholder, and the results, as well as the plausible policy/strategy pathways forward, are updated almost instantly. With this feature, a tight participatory modelling process is feasible.

Based on the above, the doctoral dissertation answers to the following main research question:

“How could energy models support the exploratory assessment of adaptive policies towards the design of electricity systems based on renewables, which are resilient to contextual uncertainties?”

More precisely, the dissertation focuses on three major challenges during the shift towards energy systems that are abundant in renewable energy sources (RES).

- consumer engagement in the energy transition,
- minimum waste of renewable energy, and

- shielding the electricity system from external disruptions.

The application of the modelling framework to the case study of Greece’s energy transition showcased its usefulness towards adaptive and robust policymaking. Specifically, policies for incentivizing citizens to participate in the energy transition through investments in small-scale photovoltaic systems were evaluated. Subsequently, mixes of RES and storage which minimize curtailment were explored, identifying those that minimize the cost of integrating renewable energy into the electricity mix. Finally, power generation mixes which disengage Greece’s electricity generation from natural gas, while concurrently achieving carbon emission and renewable energy targets in an economically efficient manner were assessed. Overall, the suggested modelling framework improves existing simulation practices, by supporting the development of energy strategies and policies which are robust under uncertainty, facilitating that way policymakers’ short- and long-term energy planning.

Keywords: Renewable energy sources; Energy system modelling; Exploratory assessment; Adaptive policy pathways; Photovoltaics; Battery energy storage systems; Renewable energy capacity mix; Energy and Climate policy; Energy transition; Cost of carbon abatement; Curtailment.

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Nomenclature

Nomenclature

Abbreviations

AIM	Adaptive polIcymaking Model	NECP	National Energy and Climate Plan
BESS	Battery Energy Storage System	PHS	Pumped-Hydro Storage
BSAM	Business Strategy Assessment Model	PRIM	Patient Rule Induction Method
CGE	Computational General Equilibrium	PV	Photovoltaics
DAPP	Dynamic Adaptive Policy Pathway	RES	Renewable Energy Sources
EC	European Commission	RQ	Research Question
EU	European Union	SFOE	Swiss Federal Office for Energy
FiT	Feed-in Tariff	STREEM	STorage RequirEmEnts and dispatch Model
GHG	Greenhouse Gas	VRES	Variable Renewable Energy Sources
Li-Ion	Lithium-Ion	WT	Wind Turbines

1.1. Background and problem formulation

This section provides the background which led to the need for answering the over-arching research question (RQ) that governs this PhD dissertation. It consists of a (i) brief summary of recent energy strategies that were adopted in the European Union (EU), (ii) an overview of modelling techniques that have facilitated policymaking thus far, and (iii) reasoning behind the need for the adaptive policies' incorporation into energy modelling.

1.1.1. A brief history of European energy policy

A retrospection at the EU agenda of the last decades clearly indicates that the transformation of the energy system has long been one of its core priorities. Since 2010, the adoption of energy strategies, have laid the ground for energy laws and initiatives that were announced subsequently, and are still under effect (European Commission, n.d.). The 2020 energy strategy (European Commission, 2010), published in 2020, started with a strong statement that *"The price of failure is too high"*, acknowledging the need for safe, secure, sustainable and affordable energy supply in order to ensure well-functioning of the society, industries and the economy. It also recognized that the shift to sustainable energy would be a decade-long journey, whose decisions however, need to be taken immediately, and may have an effect for the next 30 years and beyond. Concepts, such as, decoupling economic growth from energy use, decrease of dependence from imported fossil fuels, or energy consumers empowerment, date back to 2010 when the 2020 energy strategy was released. Overall, the strategy aimed for at least 20% reduction in EU greenhouse gas (GHG) emissions, at least 20% renewable energy consumption, and at least 20% energy savings by 2020. The 2050 energy roadmap (European Commission, 2011), which was published one year later, extended the EU ambition, presenting different routes towards 80-95% reduction of GHG emissions by 2050, which are based on energy efficiency, renewable energy, nuclear energy, and carbon capture and storage, combined in seven transition scenarios. The aim was to highlight what follows the 2020 agenda, therefore, reducing investors', governments', and citizens' uncertainties. Specific steps for the period 2020-2030 were more precisely formulated in the 2030 climate and energy framework (European Commission, 2014a), published in 2014, where EU-wide targets and policy objectives for the period 2020-2030 where agreed by the European Council. Two binding targets for 2030 were adopted, namely (i) at least 40% reduction in GHG emissions compared to 1990, and (ii) at least 27% renewable energy consumption, which were complemented by two indicative targets of (iii) at least 27% energy efficiency improvements, and (iv) 10-15% electricity system interconnection. Alongside, the energy security strategy was published (European Commission, 2014b), which specifies mutually beneficial priorities for all member states, towards limitation of short- to long-term energy security concerns.

Since the publication of these ground-setting strategies, the EU ambition has grown significantly stronger. In 2019, the EU Green Deal (European Commission, 2019a) was published, aiming to *"make Europe the first climate-neutral continent by 2050, boosting the economy, improving people's health and quality of life, caring for nature, and leaving no one behind"* (European Commission, 2019b). The Green deal, along with the recast Renewable Energy Directive (European Commission, 2018a) and the amended Energy Efficiency Directive (European Commission, 2018b), which are the two key legislative acts of the Clean energy for all Europeans package (European Commission, 2020), boosted the targets that were set in the 2030 climate and energy framework, and required 55% reduction in GHG emissions, 32% renewable energy consumption and 32.5% energy efficiency improvements by 2030. In parallel, as part of the Clean energy for all Europeans package, member states were required to draft national energy and climate plans (NECPs) for the period 2021-2030, describing how they intend to contribute towards the 5 dimensions of the energy union, namely (i) decarbonization, (ii) energy efficiency, (iii) energy security, (iv) internal energy market and (v) research innovation and competitiveness (European Commission, 2023a). Long-term strategies were also drafted, describing member states' mid-century, long-term low GHG emission development strategies (European Commission, 2023b). Since the drafting of the NECPs, the renewable energy and energy efficiency targets have again been raised, as part of:

- the "Fit-for-55" package (European Commission, 2023c) published in 2021, which aimed to update EU legislation on the way towards 55% reduction of GHG emissions by 2030, and
- the REPowerEU plan, published in 2022, as a response to the energy crisis stemming from the Russian invasion to Ukraine, aiming for reduced dependency on imported fossil fuels (European Commission, 2022a).

At the time of writing of this dissertation, the European Parliament and the Council have reached a provisional agreement in March 2023 for 42.5-45% renewable energy consumption and 38% energy efficiency improvements in final energy consumption (40.5% for primary energy) by 2030, with respect to the energy consumption projections made in 2007 for 2030.

This short journey to EU legislation towards a transformed energy system, highlights that EU plans and regulations, driven by changes in the context (e.g., environmental damage, geopolitical tendencies), are constantly updated, possibly creating difficulties to member states in keeping up. In some cases, updates are only an increase in scale, such as the augmentation of renewable energy and energy efficiency targets. In other cases, however, the changes are structural, such as the abolition of natural gas use as an intermediate fuel. Since 2010, the 2020 energy strategy acknowledged that member states are challenged in choosing the appropriate technologies and infrastructure for their energy transition. When structural changes in EU policy takes place, member states are further challenged, since not only a new technological route needs to be chosen, but also, they need to cope with investments that have been initiated and might contradict with the updated EU policy. Long-term strategies try to analyze a variety of pathways that can be followed towards 2050. Nevertheless, as the 2050 energy roadmap acknowledges, *"perfect forecasting of the long-term future is not possible"* (European Commission, 2011), therefore alternatives are not always available in long-term plans. This is partially owed to the fact that usually energy models, which support energy planning, are typically resource-intensive in their calibration and simulation time (Frilingou et al., 2023). Therefore, in a continuously changing EU context, analyses are restricted to a few energy system transition pathways, with limited context scenarios incorporation. Thus, the relevant results are prone to uncertainty due to inherent uncertainty in assumptions, as well as their infeasibility to anticipate many potential extreme externalities (i.e., energy crisis, maturity of technologies, etc.). This highlights that in recent view of the uncertainties that the EU and the world have experienced in the past years (i.e., the 2008 financial crisis, the 2019 pandemic, and the 2022 energy crisis), policymaking, and the respective models supporting it, need to move away from projections based on best estimates. Instead, they should be flexible to adapt to potential external disruptions of the context, being robust to negative impacts, while exploiting opportunities that emerge from positive contextual developments. This is the case of exploratory analysis and adaptive policymaking, which focuses on short-term actions, with concurrent contextual planning in case of future contextual externalities.

1.1.2. Uncertainty in energy modelling

Tackling with uncertainty is inevitable when planning for the future (Offermans and Corvers, 2012). Decision-making in the face of uncertainty can present substantial challenges for policymakers, often resulting in their inability to arrive at well-informed choices (Forni et al., 2016). The energy sector faces numerous uncertainties as it strives to achieve sustainable, affordable, and secure energy supply, in line with the REPowerEU plan (European Commission, 2022a). Contextual factors such as capital costs, fuel prices, GHG emissions cost, risk aversion of consumers and investors, or evolving regulations, influence investment decisions in energy infrastructure. Additionally, bureaucratic processes, construction timelines, and the long-term nature of investments create delays in the response to investment portfolios. On top, past decisions may also lead to unforeseen long-term effects which may delay, or financially burden the desired energy transition path. It is, thus, evident that policymakers are called to develop energy and climate policies that have lasting impacts on the energy system, when the most suitable set of policies or strategies to achieve the desired goals under an uncertain context remains vague (Chappin et al., 2017).

Policies designed to function effectively under specific conditions, may be ineffective outside the considered boundaries. In this respect, computer-aided optimization and predictive modelling, which historically support policymaking, has proven to be insufficient, since they provide insight for the path to be followed, only under specific assumptions or best estimates (Swanson et al., 2010). Despite this fact, optimization and equilibrium models dominate the climate and energy policy landscape. According to Chappin et.al., computational general equilibrium (CGE) models are used to simulate economy wide effects in a top-down approach, while partial equilibrium and techno-economic optimization models, are used to deepen in specific sectors in a bottom-up manner. CGE models use agents to represent sectors in an aggregate manner, and can be used to answer what would happen if an economy-wide equilibrium is achieved given a set of policies and assumptions, or which policies would be needed in order to achieve specific goals. Partial equilibrium modes use the same logic of calculating equilibrium conditions, but applied within one sector rather than the entire economy. In this respect, they are capable of simulating one sector in greater detail, but they omit the interaction with other sectors of the economy. Finally, techno-economic models, delve into detailed simulation of specific technologies within the energy sector, in order to analyze the least cost end-system configuration and/or the pathway leading to it (Chappin et al., 2017).

The degree that each model is capable of dealing with the complex context within which policies and strategies are applied, depends on their combined temporal, spatial, and technological resolution, which affects their computational efficiency. Models can focus either on the present energy system and its short- or medium-term evolution, or on the desired end-state of the energy system, or on the entire transition pathway from the current regime to the desired future technological configuration (Chappin et al., 2017). An increase in temporal resolution can provide more accurate results in all time horizons. For example, when simulating energy systems with large shares of renewable energy sources (RES), and fluctuating demand, simulating in high temporal resolution can improve model estimations, such as the cost of technological expansion in order to balance demand and supply (Marcy et al., 2022), or the needs for electricity storage capacity to minimize curtailment (Michas and Flamos, 2023). However, in some cases, some degree of temporal resolution is sacrificed, in order to improve the computational tractability of the model (Marcy et al., 2022). In this respect, more scenarios can be run, and therefore better degree of uncertainty incorporation in modelling can be achieved. The computational efficiency gains, however, depend also on the horizon of analysis, as well as the spatial and technological resolution of the model. Traditionally, there was a trade-off between temporal and technological resolution, in order to maintain the necessary computational performance and accuracy. For instance, models focusing on a single sector may have high temporal resolution, while multi-sector models may apply resolution reduction techniques, such as time slicing. With the uptake of RES, spatial resolution has also become increasingly important, increasing the trade-off dimensions (Martínez-Gordón et al., 2021). Indicatively, increased spatial resolution, and therefore, increased computational effort, is required when simulating regions with high heterogeneity in renewable energy potential (Aryanpur et al., 2021), or in allocation of demand and generation profiles (e.g., country level) (Martínez-Gordón et al., 2021).

Incorporating uncertainty analysis is a fourth dimension, which along-side the need for high temporal, spatial and technological resolution is constrained by computational resources. Still, uncertainty cannot be neglected. Deterministic and simplified optimization of fossil-fueled resources used to be adequate, however the variability of RES generation profiles, calls for higher resolution and uncertainty incorporation in modelling (Yliruka et al., 2023). While equilibrium and techno-economic models are capable of incorporating some kind of uncertainty, in general they are not designed to represent the system out of equilibrium. In other words, they provide insight on which investments or policy options should be chosen, given their perfect foresight on assumptions. Therefore the model user is not informed about the reasons that might lead to missing the target, and this has been acknowledged as a crucial feature that needs to be incorporated in energy modelling (Chappin et al., 2017). Thus there is a need in designing a modelling framework which focuses on robustness rather than in optimality, meaning that the results provided perform well under many plausible scenarios, rather than under best assumptions (Forni et al., 2016). Policymakers informed by such models can focus on equipping policies with the transformative capacity to effectively handle uncertainties, adapting to anticipated and unanticipated conditions of the context (Swanson et al., 2010). In other words, the focus is on short-term planning, while describing potential future adaptive actions, defined from the design phase and not on an ad-hoc basis (Haasnoot et al., 2013).

1.1.3. Needs for model expansion towards adaptive policies

Strategic planning based on optimization which assumes that the future can be sufficiently predicted, has been parallelized to *"dancing on the top of a needle"*, since the so-perceived optimal strategies might be highly sensitive to uncertainties, and therefore lose their value in the case of less probable but impactful events (Forni et al., 2016; McInerney et al., 2012). Furthermore, often used cost-optimal solutions, can cause confusion regarding what is cost-optimal and what is feasible (Lombardi et al., 2023). When dealing with a future filled with uncertainties, traditional prediction or scenario-based modelling methods are not sufficient for decision-makers and analysts. In fact, during interviews performed with stakeholders from the fields of academia, policymaking, industry and non-governmental organizations, by Süsser et.al. (2022), a point raised by interviewees was **that uncertainties and unforeseen events** should be incorporated in energy models. In this respect, methods supporting the design of adaptive plans become crucial. Such plans focus on identifying actions that should be followed in the present to prepare for the near-term future, while maintaining the flexibility to adapt, if necessary, in the long-term. The goal of long-term adaptation is to keep options open and ensure preparedness in an uncertain environment.

Such an adaptive policy design can only be enabled though **exploratory analysis** of the candidate policy/strategy options, and assessment of their performance under uncertainty. Exploratory modelling allows decision-makers to explicitly assess their policy options under a wide range of potential future evolutions, providing a more comprehensive understanding of the potential outcomes and implications of their decisions. In this respect, formulation of robust strategies, which can perform well across a wide range of conditions, and adapt to potential future evolution scenarios, is feasible, stepping away from optimised solutions based on a limited set of projections (Moallemi and Malekpour, 2018). Exploratory analysis can only be made possible, with the **active participation of policymakers** who need to explore their policy options. Accordingly, models need to abolish their detached nature from policymakers, for which they have received criticism (Nikas et al., 2021). This is in line with an expressed stakeholder need (Süsser et al., 2022) which calls for active engagement in the modelling processes, by means of informing modellers about simulations' assumptions, and co-designing simulation scenarios. By doing so, stakeholders can be informed for what could be the effects of each scenario, strategy of policy under consideration, and what changes when choosing one option over another. Furthermore, though **participatory modelling**, simulation assumptions are made explicit, allowing modellers and stakeholders to mutually identify which parameters are important to be included in modelling exercises. That way, not only modellers gain valuable insight on their assumption, but also stakeholders can be informed on which factors lie behind the various actors disagreements (Moallemi and Malekpour, 2018).

In order to enable such a participatory modelling process, models applied need to provide **fast responses to stakeholders**. Already from the analysis performed in the European energy policy landscape in **section 1.1.1**, it becomes apartment that developments in energy strategy formulation are proceeding at a fast pace. This is acknowledged also by stakeholders, who mention that *"Now things have to go faster, we need to move faster: policymaking has to be faster; so models also have to follow it"* (Süsser et al., 2022). The pitfall is that in order to achieve this, modelers usually need to reduce their models' temporal, spatial and/or technological resolution, running in the risk of stepping into infeasibility or sub-optimality of solutions (Fattahi et al., 2021). However, this is not much of a valid option anymore, because it contradicts with the need of stakeholders for **higher simulations resolution**

(Süsser et al., 2022). Furthermore, such a technique ignores the gaps related to modelling resolution elicited by Chatterjee et.al. (2022). Specifically, modelling at high spatial resolution, could capture the contribution of electricity demand at different city scales to the total CO_2 emissions, or the potential of demand side management due to heating electrification. On the supply side, simulating renewable energy scenarios at hourly resolution, could provide a better picture regarding the feasibility of RES in covering the entire demand profile uninterruptedly and without causing discomfort to electricity consumers, or integrating photovoltaics (PV) with heat pumps and electricity storage at the building level (Chatterjee et al., 2022; Manfren et al., 2020).

From the above, it becomes apparent that in an evolving energy system which is gradually dominated by RES and their intermittent nature, along other long-standing uncertainties (as presented at the beginning of **section 1.1.2**), trade-offs in energy models capabilities should be held at a minimum, in order to enable **exploratory and participatory modelling towards adaptive policy design**. Specifically, models should:

i. Account for uncertainties and unforeseen events through exploratory modelling in order to support robust policy making,
ii. be user-friendly and transparent, enabling participatory modelling approaches, establishing a tight loop between policymakers and the modelling teams,
iii. support high resolution simulations, and
iv. be fast, in order to provide policymakers with quick answers to multiple “what-if” scenarios.

1.2. Scope and objective

The European Commission (EC) has published in 2021, guidelines for designing better regulation (European Commission, 2021). These guidelines are meant for internal use by the Commission staff and aim in designing *“legislation that achieves its objectives while being targeted, effective, easy to comply with and with the least burden possible”*. Key principles that should be followed when designing policies and regulations include:

- **Comprehensiveness**: consideration of regulation impacts in all sectors (i.e., economic, environmental, social, etc.), interested parties, and throughout the policy cycle (i.e., preparation, adoption, implementation and application),
- **Coherency**: alignment with high-level and long-term objectives (e.g., sustainable development goals),
- **Proportionality**: target areas where policy results matter most,
- **Participation**: design of policies and regulations with all interested parties,

- **Evidence-base**: consider best available evidence sources, including scientific,
- **Transparency**: disclosure of the regulation design process, including the evidence supporting it and the rationale behind it,
- **Learning from experience**: Apply the “evaluate first” principle to improve new regulation based on the experience gained during the implementation of previous ones.

This dissertation, driven by evidence collected by the scientific community, suggests that the ensemble of these guidelines can also be applied at the member state level when designing energy policies and strategies, given that the modelling tools are enhanced to meet the needs of adaptive policymaking described in the previous section.

Comprehensiveness and proportionality combined can be challenging in terms of energy modelling. Comprehensiveness requires energy models capable of capturing multiple effects of a policy or strategy, across the entire policy life cycle, which calls for much detail and high temporal resolution in simulations. On the other hand, proportionality calls for high spatial or technological resolution in order to delve into specific regions or sectors, which policies need to target primarily. While high level of detail in all dimensions (i.e., temporal, spatial and technological) can be implemented in energy models, it may be restricted by computational capacity (Fattahi et al., 2021), limiting modeling exercises to only a limited set of scenarios. Nevertheless, in order to handle the deep uncertain context where policies are applied, literature suggests that robustness instead of optimality should be sought (Forni et al., 2016). This is enabled only if a wide range of scenarios are modelled, making uncertainty explicit, by designing and quantifying scenarios which may have slipped stakeholders’ attention (Yung et al., 2019). It becomes thus obvious that in order to meet the comprehensiveness and proportionality criteria in a robust way, **computational efficiency which enables quick, high-resolution simulations is required** by the models.

Such features are also valuable in order to achieve coherent policy design, which learns from the past. Usually optimization models, describe which policies or strategies should be implemented under specific circumstances (Swanson et al., 2010). Nevertheless, such a modelling exercise does not guarantee that the solution provided will not be similar to the one(s) that led to failure in the past. To avoid this, literature suggests that **models should aim to provide answers to many “what-if” scenarios** regarding the effect of policy options implementation, instead of aiming for optimal policy trajectory planning (Chappin et al., 2017). In this respect, models can be viewed as tools, which facilitate stakeholders’ discussion about future policy options, while considering evidence that is collected from the past (Yung et al., 2019).

This is also relevant to the need for **participatory processes** which has been pointed out in literature, in order to trigger a mutual learning procedure between modelers and stakeholders. Participatory modelling processes leverage the expertise of stakeholders, for validating simulation results and advising on simulation assumptions and uncertainties to be considered (Yung et al., 2019). Towards this direction, transparency in modelling exercises is crucial, not only for the better communication between modelers and stakeholders, but also because from a stakeholder's perspective, providing more information and reasoning behind their decisions, can reduce the public's opposition to new polices (Pfenninger et al., 2018). Therefore, openness should be aimed both for the modelling techniques, as well as the assumptions used and their data sources (Yung et al., 2019). That way, policymaking is actually evidence-based, since a tight loop between stakeholders and modeling teams is established, bridging the expertise of scientists and practitioners.

Even though several techniques of energy modelling (e.g., CGE, partial equilibrium, techno-economic optimization, etc.) has been used in literature, with the specificities mentioned in **section 1.1.2**, models supporting participatory and exploratory techniques, through high-resolution and quick simulations of multiple "what-if" scenarios, to the best knowledge, has received little attention. Moallemi et.al. (2018) present a participatory, exploratory modelling approach, towards the design of long-term energy transition plans. Their approach consists of three phases. The first phase includes the identification of the societal needs that the energy system needs to satisfy, the development of storylines which describe the transition process and the interactions among actors in the energy system, and the development of a model based on the identified societal needs and the created storylines. The second phase is the scenario exploration, which means the identification of uncertainties that could affect the performance of candidate policies/plans, the development of quantitative uncertainty scenarios, and the discovery of uncertain parameter ranges, under the effect of which a policy or plan performs in a particular way. Finally, the third phase includes planning for contingency, which entails defining coping strategies, which increase the robustness of polices and plans, against changing uncertain conditions. Another study by Wu et al. (2020) suggests a similar approach for exploratory modelling of power system evolution consisting of five steps. The approach begins with (i) an examination of the power system's historical development and a definition of its potential future structure. Next, (ii) a tailored power system planning model suited to the anticipated future structural form of the power system is defined and developed. Consequently, (iii) sources of uncertainty are identified and (iv) a multitude of scenarios are generated using computer experiments. Finally, (v) the analysis of the scenarios is performed, in order to identify crucial elements of evolution, establish timelines, categorize types of evolution, and understand their respective combined uncertainties. While both works provide valuable steps for engaging in participatory "what-if" scenario analyses, they lack a thorough description of a modeling framework and its technical capabilities, supporting adaptive policymaking towards renewable energy systems. Instead, indicative modeling techniques, such as modeling software and

Python libraries are mentioned by Moallemi et.al. (2018), which could aid in implementing their proposed approach. Mir Mohammadi Kooshknow et.al. (2022) employ an exploratory agent-based modeling approach called EABMA, to assess electricity storage business models in the Netherlands under deep uncertainties. They simulate 10368 scenarios of uncertainty, which are combinations of 11 uncertain parameters, each one taking one to three possible values, in a 20-year time horizon. Even though they achieve good quantification of uncertainty by simulating each scenario 20 times, they apply significant time slicing, with only 288 hourly simulation timesteps in a yearly basis, which equals 3.3% representation of the year. However, this contradicts with the requirement for high resolution, especially in energy systems abundant of RES. Furthermore, their simulations are performed in a computer cluster for several days, which shows that interactive participatory modelling processes with stakeholders would be challenging. Eker and van Daalen (2015) use exploratory analysis in order to assess subsidization policies promoting biomethane production in the Netherlands, with the policies trying to achieve three conflicting targets, namely, biomethane production maximization, emissions reduction, and policy cost minimization. The authors use exploratory modelling to assess the performance of two candidate policies under 5000 scenarios of a wide range of uncertain parameters with a system dynamics model. Then, they use robust multi-objective optimization in order to find a pareto front of solutions for the key parameters of the subsidization policy (i.e., subsidy level and subsidy duration), which allow the policy to perform well under uncertainty. Finally, they use the Patient Rule Induction Method (PRIM) scenario discovery algorithm, to identify which uncertain parameters can still cause failure of the policies selected from the pareto front. Their approach is an exemplary application for robust policy design. Still, their approach does not explicitly provide implications for contingency actions (i.e., policy parameterization) that could be implemented in case of realization of less likely uncertainties, which can provoke poor performance of the selected policies. Furthermore, the subsidy level is assumed to be constantly applied over the simulation time, with the authors mentioning that adaptive policies based on market signals are suggested for further research. Finally, the simulation time needed to perform the analysis is not reported, leaving a gap for the modelling ensemble's feasibility to be applied in participatory policy design processes.

Several other studies share similar methodological techniques with the above-mentioned studies (Auping et al., 2016; Hamarat et al., 2014; Moallemi et al., 2017), whose further elaboration is, however, omitted to avoid repetitions. The main outcome from the literature review on the limited set of available studies on exploratory and adaptive energy modelling, is that, to the best of our knowledge, currently there is a lack of a modelling framework satisfying all the criteria for **high simulations resolution**, **computational efficiency** and **consideration of uncertainty and unforeseen events** through **"what-if" exploratory scenario analyses**, while supporting **participatory stakeholder evaluations**.

In this respect, this dissertation presents and applies a modelling framework, that addresses the needs that have been expressed in scientific literature, and meets the requirements for adaptive policy design presented in the previous section (**Fig. 1.1**), supporting that way policymaking according to the EC guidelines for better regulation. More specifically, the modelling framework:

- Performs exploratory analysis of policy/strategy options, to identify those that perform well under deep uncertainty, while specifying coping strategies that can be implemented in the case of realization of unlikely uncertainties.
- Supports adaptive policy making, by specifying why and when a policy change should be sought, which policies/strategies are prone to specific uncertainties, and therefore making explicit what should be monitored to trigger adaptation during actual implementation.
- Achieves good computational efficiency, through a highly efficient simulation model, and a plug-in exploratory and participatory assessment model which performs meta-analysis of other models' results. Especially for the latter, it has the ability to augment the uncertainty analysis space, even with reduced simulations from the original simulation model, therefore limiting the trade-offs in simulations' resolution.
- Supports stepwise implementation of policies, which is a feature not found in scientific literature. This means that a policy or strategy may be chosen for implementation for a specific period of time by a stakeholder, and the results, as well as the plausible policy/strategy pathways forward, are updated almost instantly. With this feature, a tight participatory modelling process is feasible.

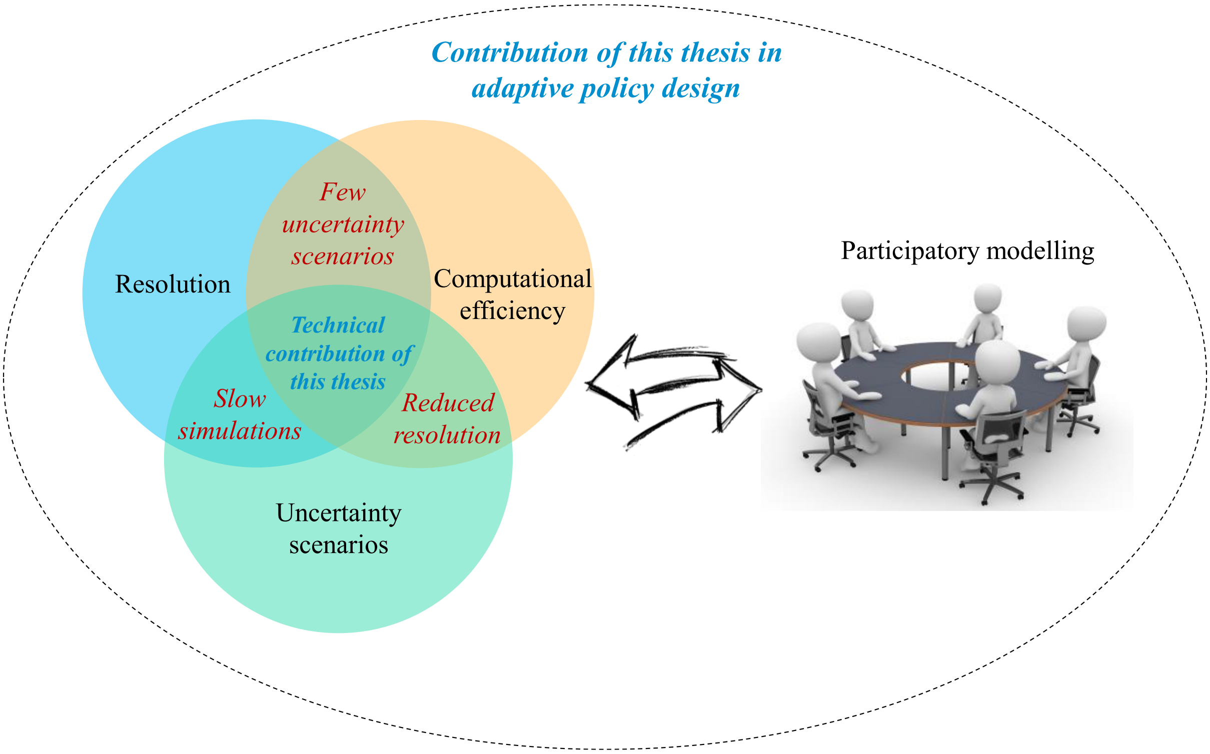

Fig. 1.1. Contribution of the modelling framework developed in this dissertation in designing adaptive policy pathways

The modeling framework consists of the Adaptive polIcymaking Model (AIM), and the STorage RequirEmEnts and dispatch Model (STREEM), which have been developed based on stakeholders' needs, elicited during consultations performed within the EC funded Horizon 2020 projects TRANSrisk[1], SENTINEL[2], and TIPPING+[3], and the POLIZERO[4] project funded by the Swiss Federal Office for Energy (SFOE). The models, as well as their structure, assumptions and methods used, which prove the merits mentioned in the above bullet list, are openly and transparently described in **chapters 2, 3** and **4**. To facilitate the readability of the dissertation, a brief description of the developed models is also provided in **Appendix 1**. The next section presents the overarching RQ that is tackled with the developed modelling framework, as well as a set of thematic RQs, which were formulated as steps, whose answering lead to robust policy/strategy design towards a power system dominated by RES.

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[1] https://cordis.europa.eu/project/id/642260
[2] https://sentinel.energy
[3] https://tipping-plus.eu
[4] https://www.polizero.ch

1.3. Research Questions (RQ)

The analysis of the previous sections has demonstrated that effective policymaking in a highly uncertain world necessitates the use of exploratory modeling techniques that explicitly incorporate uncertainty. In this regard, it is imperative for energy models to align with the evolving dynamics of the energy system. This entails a shift away from a centralized and uniform nature, towards versatile and efficient tools that cope with decentralized energy systems based on RES. To do so, energy models need to augment their representation of agents beyond centralized entities which invest in large power plants, and consider citizens as active energy transition agents who invest in decentralized projects. Furthermore, models need to be modified in order to consider factors beyond the efficient allocation of dispatchable resources. Instead, they should support the design of renewable energy portfolios which achieve a balance among the available intermittent technologies, towards optimal generation complementarity, and minimization of supporting technologies (e.g., storage) or thermal electricity generation, which increase the cost and/or the environmental footprint of the produced energy. Finally, it is crucial for models to provide users a high degree of adaptability. This entails facilitating effective decision-making that can withstand uncertainty, while also offering contingency plans that can be implemented in the event of less likely occurrences, such as an energy crisis. In this regard, it is imperative for models to offer users a diverse range of potential solutions, as well as a participatory interface that enables them to evaluate the consequences of applying one choice over another. Driven by the above analysis, the overarching RQ tackled in this dissertation is formulated as follows:

How could energy models support the exploratory assessment of adaptive policies towards the design of electricity systems based on renewables, which are resilient to contextual uncertainties?

To answer this overarching RQ, this PhD dissertation comprises of three stand-alone research chapters (i.e., **Chapter 2**, **Chapter 3**, and **Chapter 4**). These research chapters present methodological approaches that have been developed into energy models, to effectively put the exploratory and participatory concept into practice, towards robust policy- and strategy-making, which builds on the notions of resilience and adaptability. The models are used to study three main pillars of the energy transition towards decentralized RES-based power systems (**Fig. 1.2)**, namely: (i) consumer engagement in the energy transition, (ii) minimum waste of renewable energy, (iii) shielding the electricity system from external disruptions. Each research chapter focuses on one aspect, and presents the relevant methodology, as well as the models supporting its implementation.

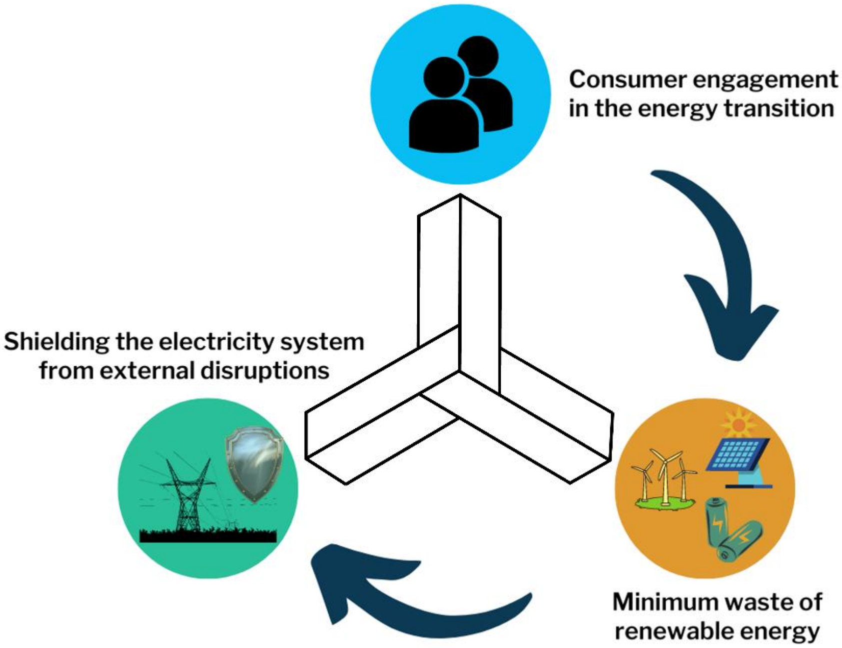


Fig. 1.2. Pillars of the PhD dissertation

The first pillar abides by the notion of the EU Green Deal that *"Citizens are and should remain a driving force of the transition"* (European Commission, 2019a). Especially after the 2022 energy crisis and the uncertainty about using natural gas as a transition fuel, the EU commission mandates member states to designate renewable "go-to-areas", which are areas with low environmental impact when installing RES and storage projects (European Commission, 2022b). Among the priority areas are building roofs, which give a great opportunity for citizens to be at the core of the energy transition, by installing rooftop PV systems. Nevertheless, even if rooftop PV installations are prioritized, citizens need to be incentivized to invest in such projects. The past has shown that some kind of subsidization needs to be in place to initiate investments. The subsidy though, needs to be designed in a way that does not lead to deficits, retrospective rate cuts, or shift to abrupt subsidy-free schemes that cause distrust to the investment environment and stagnation of new projects. In this respect, the aim of the first pillar is to identify sequences of support schemes incentivizing rooftop PV installations, which adapt according to context signals (e.g., cost of technologies, cost of electricity, etc.), and achieve the desired rooftop PV capacity expansion, without leading to observed market failures of the past.

The second pillar acknowledges that with increasing shares of renewable energy fed into the grid, there is a challenge in balancing the demand and renewable generation profiles, both of which are highly uncertain throughout the day. With thermal generating resources as baseload electricity sources, the electricity supply planning procedure ought to consider only the uncertainty of the demand side. Even if deviations occurred, the re-scheduling of generation was feasible with ad-hoc changes in the amount of electricity injected by committed power plants, or by committing new, peaking units. In electricity systems dominated by RES, the uncertainty dimensions are expanded to the supply side, which is not dispatchable, running the risk of supply shortages at high demand and low generation hours, or curtailment in the opposite case. The combination of these two events, leads to under-exploitation of the potential renewable energy yield, since electricity is wasted, when it could be used to cover the electricity needs at other times. Electricity storage can contribute in minimizing this problem, by transferring renewable energy to the times when it is most needed, as stressed by the REPowerEU plan (European Commission, 2022a). Nevertheless, deploying mass storage capacity, despite being unrealistic to implement, is also costly. In this respect, the aim of the second pillar is in identifying how much storage is needed to reduce the waste of renewable energy, under various capacity mix scenarios of RES technologies, achieving cost-effective RES integration without electricity waste.

Finally, the third pillar of this dissertation acknowledges that while cost minimization is the most commonly used criterion in decisions taken about the future electricity generation portfolio, it can be at the expense of other criteria, such as reduced electricity yield, prolonged dependency on fossil fuels, slow abatement of carbon emission, or cost-inefficient renewable energy integration (i.e., low energy return compared to the cost of the systems producing it). After the 2022 energy crisis, energy security criteria were prioritized, aiming for reduced natural gas use as a transition fuel, through accelerated RES deployment (Gürsan and de Gooyert, 2021). It becomes thus, obvious, that when designing the future electricity system build-out, policymakers may face a trade-off between the environmental, energy security and cost-minimization objectives they need to achieve. This pillar aims to find a balance between these three objectives, by investigating RES and storage deployment pathways, which achieve all targets at once, despite the uncertainty governing the price of natural gas. That way, it aims to inform policymakers about potential strategic decisions, which shield the power system from the externalities caused by the 2022 energy crisis.

The aforementioned pillars constitute the steps followed to conduct this doctoral dissertation, as shown in **Fig. 1.3**, highlighting how the exploratory assessment of adaptive policies can be implemented at different scales and objectives. Considered as a whole, they lead to the answering of the overarching RQ, which is facilitated by the formulation of the following thematic research questions (**RQs 1-3**) which comply with each pillars' scope, and are thoroughly elaborated and answered in the research chapters **2-4**:

RQ1 Which policy pathways could re-initiate small-scale PV investments (i.e., ⩽ 10kWp) in Greece without leading to the RES market failure that was observed in the past?

RQ2 Assuming an increase in overall RES capacity, which RES plus storage deployment pathways to 2030 enable least electricity curtailment and what criteria can be used for their selection?

RQ3 Which RES plus storage deployment pathways enable decoupling from imported gas, while achieving the emissions reduction and renewable integration targets in an economically efficient way, despite contextual uncertainties?

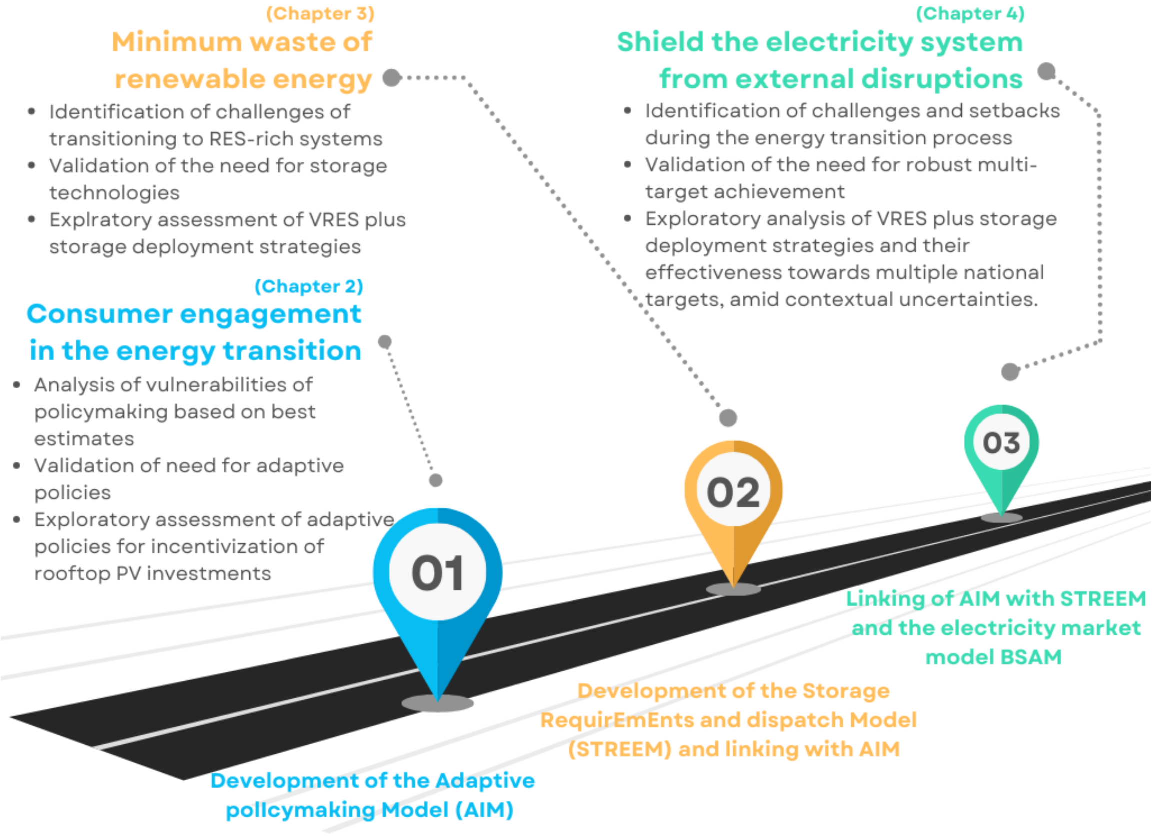


Fig. 1.3. Steps taken and models developed and used for the answering of the thematic research questions of this dissertation. A brief description of the models is provided in Appendix 1.

Greece was chosen as the case study country to answer these RQs due to its ambitious plans for variable renewable energy sources (VRES) capacity expansion (i.e., PV and wind turbines (WT)) by 2030, shifting away from its current regime, which is characterized by limited capacity of interconnection transmission lines compared to its peak demand (i.e., about 20%), high shares of fossil fuels in its electricity mix and high dependency on imported fuels for electricity generation. To be more specific, with the publication if its 2019 NECP (Greek Ministry of Environment and Energy, 2019), which is still under effect, Greece opted for the phase-out of its lignite power plant fleet, the only technology operated with domestically extracted fossil fuels, and a 200% VRES capacity expansion (i.e., PV and WT) by 2030 compared to 2019, equal to 14.7 GW. During the transition phase, imported natural gas was selected as the transition fuel for power generation. However, this plan was jeopardised by the 2022 Russian invasion to Ukraine, the weaponization of energy sources and the consequent energy crisis, revealing aspects of security of supply and turbulent energy prices. The Greek answer was a doubling in ambition, aiming for 400% increase in VRES capacity compared to 2019, reaching a total of 23.9 GW by 2030 as presented in the Greek proposal for the 2024 update of its NECP (Greek Ministry of Environment and Energy, 2023). Greece is, thus, a good example for assessing renewable energy integration maximization in an effort to rely more on domestic resources and minimize reliance on imported fossil fuels, under a deeply uncertain environment. Considering also Greece's solar irradiation potential (Nikas et al., 2018), the answering of RQ1 is of paramount importance, in order to support policymakers in the incentivization of consumers to contribute with small-scale PV towards the Greek VRES targets. It is important to mention that even though this dissertation is focused on the Greek context, the presented methodological framework is applicable to any country, and the relevant results could provide an initial assessment for other countries with a power sector transformation plan based on RES.

1.3.1. RQ1: Which policy pathways could re-initiate small-scale PV investments (⩽10kWp) in Greece without leading to the RES market failure that was observed in the past?

From 2008 to 2013, Greece saw a surge in PV installations due to an appealing funding program for residential solar installations that offered generous Feed-in Tariffs (FiT) and simplified bureaucratic installation procedures. Although the policy led to capacity overachievement with respect to the set target, the respective policy cost led to a significant deficit in the Greek RES Special Account (Koumparou et al., 2017; Kyritsis et al., 2017), which raised concerns about the sustainability of the Greek RES market. The Greek government's response was the introduction of additional taxation on prosumers' income. However, this additional taxation along with a pre-agreed reduction in FiT, resulted in a declining rate of PV installations, as the investment environment was considered less safe (Flamos, 2016; Papadelis et al., 2016). Eventually, since 2015, a net-metering scheme came into effect, which does not reimburse the prosumer for the electricity injected to the grid, but nets the produced electricity generation from the PV system with the consumed electricity at the household over a three year period, without remunerating the PV owner in case of excess electricity generation.

Contrary to net-metering, self-consumption makes the investment of consumers more profitable for them, as they consume more of their electricity yield (Abdin and Noussan, 2018), grid charges do not apply to self-consumed electricity (Stavrakas et al., 2019), and therefore, the household's electricity cost is reduced and the respective PV system's payback period is shortened (Gil Mena et al., 2023). Especially, when combined with battery energy storage systems (BESS), apart from increasing the self-consumption of locally generated electricity, which further incentivizes PV installations, it also helps resolve supply and demand imbalances (Hassan et al., 2023). That way consumers are becoming more active participants in the energy transition process (European Commission, 2015). However, due the high investment cost of batteries, it has been stressed in literature that subsidies are needed in order to make them economically viable (J. Liu et al., 2023).

The objective of answering the first thematic RQ of this dissertation lies in assessing the efficacy of the net-metering scheme, in effect since 2015 in Greece, and of a potential alternative self-consumption scheme that subsidizes part of the BESS which accompanies the PV installation, in driving small-scale PV investments in Greece. Ultimate goal is the design of policy pathways towards the target of 1 GW of installed capacity by 2030, as mandated by the 2019 NECP, without leading to under- or over-investment and the market failure that was observed in the past. To do so, AIM was developed, which is a model **(i)** investigating the conditions under-, and the timeframe beyond- which a policy/strategy starts to deviate from the set targets, **(ii)** visualizing a map of dynamic adaptive policy pathways (DAPP), and **(iii)** setting up a monitoring system for real world policy adaptation. AIM has been linked with the technology adoption model ATOM (Stavrakas et al., 2019), which was used to simulate the decision-making process of agents towards PV investments, by correlating the investment decision with the agents' perceived investment value (for a brief description of ATOM please refer to **Appendix 1**).

Overall, answering **RQ1**, which is performed in **Chapter 2**, contributes to this dissertation by:

- validating the need for adaptive policies,
- developing the Adaptive polIcymaking Model (AIM), and
- verifying AIM's applicability to the rooftop PV sector of Greece

1.3.2. RQ2: Assuming an increase in overall RES capacity, which RES plus storage deployment pathways to 2030 enable least electricity curtailment and what criteria can be used for their selection?

The increasing presence of RES in the power generation portfolio poses integration challenges due to their intermittent nature (Antweiler, 2021), possibly resulting in electricity curtailment (Jorgenson et al., 2018). Curtailment is a known practice for controlling electricity injection from uncontrollable RES and ensure safe network operation (Michas et al., 2019). However, it also leads to waste of renewable electricity (Chang and Phoumin, 2021), reduced economic benefits for RES generators (Mayyas et al., 2022), and, if applied extensively, breaching of the limit set by the EU, which restricts curtailment up to 5% of the annual renewable electricity generation (European Parliament and the Council, 2019).

To address the challenge of maximum exploitation of renewable electricity yield (and consequently reduced curtailment enforcement) storage and demand response are two promising technologies, each one with its own challenges when it comes to rollout. Storage systems' deployment is challenged by their high upfront investment cost. Nevertheless, the costs have been reported to drop drastically in the recent years (EIA, 2020), and can also be subsidized as shown in **RQ1**. On the other hand, demand response is challenged by the unpredictability of participants' reaction to demand response signals, which might reduce system operators' trust in applying the measure extensively (Oconnell et al., 2014). The importance of both technologies is undisputed, however, **RQ2** focuses specifically on energy storage as a supplement to efficient renewable generation, given the REPowerEU plan's (European Commission, 2022a) emphasis on using energy storage to provide flexibility to the system and facilitate renewable energy integration.

The need for electricity storage to optimally integrate variable RES (or VRES) and avoid curtailment, ensuring their sustainability, has also been recognised in the 2019 Greek NECP (Greek Ministry of Environment and Energy, 2019). The formulation of the second thematic RQ of this dissertation builds on the 2019 NECP premise that *"[...] the shares and amounts of installed capacity of both thermal power generation plants and RES technologies, [...] have been determined in the context of energy simulation, taking into account specific assumptions regarding the reduced cost of electricity generation by such plants and they should be considered indicative and possible, but not binding, at technology and project category level"* (Greek Ministry of Environment and Energy, 2019). Therefore, the aim of addressing this RQ is to investigate different capacity deployment pathways of VRES combined with energy storage, with the goal of maximizing the utilization of domestically produced renewable electricity and minimizing instances of curtailment in the Greek electricity system until 2030. The technologies, whose combined capacity is explored, consist of PV and WT which are the renewable energy technologies with the highest potential in Greece, accompanied with utility-scale lithium-ion (Li-Ion) BESS, which, along with the already installed capacity of pumped-hydro storage (PHS), can facilitate the integration of renewable energy generation. To do so, STREEM was developed and linked with AIM. STREEM enables the exploration of storage capacity requirements to achieve specific curtailment levels through high-resolution simulation of storage technologies. Its main feature lies in its ability to model various storage technologies, achieving efficient computational performance in approximating storage/curtailment correlations, despite the storage technology specifications.

Overall, answering **RQ2**, which is performed in **Chapter 3**, contributes to this dissertation by:

- developing the STorage RequirEmEnts and dispatch Model (STREEM) and linking it with AIM,
- upscaling AIM's applicability to national grid scale, accounting for multiple RES technologies, and

- investigating VRES plus storage deployment pathways to 2030, limiting curtailment enforcement.

1.3.3. RQ3: Which RES plus storage deployment pathways enable decoupling from imported gas, while achieving the emissions reduction and renewable integration targets in an economically efficient way, despite contextual uncertainties?

As the shift towards RES-based electricity systems advances, natural gas was initially chosen as a transitional fuel due to its lower carbon emissions compared to other fossil fuels (Gürsan and de Gooyert, 2021). However, the 2022 energy crisis stemming from the Russian invasion to Ukraine, turned natural gas into an expensive and unreliable energy resource (Osička and Černoch, 2022). The EU responded immediately, by publishing the REPowerEU plan, which augments and accelerates the European ambition for RES capacity expansion, towards reduced use of natural gas as a transition fuel for power generation (European Commission, 2022a). Accordingly, Greece drafted its proposal for the 2024 update of its NECP, doubling the ambition for VRES deployment by 2030 compared to the 2019 NECP. It specifically highlights a remarkable 400% increase in VRES capacity compared to 2019, aiming to achieve a total capacity of 23.9 GW by 2030 (Greek Ministry of Environment and Energy, 2023).

Therefore, the 2022 energy crisis can be considered a tipping point that has accelerated the efforts towards RES-based energy systems and reduced reliance on natural gas. Nevertheless, in the short-run, and in view of securitization of energy supply, many countries have returned to operating coal- and oil-fuelled power plants (Y. Liu et al., 2023). This is also the case for Greece, which turned to increased operation of existing lignite power plants (Karamaneas et al., 2023), extending their phase-out from 2023, as originally planned with the 2019 NECP, for at least another two years (Greek Ministry of Environment and Energy, 2023). Such reactions by member states has caused concerns for a new lock-in to fossil fuels, which might cause economic instability and intensify energy poverty (Frilingou et al., 2023; Karamaneas et al., 2023). The latter makes clear that decoupling from imported natural gas should be perused quickly, but without jeopardizing decarbonization efforts, or causing socioeconomic hardship (Karamaneas et al., 2023).

In this respect, beyond the issue of "how many" renewables, the third thematic RQ of this dissertation focuses on determining how the different power generation technologies can be combined, and when should they be deployed, in order to achieve ambitious renewable energy shares, reduce emissions, and effectively decouple from the short-term uncertainties associated with natural gas. The aim is to find an economically efficient power generation portfolio that addresses not only the quantity of renewable energy, but also the integration of various technologies to meet these goals sustainably. To achieve this objective, AIM and STREEM were linked with the Business Strategy Assessment Model (BSAM)

(Kontochristopoulos et al., 2021), which is an agent-based, wholesale electricity market model, simulating the unit commitment and economic dispatch problems, considering both RES generation profiles and the technical constraints of dispatchable power plants (for a brief description of BSAM please refer to **Appendix 1**).

Overall, answering **RQ3**, which is performed in **Chapter 4**, contributes to this dissertation by:

- linking AIM with STREEM and the electricity market model BSAM to simulate the electricity scheduling problem, taking into account both RES and thermal power plants,
- upscaling AIM's applicability to account for multiple national targets (i.e., RES integration, emissions and dependency in imported gas), and
- investigating VRES plus storage deployment pathways and their capability in limiting the effects of the 2022 energy crisis, while ensuring a cost-efficient energy transition.

1.4. Structure of the PhD dissertation

The dissertation is structured in five chapters as visually illustrated in **Fig. 1.4** and described subsequently.

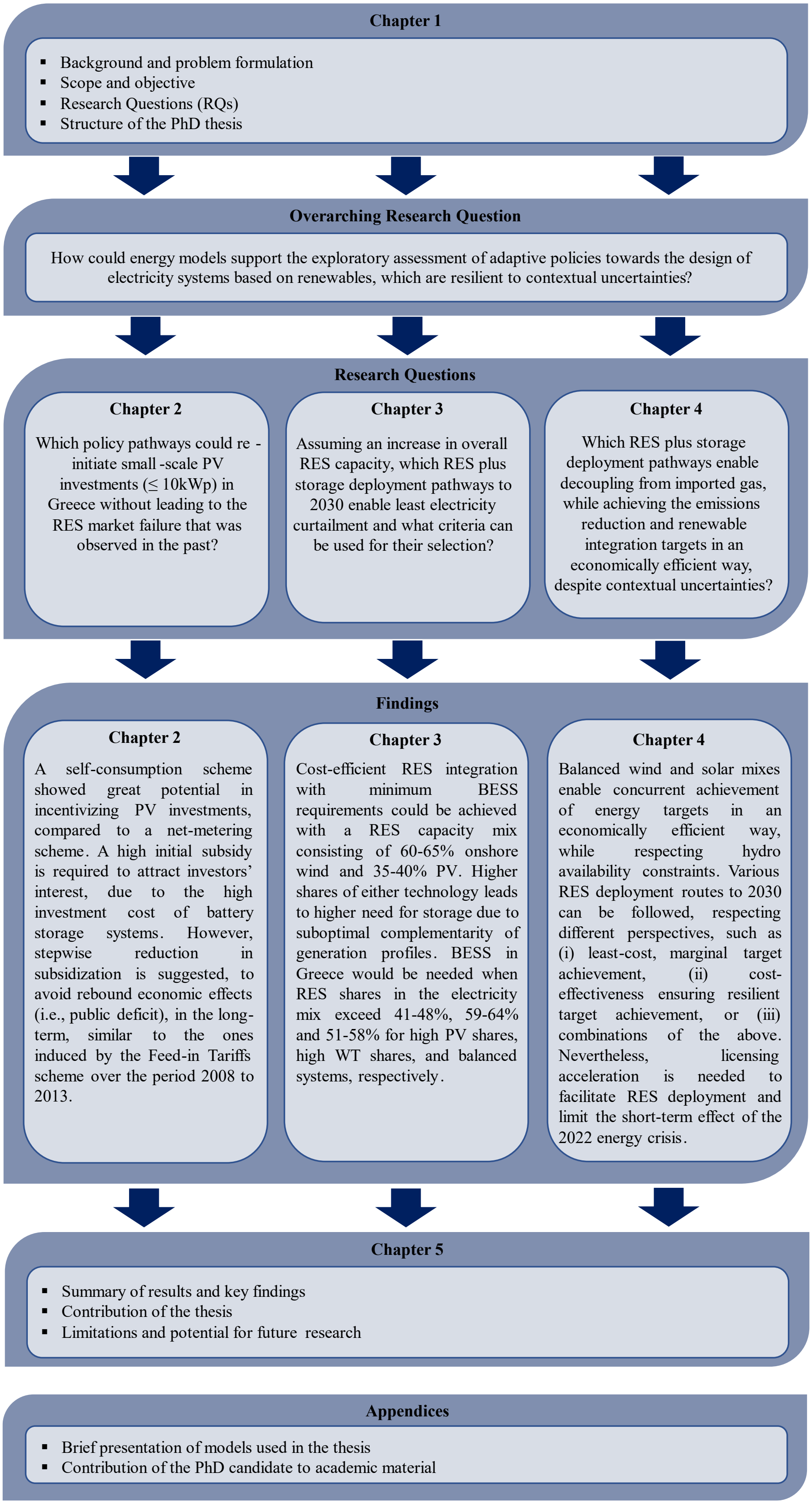
Chapter 1: This chapter starts with a brief timeline of European energy policy and regulations, highlighting the speed and complexity of policy-/decision-making with which members states need to cope with, especially under a deeply uncertain context. Following, an analysis of common energy modelling techniques supporting energy decision-making is performed, discussing their ability to capture uncertainty, as well as the trade-offs that need to be performed in order to do that. This led to the identification of the need for versatile, highly efficient tools, which feature combined high temporal, spatial and technological resolution, and consideration of uncertainty and unforeseen events, allowing them to support the design of decentralized energy systems based on intermittent RES. The chapter concludes with the presentation of the dissertation's objective, which aligns with the identified modelling needs, and the RQs that this dissertation answers with the developed modelling framework.

Chapter 2: In this chapter, the need for adaptive policies is validated and a new model is presented which treats policies/strategies as experiments and focuses on short-term planning while prescribing future corrective actions in case of contextual evolutions which alter policies'/ strategies' performance. Specifically, the AIM model **(i)** investigates the conditions under-, and the timeframe beyond- which a policy/strategy starts to deviate from the set targets, **(ii)** visualizes a map of dynamic adaptive policy pathways, and **(iii)** sets up a monitoring system for real world policy adaptation. Its applicability is demonstrated for the investigation of policy pathways incentivizing the uptake of rooftop PV in Greece, which is made feasible by linking it with a technology adoption model.

Chapter 3: In this chapter, a new model capable of simulating storage technologies, at high temporal, spatial and technological resolution, is presented. The STREEM model simulates the hourly operation of energy storage systems and calculates the required storage capacity towards exploitation maximization of the renewable electricity potential. Furthermore, in this chapter, AIM's applicability has been expanded to account for multiple RES technologies, allowing national-wide analyses to be performed. Both models have been linked to investigate VRES plus storage deployment pathways to 2030, limiting the enforcement of curtailment.

Chapter 4: In this chapter, AIM's clustering functionality has been upgraded to account for multiple policy/strategy targets (i.e., emissions reduction, renewable energy penetration, dependency on gas), while decomposing the impact of each assessed contextual factor on the success or failure of a policy/strategy towards a specific target. Furthermore, AIM has been expanded in order to calculate the carbon abatement cost of the examined electricity generation portfolio buildouts. The expanded AIM has been linked with STREEM and a wholesale electricity market simulation model, to investigate VRES plus storage deployment pathways limiting the effects of the 2022 energy crisis, accounting for the operation of both RES and thermal power plants.

Chapter 5: In the last chapter of this dissertation, the summary of the results is presented, both with respect to the thematic RQs governing **Chapters 2-4**, as well as the overarching RQ presented in **Chapter 1**. The contribution of the dissertation in the fields of energy modelling, policymaking and academia are also made explicit. Finally, limitations of the presented modelling framework and the analyses performed with them are presented, making suggestions for further improvements and research.



Chapter 1

- Background and problem formulation
- Scope and objective
- Research Questions (RQs)
- Structure of the PhD thesis

Overarching Research Question

How could energy models support the exploratory assessment of adaptive policies towards the design of electricity systems based on renewables, which are resilient to contextual uncertainties?

Research Questions

Chapter 2

Which policy pathways could re-initiate small-scale PV investments (≤ 10kWp) in Greece without leading to the RES market failure that was observed in the past?

Chapter 3

Assuming an increase in overall RES capacity, which RES plus storage deployment pathways to 2030 enable least electricity curtailment and what criteria can be used for their selection?

Chapter 4

Which RES plus storage deployment pathways enable decoupling from imported gas, while achieving the emissions reduction and renewable integration targets in an economically efficient way, despite contextual uncertainties?

Findings

Chapter 2

A self-consumption scheme showed great potential in incentivizing PV investments, compared to a net-metering scheme. A high initial subsidy is required to attract investors' interest, due to the high investment cost of battery storage systems. However, stepwise reduction in subsidization is suggested, to avoid rebound economic effects (i.e., public deficit), in the long-term, similar to the ones induced by the Feed-in Tariffs scheme over the period 2008 to 2013.

Chapter 3

Cost-efficient RES integration with minimum BESS requirements could be achieved with a RES capacity mix consisting of 60-65% onshore wind and 35-40% PV. Higher shares of either technology leads to higher need for storage due to suboptimal complementarity of generation profiles. BESS in Greece would be needed when RES shares in the electricity mix exceed 41-48%, 59-64% and 51-58% for high PV shares, high WT shares, and balanced systems, respectively.

Chapter 4

Balanced wind and solar mixes enable concurrent achievement of energy targets in an economically efficient way, while respecting hydro availability constraints. Various RES deployment routes to 2030 can be followed, respecting different perspectives, such as (i) least-cost, marginal target achievement, (ii) cost-effectiveness ensuring resilient target achievement, or (iii) combinations of the above. Nevertheless, licensing acceleration is needed to facilitate RES deployment and limit the short-term effect of the 2022 energy crisis.

Chapter 5

- Summary of results and key findings
- Contribution of the thesis
- Limitations and potential for future research

Appendices

- Brief presentation of models used in the thesis
- Contribution of the PhD candidate to academic material

Fig. 1.4. Visual illustration of the dissertation's structure

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Chapter 2 – Consumer engagement in the energy transition

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Nomenclature

Nomenclature

Abbreviations

AIM	Adaptive polIcymaking Model	GP	Gaussian Process
ATOM	Agent-based Technology adOption Model	LHS	Latin Hypercube Sampling
BESS	Battery Energy Storage System	NECP	National Energy and Climate Plan
BSAM	Business Strategy Assessment Model	NEM	Net-Metering
CO_2	Carbon di-oxide	PRIM	Patient Rule Induction Method
DAPP	Dynamic Adaptive Policy Pathway	PV	Photovoltaics
DREEM	Dynamic high-Resolution dEmand-sidE Management model	RES	Renewable Energy Sources
EC	European Commission	SC	Self-Consumption
EMA	Exploratory Modelling and Analysis	STEEM	STatistical approximation-based modEl EMulator
FiP	Feed-in Premium	TEEM	TEESlab Modelling
FiT	Feed-in Tariff	TEESlab	TechnoEconomics of Energy Systems laboratory

Indices and Sets

alt	Alternative policy	m	Simulation year until which the selected policy is implemented
D	Sets of inputs and outputs simulated by a model	n	Number of simulation years
i	Simulation year	X_*	New inputs whose outputs are not known
imp	Implemented policy	y	Outputs of the input/output set D

Parameters

BC	Initial investment cost of BESS	N	Number of LHS scenarios
BDR	BESS Cost decrease Rate	SL	Subsidy Level

Variables

A_i	PV capacity additions until year i	K_{f*}, K_{*f}	Kernel of known and new inputs
$Cost_i$	Policy cost until year i	$m_f(X_*)$	Expected value of f_* given X_*
K	Covariance kernel	$m_f(X)$	Expected value of f given X
K_{ff}	Kernel of known inputs	$p(f_*\|D)$	Prediction of functions governing the new inputs drawn from the calibrated $p(f\|D)$ estimation of functions
K_{**}	Kernel of new inputs	$p(f\|D)$	Estimation of functions governing the known input/output dataset D

A transdisciplinary modeling framework for the participatory design of dynamic adaptive policy pathways

Efficient policymaking is crucial towards climate change mitigation. However, policies' successful implementation depends largely on the context where they are applied. Classic decision-making used to be based on a static plan that was considered optimal for the "most likely" future contextual outcome. However, predicting the most probable evolution of this context has been proved unsuccessful, since it is vulnerable to unanticipated parameter change. Dynamic Adaptive Policy Pathways can address this problem focusing on the design of short-term policies, with simultaneous definition of adaptive interventions to be chosen on the long-term. This chapter presents a transdisciplinary modeling framework, which builds on the original Dynamic Adaptive Policy Pathways methodology. To demonstrate the applicability of this framework the author used it to explore the evolution of the small-scale solar photovoltaics share in Greece, towards the achievement of the national capacity targets of 2025 and 2030. Model outcomes facilitated the identification of several pathways achieving the capacity targets, while reducing the risk for retroactive policy changes. Overall, the presented study demonstrates potential to support the design of adaptive policies over contextual evolutions so that social, economic and technological aspects of integrative planning are balanced towards the achievement of climate targets.

Keywords: Dynamic adaptive policy pathways, Emulation, Energy policy, Technology adoption, Adaptive Policies, Solar PV

2.1. Introduction

Energy policymaking is a complex process. Most systems in which policies are implemented, are characterized by deep uncertainties and continuous changes in the external factors (e.g., technological innovation, social behavior, economic development, etc.) affecting its dynamics (Zhang et al., 2014). As such, decisionmakers, in their effort to create robust policies, can find themselves confused or incapable of making proper decisions, often due to insufficient information about the uncertainties they need to consider (Chappin et al., 2017; Forni et al., 2016; Pfenninger et al., 2018). Since policymaking is highly corelated to the future, many researchers have focused on studies regarding the uncertain evolution of the context, within which policies are applied (Offermans and Corvers, 2012; Swanson et al., 2010). Classic decision making used to be based on a static plan considered optimal for the "most likely" future outcome. This strategy has been proven vulnerable to unexpected future evolutions leading to failure of the once considered optimal plan. Especially when studying complex systems, the selection of a policy based on the most probable future evolution is risky and unrealistic. This indicates that policies should not be optimally designed for the best estimation, but should be robust in most of the future evolutions (Walker et al., 2001), and flexible to adapt according to the evolution of their context (Kwakkel et al., 2016). Following this notion, the concept of adaptive policies, which focuses on short-term planning and describes potential future adaptive actions, defined from the design phase and not on an ad-hoc basis, has emerged in the past few years (Haasnoot et al., 2013; Spyridaki et al., 2016).

Reference to adaptive policies is traced back to 1927, when Dewey (1927) proposed that policies should be treated as experiments and adapt over time as new information and experience are acquired (Swanson et al., 2010). Since then, the concept of adaptive policies has experienced significant improvements and variations. In 2001, Walker et.al. (2001) presented an analytical methodology which can be used for the design of adaptive policies. In 2010, Kwadijk et.al. (2010) used adaptation tipping points, which are points at which a strategy change is initiated to cope with significant changes to uncontrollable contextual influences for the design of adaptive strategies for climate change and sea level rise preparation. In 2011, Haasnoot et.al. (2011) explored adaptation pathways, defined as sequences of actions succeeding one another towards the achievement of a target, to identify sustainable water management strategies in river deltas. Integrating the concepts of adaptive policy making, adaptation tipping points and adaptation pathways led to the development of the Dynamic Adaptive Policy Pathways (DAPP) methodology by Haasnoot et.al. in 2013 (Haasnoot et al., 2013), which is a novel framework combining the benefits of all the three previous concepts. The methodology achieves dynamic robustness by using **(i)** the concept of “sell-by” date, which is the date after which a policy starts to perform poorly and an alternative policy is implemented, and **(ii)** a monitoring system which allows the end-user to monitor real-world critical contextual evolutions that trigger the initiation of the policy adaptation process. As a result, according to the evolution of the future, the appropriate adaptation plan is chosen dynamically. The above methodologies find practice in a variety of research areas such as climate change (Maru et al., 2014), water resource management (Zandvoort et al., 2017), coastal flood risk management (Manocha and Babovic, 2017; Ramm et al., 2018), urban heat risk management (Kingsborough et al., 2017), agricultural management (Nguyen et al., 2019; Prober et al., 2017), and the transportation sector (Jittrapirom et al., 2018; Marchau et al., 2010; Walker and Marchau, 2017).

A problem worth being analyzed with the concept of adaptive policies is the decarbonization of the energy system and especially electricity generation which accounts for more than one third of the energy-related CO_2 emissions worldwide (Ang et al., 2011; Zhou et al., 2012). The energy system is composed of many actors, which according to Bale et.al. (2015) are: **(a)** agents with conflicting interests (e.g., generators, suppliers, consumers, etc.) dynamically interacting with each other, **(b)** technologies and infrastructure, which, while being stable actors, their adoption is uncertain, and **(c)** the environment (e.g., political, social, cultural, etc.) in which the former actors operate. Thus, it becomes apparent that the energy system is by its nature complex, characterized by high heterogeneity, and cannot be holistically controlled. Economic activities are also closely linked to the energy system, and thus, a transition to a low-carbon society should be linked to a transition to a sustainable low-carbon economy. This link is also reflected in the so-called energy trilemma or the "3Es" problem, which refers to the complex relationship of the energy system, economic development and the environmental protection, with significant implications for the social and political dimensions (Nakata et al., 2011). It is proposed that energy transitions should be considered as evolutions of three discernible systems which change together: **(i)** a techno-economic system featuring the energy flows in an energy market, **(ii)** a socio-technical system featuring the energy technologies within a social context, and **(iii)** a political system featuring energy policies (Bolwig et al., 2019).

Designing policies to support the decarbonization of the energy system is a non-trivial problem since the interests of all the involved agents must be balanced. Energy models have played a crucial role in understanding the dynamics of the energy system, energy planning, energy policy, and implication analysis from the introduction of technologies in the system (Doukas, 2013; Müller et al., 2018). However, until recently, modeling practices used to be unilateral, because usually models address the energy transition issue in an one-sided manner (e.g., technological/economic, etc.) (Bale et al., 2015). In order to capture multiple dimensions of the energy transition and satisfy multiple aspects of the "3Es" problem, a transdisciplinary modeling approach is required (Nakata et al., 2011). To this end, this chapter presents such a transdisciplinary modeling framework that implements the original DAPP methodology via the use of a modeling ensemble, capturing the correlation between the economic, social and political dimensions of renewable energy source (RES) technology diffusion. In particular, the modeling ensemble includes: **(i)** an agent-based model which is considered a valuable tool for analyzing complex private decisions of consumers, **(ii)** a Gaussian Process (GP)-based emulator accelerating heavy model simulations, making the analysis of many scenarios possible, and **(iii)** a new plugin toolbox facilitating decision-making under deep uncertainty, which builds on the strengths of Exploratory Modeling and Analysis (EMA) (Kwakkel and Pruyt, 2013). Each model is used in different steps of the DAPP methodology, compiling a complete framework for decision support and uncertainty appraisal.

To demonstrate its applicability, the framework was used to explore sustainable pathways for the support of the further diffusion of small-scale solar photovoltaics (PV) (i.e., up to 10kWp) in Greece, towards the achievement of the 2025 and 2030 capacity targets. Solar PV is considered a fundamental technology, ranked among the RES technologies with the highest potential (Zhang et al., 2016), for the support of the transition towards a low-carbon energy system (Michas et al., 2019). The attractiveness of PV is especially reported in Greece where the solar irradiation levels are high (Nikas et al., 2018). Additionally, this work aims at providing more practical guidelines on the implementation of the DAPP methodology, to assist end-users from the modeling community to replicate the methodology to the benefit of their research and to develop modeling frameworks similar to the one presented here.

Overall, to the best of the author's knowledge, the novel contribution of this study to the scientific literature is twofold:

- The development of a new plugin toolbox facilitating the participatory design of DAPP, through real time visualizations and interactive stakeholder consultation. The implementation of a policy for a time period affects the performance of the alternative policies succeeding it. The presented toolbox updates the policy adaptation map showing only the available options from the last timeframe a policy is implemented and forward. This means that opportunities and dead-ends are explicitly visualized in a stakeholder-friendly fashion.
- The development of a transdisciplinary modeling framework that implements the original DAPP methodology, capturing several aspects of the "3Es" problem by: (i) modeling various policies (i.e., net-metering (NEM), self-consumption (SC)) supporting the diffusion of small-scale PV in Greece, (ii) correlating the technology adoption with its value for consumers (i.e., guiding their decision to invest in PV), and (iii) generating energy transition pathways towards the national targets, that balance the economic interests of consumers and public authorities.

The remainder of this chapter is organized as follows: **Section 2.2** presents the models composing the transdisciplinary modeling framework. **Section 2.3** shows the application of this framework to the geographic and socioeconomic context of Greece, and the design of DAPP towards the achievement of the 2025 and 2030 PV capacity targets. **Section 2.4** reports simulation results visualizing different potential transition pathways. Finally, **section 2.5** provides conclusions, discusses key policy implications for potential policymakers and end-users, and shapes directions for future research.

2.2. A transdisciplinary modeling framework

This research builds on the original DAPP methodology as introduced by Haasnoot et.al (2013), adapted to fit the purpose of the case under study and implemented with the use of an appropriate modeling ensemble as visualized in **Fig. 2.1**. The modeling ensemble that implements the DAPP methodology and compiles the transdisciplinary framework consists of the **A**gent-based **T**echnology ad**O**ption **M**odel (ATOM) (Stavrakas et al., 2019), the **ST**atistical approximation-based mod**E**l **EM**ulator (STEEM) (Papadelis and Flamos, 2018) and, the **A**daptive pol**I**cymaking **M**odel (AIM), presented for the first time in this chapter. The modeling ensemble is part of the **T**echno**E**conomics of **E**nergy **S**ystems **lab**oratory (**TEE**Slab) **M**odeling (TEEM) suite and was developed in the context of the EC-funded Horizon 2020 project “TRANSrisk[5]”.

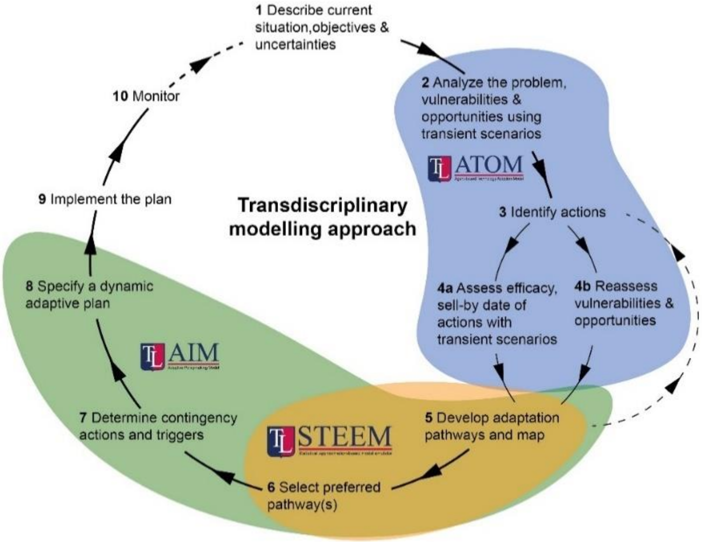

Fig. 2.1. The DAPP methodology augmented with the use of a transdisciplinary modeling ensemble as presented in the context of this study. Original figure adapted by Haasnoot et.al. (2013)

2.2.1. ATOM

ATOM is an agent-based model, which apart from exploring the expected technology adoption by consumers under different supporting policy schemes, allows the user to consider and explicitly quantify uncertainties related to agents’ preferences and decision-making criteria (i.e., behavioral uncertainty). To develop ATOM, the initial framework of the Business Strategy Assessment Model (BSAM), presented by Papadelis et al. (2012), has been expanded and further developed to focus on the consumers, rather than the power generators, as the unit of analysis . The novelty of the model, compared to other similar ones in the field, lies in obtaining realistic uncertainty bounds and splitting the total model output uncertainty in its major contributing uncertainty sources, based on a variance decomposition approach, while accounting for model-structure uncertainty. ATOM simulates the decision of agents (i.e., consumers) to adopt or not residential solar PV – based on an intertwined variety

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[5] http://transrisk-project.eu/

of factors – by correlating the adoption decision with its value for them. Those factors are social, market-related and technological and are presented in **Table 2.1**. The analytical modeling framework and mathematical formulae of the model are presented in Stavrakas et.al (2019).

Table 2.1. Contextual parameters affecting the decision of agents to invest in small-scale solar PV as simulated in ATOM

Parameter type	**Description**
Social	The agents' initial beliefs regarding the profitability of the investment
	The agents' social learning effect, by which agents update their initial beliefs regarding the profitability of the investment, based on the experiences of other agents in their social cycle that have already invested
	The agents' resistance to invest which depends on the degree of profitability of the investment (measured in terms of return of investment) and the proportion of agents (from the total agents simulated) who have already invested
	The agents' probability to invest, which increases as the resistance decreases
	The agents' inertia to invest, which describes the trend of agents to delay investments in new technologies
Market-related	The evolution of the electricity retail price
	The evolution of the total residential electricity demand
Technological	The evolution of the battery energy storage system's (BESS) investment costs (in case of a SC scheme)
	The evolution of the solar PV panels' cost

2.2.2. STEEM

STEEM is a "black-box" emulator, that serves as a plugin toolbox to facilitate fast model estimations. A two-step approach is followed to run a "black-box" emulator: The first step is called calibration: sets of inputs and outputs D simulated in the original model are given to the emulator for its training. Training means that the "black box" emulator learns the correlation between inputs and outputs without the need to "know" the usually non-linear (and as such time consuming and computational heavy) formulae governing the original model. After its training, the calibrated model can be used to make quick estimations of the original model's outputs given new inputs. Several machine learning algorithms (e.g., statistical regressions, neural networks, etc.) can be used to build a "black-box" emulator (Reynolds et al., 2018). STEEM uses GP regression for both the calibration and output estimations procedures (Papadelis and Flamos, 2018), as it is simple to implement and it provides estimations in the form of a probabilistic distribution with a mean and a variance (Yoon and Moon, 2018). The latter makes it possible to quantify the uncertainty of output estimations and reapply calibration, if necessary. STEEM's simulation speed and low computational requirements make it a valuable participatory tool for providing quick answers to relevant experts and end-users, allowing a tight loop between stakeholders and modeling teams to be established; the timely identification of options and scenarios that are of stakeholders' interest or disinterest is thus facilitated. Eq. (2.1) and (2.2) briefly describe how calibration and prediction is performed in STEEM. As GP regression presentation is out of scope of this research work, for further analysis the reader is referred to the original publication for STEEM (Papadelis and Flamos, 2018).

$$p(f|D) = N\sim\left(f|K_{ff}K_{ff}^{-1}y,\ K_{ff} - K_{ff}K_{ff}^{-1}K_{ff}\right) \tag{2.1}$$

$$p(f_*|D) = N\sim\left(f_*|m_f(X_*) + K_{*f}K_{ff}^{-1}\left(y - m_f(X)\right),\ K_{**} - K_{*f}K_{ff}^{-1}K_{f*}\right) \tag{2.2}$$

where:

- $p(f|D)$: the estimation of functions governing the known input/output dataset D,
- K: a covariance matrix (kernel) which is formed by evaluating a covariance function on data (describing how data change together). The parameters of the covariance function are calculated using historical data,
- K_{ff}: the kernel of known inputs,
- K_{**}: the kernel of new inputs,
- K_{f*}, K_{*f}: the kernel of known and new inputs,
- y: the outputs of the input/output set D,
- X_*: new inputs whose outputs are not known,
- $p(f_*|D)$: the prediction of functions governing the new inputs drawn from the calibrated $p(f|D)$ estimation of functions,
- $m_f(X_*) = E[f_*(X_*)]$: the expected value of f_* given X_*,
- $m_f(X) = E[f(X)]$: the expected value of f given X.

2.2.3. AIM

The original DAPP methodology served as the central pillar for the development of AIM. AIM **(i)** investigates the conditions under-, and the timeframe beyond- which a policy starts to deviate from the set targets, **(ii)** visualizes a map of DAPP, and **(iii)** sets up a monitoring system for real world policy adaptation. To do so, AIM performs exploratory analysis (Kwakkel and Pruyt, 2013) on many scenarios, with ultimate goal the visualization of a map showing sequences of policies that lead to a predefined target, regardless the evolution of the context within which they are applied. Scenarios are defined as sets of inputs (usually policy typologies and uncontrollable contextual variables) and outputs (policy outcomes), generated by a simulation model. Emulation can also be used if the number of scenarios required is very large, or if the simulation model requires significant simulation time for each scenario. The large number of scenarios is a key component to the analysis performed by AIM, since it allows a significant level of resolution for each contextual parameter to be considered. Scenarios are created using Latin Hypercube Sampling (LHS) (Mckay et al., 2000) to cover the whole uncertainty space of the contextual parameters. AIM consists of three modules visually presented in **Fig. 2.2** and analytically described in the following sections.

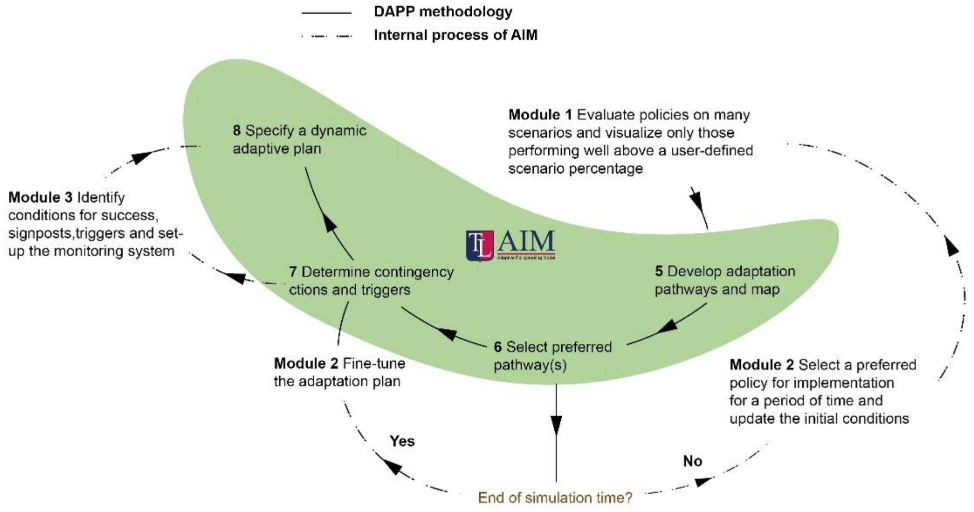
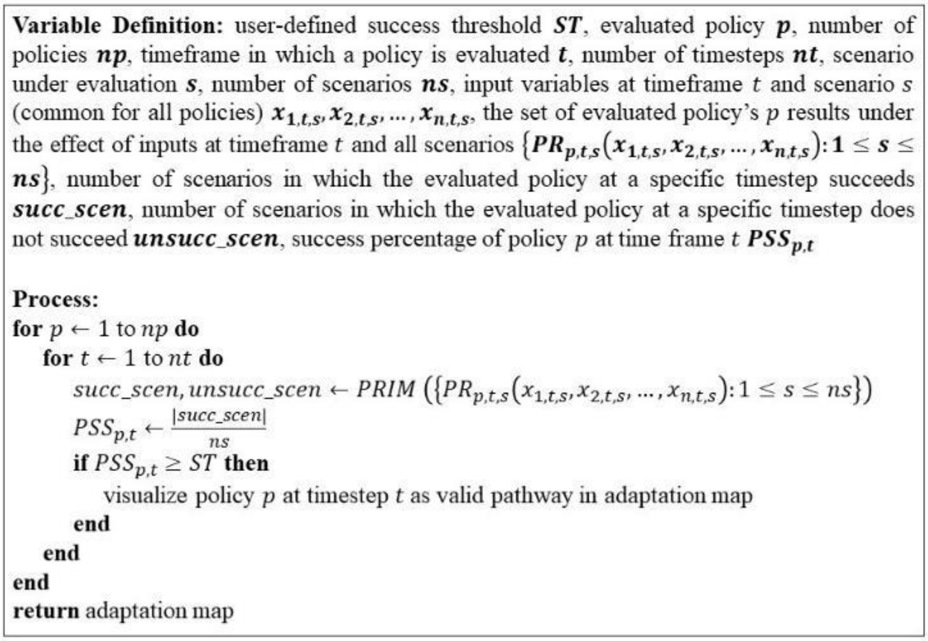


Fig. 2.2. The modules of AIM as applied in the original DAPP methodology presented by Haasnoot et.al. (2013).

Module 1: Definition & identification of successful policies

Every policy outcome is evaluated across every timeframe of the simulation period in each scenario. The aim is to identify those polices that perform well in a user-defined percentage of the scenarios under study (i.e., future contextual evolutions), thus being valid options for visualization as potential pathways in an adaptation map. This is done using a heuristic algorithm called Patient Rule Induction Method (PRIM), which identifies segments (clusters) of the input space, in each simulation timeframe, corresponding to successful policy results (Papadelis and Flamos, 2018). The inputs that belong in a cluster, correspond to scenarios under which a policy succeeds. The number of successful scenarios is divided with the total number of scenarios to acquire the success percentage of the policy in each timeframe of the simulation period. If this percentage is larger than the user-defined threshold, the policy is visualized in the map as a straight line from the start of the simulation time until the timeframe it starts to perform poorly. **Fig. 2.3** visualizes the operations within Module 1.



Variable Definition: user-defined success threshold $\boldsymbol{ST}$, evaluated policy $\boldsymbol{p}$, number of policies $\boldsymbol{np}$, timeframe in which a policy is evaluated $\boldsymbol{t}$, number of timesteps $\boldsymbol{nt}$, scenario under evaluation $\boldsymbol{s}$, number of scenarios $\boldsymbol{ns}$, input variables at timeframe t and scenario s (common for all policies) $\boldsymbol{x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s}}$, the set of evaluated policy's p results under the effect of inputs at timeframe t and all scenarios $\{\boldsymbol{PR_{p,t,s}(x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s}): 1 \leq s \leq ns}\}$, number of scenarios in which the evaluated policy at a specific timestep succeeds $\boldsymbol{succ\_scen}$, number of scenarios in which the evaluated policy at a specific timestep does not succeed $\boldsymbol{unsucc\_scen}$, success percentage of policy p at time frame t $\boldsymbol{PSS_{p,t}}$

Process:

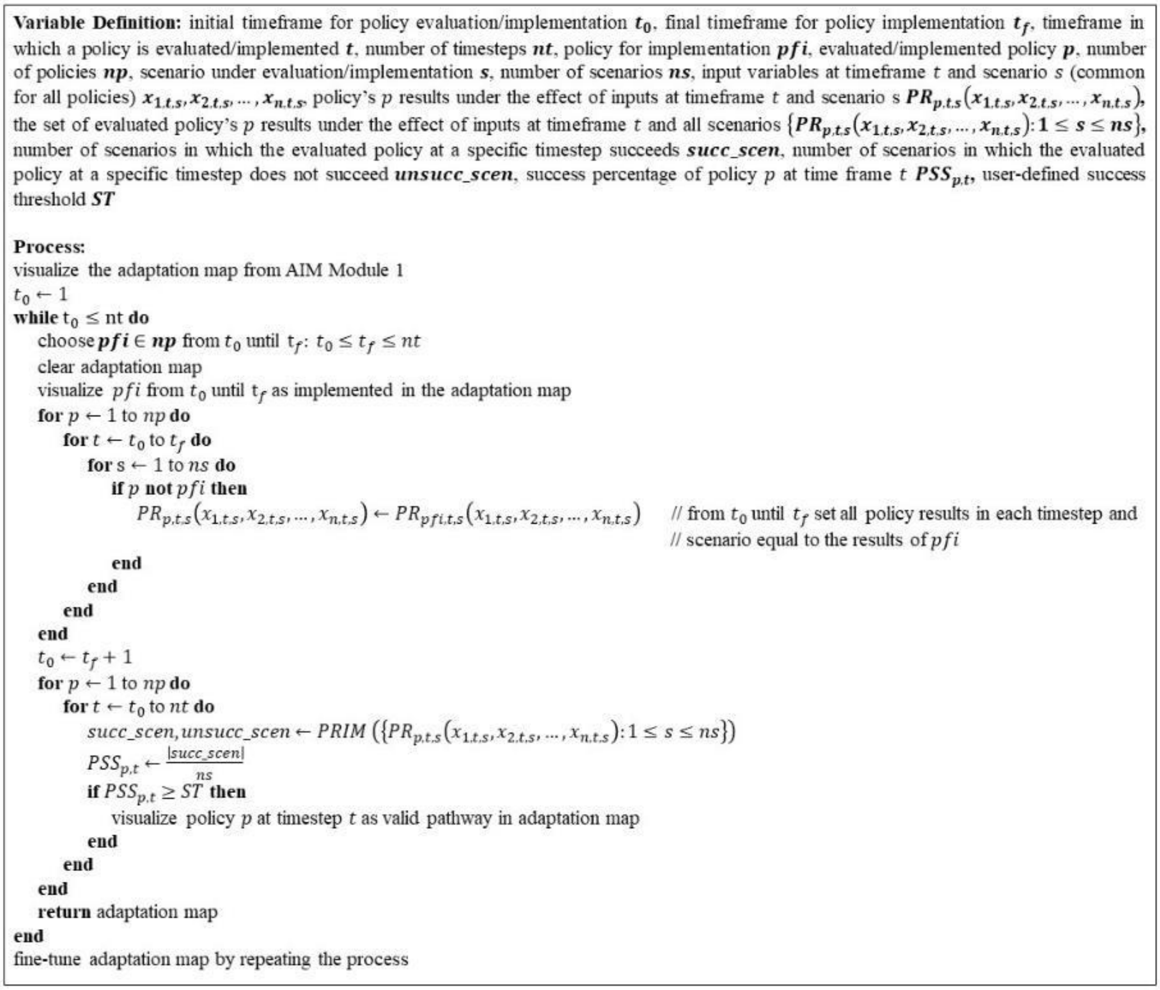
```
for $p \leftarrow 1$ to $np$ do
    for $t \leftarrow 1$ to $nt$ do
        $succ\_scen, unsucc\_scen \leftarrow PRIM\left(\{PR_{p,t,s}(x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s}): 1 \leq s \leq ns\}\right)$
        $PSS_{p,t} \leftarrow \frac{|succ\_scen|}{ns}$
        if $PSS_{p,t} \geq ST$ then
            visualize policy $p$ at timestep $t$ as valid pathway in adaptation map
        end
    end
end
return adaptation map
```

Fig. 2.3. Pseudocode of AIM: Module 1

Module 2: Selection & design of adaptation pathways

The novelty of AIM lies in allowing for a participatory approach when designing the adaptation plan. Stakeholders' perspectives, regarding the choice of pathways, are incorporated in real-time and the adaptation map is updated within seconds (depending on the number of scenarios). AIM starts by visualizing the available actions from the start of simulation time (i.e., stakeholder's "today") until the time they start to perform poorly, with reference to the set targets ("sell-by" date). At this point, the initial conditions of the available actions are the outcome achieved until the stakeholder's "today" from previous policy implementations. A stakeholder chooses the first action to be implemented and for how long. After this choice, the initial conditions are the outcome of the last implemented policy. Module 1 runs again for the new initial conditions and the map is updated, showing only the available actions from the last timeframe the policy was implemented and forward. The new map is completely different from the initial, as the implementation of a single action affects the performance and the "sell-by" dates of all the other actions. A next policy is chosen, and the process continues until the end of simulation time, at which point iterations can be made to fine-tune the basic plan, slightly changing the duration of each implemented action to take advantage of opportunities according to a stakeholder's perspective.

The resulting sequence of policies is the selected adaptation pathway, built directly by the stakeholder. **Fig. 2.4** describes the operations within Module 2.



Variable Definition: initial timeframe for policy evaluation/implementation $\boldsymbol{t_0}$, final timeframe for policy implementation $\boldsymbol{t_f}$, timeframe in which a policy is evaluated/implemented $\boldsymbol{t}$, number of timesteps $\boldsymbol{nt}$, policy for implementation $\boldsymbol{pfi}$, evaluated/implemented policy $\boldsymbol{p}$, number of policies $\boldsymbol{np}$, scenario under evaluation/implementation $\boldsymbol{s}$, number of scenarios $\boldsymbol{ns}$, input variables at timeframe t and scenario s (common for all policies) $\boldsymbol{x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s}}$ policy's p results under the effect of inputs at timeframe t and scenario s $\boldsymbol{PR_{p,t,s}(x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s})}$, the set of evaluated policy's p results under the effect of inputs at timeframe t and all scenarios $\boldsymbol{\{PR_{p,t,s}(x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s}): 1 \leq s \leq ns\}}$, number of scenarios in which the evaluated policy at a specific timestep succeeds $\boldsymbol{succ\_scen}$, number of scenarios in which the evaluated policy at a specific timestep does not succeed $\boldsymbol{unsucc\_scen}$, success percentage of policy p at time frame t $\boldsymbol{PSS_{p,t}}$, user-defined success threshold $\boldsymbol{ST}$

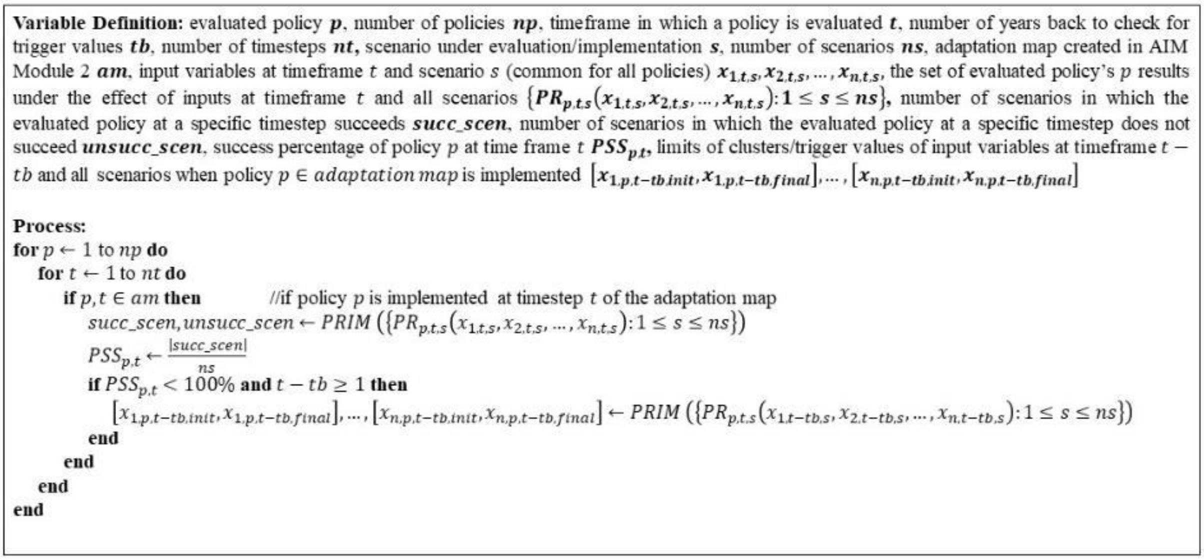
Process:

```
visualize the adaptation map from AIM Module 1
$t_0 \leftarrow 1$
while $t_0 \leq nt$ do
    choose $pfi \in np$ from $t_0$ until $t_f$: $t_0 \leq t_f \leq nt$
    clear adaptation map
    visualize $pfi$ from $t_0$ until $t_f$ as implemented in the adaptation map
    for $p \leftarrow 1$ to $np$ do
        for $t \leftarrow t_0$ to $t_f$ do
            for $s \leftarrow 1$ to $ns$ do
                if $p$ not $pfi$ then
                    $PR_{p,t,s}(x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s}) \leftarrow PR_{pfi,t,s}(x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s})$    // from $t_0$ until $t_f$ set all policy results in each timestep and
                                                                                                    // scenario equal to the results of $pfi$
                end
            end
        end
    end
    $t_0 \leftarrow t_f + 1$
    for $p \leftarrow 1$ to $np$ do
        for $t \leftarrow t_0$ to $nt$ do
            $succ\_scen, unsucc\_scen \leftarrow PRIM\left(\{PR_{p,t,s}(x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s}): 1 \leq s \leq ns\}\right)$
            $PSS_{p,t} \leftarrow \frac{|succ\_scen|}{ns}$
            if $PSS_{p,t} \geq ST$ then
                visualize policy $p$ at timestep $t$ as valid pathway in adaptation map
            end
        end
    end
    return adaptation map
end
fine-tune adaptation map by repeating the process
```

Fig. 2.4. Pseudocode of AIM: Module 2

Module 3: Making the pathways dynamic

After deciding on the adaptation pathway, AIM calculates at each simulation timeframe, the success percentage of the respective policy compiling the adaptation pathway. If the success percentage is not 100%, AIM goes back a specified number of simulation timeframes (depending on the case study) and implements PRIM again to identify conditions (input clusters) at the "early" timeframe corresponding to successful policy results at the actual simulation timeframe. The contextual variables that belong in a cluster are called signpost variables because they inform the user about what should be monitored to identify imminent deviations. The clusters' minimum and maximum values are called trigger values, since outside of those, a policy change process must be activated. Those trigger values inform the stakeholder for conditions (i.e., values of contextual variables'), the realization or exceeding of which, signify imminent deviation of the policy from the set targets (policy's sell-by date). In such a case, a re-evaluation (i.e., Module 1 and Module 2) of the available alternative polices, which at this point are contingency actions, needs to be made. This monitoring system is useful because it provides the stakeholder with a reasonable amount of time to design and implement corrective actions, if deviation from the targets is observed. With this system in place, the pathway is made dynamic because real world monitoring and adaptation is feasible. **Fig. 2.5** describes the operations within Module 3.



Variable Definition: evaluated policy $\boldsymbol{p}$, number of policies $\boldsymbol{np}$, timeframe in which a policy is evaluated $\boldsymbol{t}$, number of years back to check for trigger values $\boldsymbol{tb}$, number of timesteps $\boldsymbol{nt}$, scenario under evaluation/implementation $\boldsymbol{s}$, number of scenarios $\boldsymbol{ns}$, adaptation map created in AIM Module 2 $\boldsymbol{am}$, input variables at timeframe t and scenario s (common for all policies) $\boldsymbol{x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s}}$, the set of evaluated policy's p results under the effect of inputs at timeframe t and all scenarios $\boldsymbol{\{PR_{p,t,s}(x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s}) : 1 \le s \le ns\}}$, number of scenarios in which the evaluated policy at a specific timestep succeeds $\boldsymbol{succ\_scen}$, number of scenarios in which the evaluated policy at a specific timestep does not succeed $\boldsymbol{unsucc\_scen}$, success percentage of policy p at time frame t $\boldsymbol{PSS_{p,t}}$, limits of clusters/trigger values of input variables at timeframe $t - tb$ and all scenarios when policy $p \in adaptation\ map$ is implemented $\boldsymbol{[x_{1,p,t-tb,init}, x_{1,p,t-tb,final}], \dots, [x_{n,p,t-tb,init}, x_{n,p,t-tb,final}]}$

Process:

```
for $p \leftarrow 1$ to $np$ do
  for $t \leftarrow 1$ to $nt$ do
    if $p, t \in am$ then            //if policy $p$ is implemented at timestep $t$ of the adaptation map
      $succ\_scen, unsucc\_scen \leftarrow PRIM\ (\{PR_{p,t,s}(x_{1,t,s}, x_{2,t,s}, \dots, x_{n,t,s}) : 1 \le s \le ns\})$
      $PSS_{p,t} \leftarrow \frac{|succ\_scen|}{ns}$
      if $PSS_{p,t} < 100\%$ and $t - tb \ge 1$ then
        $[x_{1,p,t-tb,init}, x_{1,p,t-tb,final}], \dots, [x_{n,p,t-tb,init}, x_{n,p,t-tb,final}] \leftarrow PRIM\ (\{PR_{p,t,s}(x_{1,t-tb,s}, x_{2,t-tb,s}, \dots, x_{n,t-tb,s}) : 1 \le s \le ns\})$
      end
    end
  end
end
```

Fig. 2.5. Pseudocode of AIM: Module 3

2.3. Application to the PV sector in Greece

In this section, the transdisciplinary modeling framework, as presented in **Section 2.2**, is applied to the PV sector in Greece. The DAPP methodology is implemented, step-by-step, using the modeling ensemble, to develop pathways for the further diffusion of small-scale PV towards the achievement of the 2025 and 2030 capacity targets. In particular, the author examines how the implementation of different policies can incentivize consumers to invest in residential PV installations, under a wide spectrum of future contextual evolutions, proposing sustainable pathways towards the achievement of the national PV capacity targets. To the best of the author's knowledge this is the first time that such a modeling exercise is attempted for the geographical and socioeconomic context of Greece.

2.3.1. Step 1: Description of the current situation, objectives and uncertainties

During the period 2008-2013, Greece experienced a boom of PV installations, owing mainly to the attractive funding programme for residential solar installations, which introduced generous Feed-in Tariffs (FiT) and at the same time reduced the excessive installation bureaucratic procedures that were in effect until 2007 (Karteris and Papadopoulos, 2013). FiT, a widely used scheme to support the promotion of RES (Zhang et al., 2016), were mostly designed as a generous subsidy to help initiate investments on the technology (Koumparou et al., 2017). During this period, the initial 2020 PV capacity target (2.2GWp) was reached and exceeded by 220MWp. However, despite the early achievement of the target, the cost of this policy for that period was €5 billion (Kyritsis et al., 2017), which led to a significant deficit to the Greek RES Special Account (Koumparou et al., 2017). This situation raised concerns about the viability of the Greek RES market, considering the increasing installation applications. To counterbalance the economic implications, the Greek government decided to impose extra taxation on the prosumers' income from PV generated electricity, which came simultaneously with the already agreed reduction of FiT. As a result, PV investments in Greece started to decrease since the investment environment was considered less safe for consumers (Flamos, 2016; Papadelis et al., 2016). The latter made clear that financial support to incentivize PV investments had to be designed in a way that does not result in public deficits or burdensome costs for consumers (Koumparou et al., 2017).

As such, the European Union (EU) analyzed different support mechanisms, including NEM, SC, Feed-in Premiums (FiP) and tenders, that could increase, once again, consumers' willingness to invest in residential PV (Kyritsis et al., 2017). A change to NEM schemes has been observed in most of the countries worldwide. Additionally, SC with Battery Energy Storage System (BESS) is starting to attract significant consumer attention, since it allows to self-consume more PV generated electricity, thus increasing the profits for prosumers (Abdin and Noussan, 2018). In Greece, for large solar parks (>500kWp), a FiP over the system marginal price is available. NEM has been in effect since 2015 for both rooftop and ground-mounted systems, up to 20 kWp for residential installations, and up to 500 kWp for commercial installations, that are intended for SC. Virtual NEM has also been legislated in 2016 to allow specific entities (i.e., public buildings) to consume net-metered PV electricity that is generated away from their premises. Finally, tenders have been introduced in Greece since 2017 for new PV projects smaller than 10 MWp. Projects that are selected through the tendering process are awarded a sliding FiP (HELAPCO, 2016; RES-Legal, 2017).

The objective of this study is the selection of proper policy measures to incentivize the further diffusion of small-scale PV towards the achievement of the national 2025 and 2030 capacity targets. Given historical data, the total PV capacity achieved until the end of 2017 was 2623 MWp (Hellenic

Association of Photovoltaic Companies (HELAPCO), 2018). The overall PV targets for 2025 and 2030, as updated in November 2018, are 5500 MWp and 6900 MWp respectively (Ministry of Environment and Energy, 2019a; Psomas, 2018). Over the period 2016 to 2018 the contribution of small scale PV to the overall capacity targets is about 14.5%, (for about every 7 MWp large-scale installation, 1 MWp small-scale PV is installed) (Operator of RES and Guarantees of Origin, 2018). Following this trend, the respective small-scale PV addition targets for 2025 and 2030 with relevance to the achieved capacity at the end of 2017 are assumed to be 417 MWp and 620 MWp respectively. Considering the updated 2020 overall PV capacity targets (3300 MWp), the target trajectory for small scale PV from January 2018 and forward is shown in **Fig. 2.6**. The flat line between years 2015 and 2018 shows the diminishing of investments that followed the retroactive changes in the PV support schemes which came concurrently with the ongoing recession in the Greek economy.

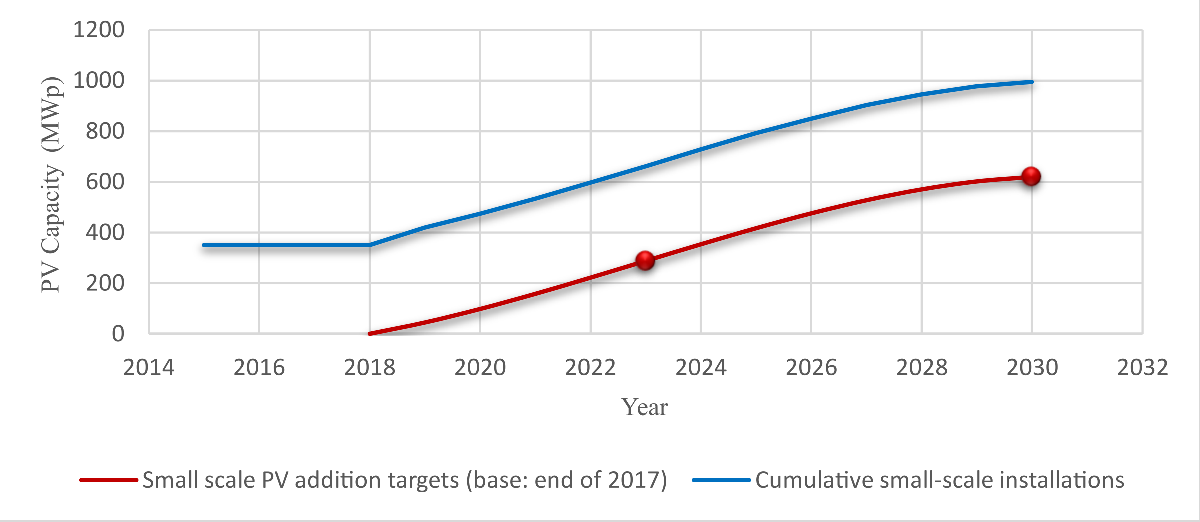


Fig. 2.6. Trajectory of the small-scale PV capacity targets until 2030 in Greece

The European Parliament has also agreed on intermediate milestones to monitor the progress towards the achievement of the national binding targets. More specifically, by 2022, 2025 and 2027, member states must achieve at least 18%, 43% and 65% respectively of the total RES increase envisaged by 2030 (The European Parliament and the Council of the European Union, 2018). Since in this study the focus is on solar PV capacity additions, it is assumed that the RES milestones can be decomposed to milestones for each generating technology. As such, comparing the milestones with the target trajectory presented in **Fig. 2.6**, the lower allowed deviation from the PV targets trajectory for the years 2022, 2025 and 2027 are equal to -5%, -12% and -10% respectively.

The policy measures under assessment are the NEM scheme, currently in operation, and a potential SC scheme that subsidizes part of a BESS. The aim of this work is to assess the effectiveness of emerging subsidy-free projects in terms of consumer-scale investments attraction, as traditional subsidy-/tariff-based RES support schemes (e.g., FiT, tenders, etc.) are globally starting to phase out (Brown et al., 2019). On the other hand, subsidy programmes, which supports residential storage, as the one recently prolonged in Germany (Goebel et al., 2017), promising a payment depending on the level of the initial investment cost of the storage, are still necessary to overcome high costs of storage projects and make them attractive to consumers.

In Greece, under the currently operational NEM scheme (Ministry of Environment and Energy, 2019b), prosumers inject all the generated electricity to the grid, while consuming from it according to their needs. The net electricity consumed by each household (i.e., electricity inflow minus electricity outflow) is calculated every four months which is the billing period for residential consumers. In the case of positive net electricity, the amount due is paid to the retailer, whereas in the case of negative net electricity, the excess electricity's value is credited to the next billing period and cleared with any positive net electricity. Crediting goes on for a three-year period, at the end of which, any surplus generation is not remunerated. This is contrary to NEM practices which remunerate the prosumer for the locally generated electricity either by the prevailing retail price, or with a standard tariff reflecting the value of generation, or the value of avoided costs for the utility (Brown and Sappington, 2017a). Finally, unlike common NEM practices where grid charges are included during the calculation of the prosumers' compensation (Brown and Sappington, 2017b), under the NEM legislation in Greece, prosumers pay specific regulated charges (hereafter mentioned as grid charges because they apply to all electricity making use of the grid) for the sum of the electricity consumed (Christoforidis et al., 2016).

On the other hand, a possible SC with BESS scheme, as presented in Stavrakas et.al (2019) is also assessed. More specifically it is assumed that the PV system is connected to the grid, but prosumers can directly consume self-generated electricity without injecting it to the grid. Grid charges do not apply to self-consumed electricity. Furthermore, when PV generation exceeds the household's demand, surplus electricity is stored to the BESS for later direct use. After charging the BESS, any excess electricity is injected to the grid without any remuneration.

As SC with BESS is not yet legislated in Greece, examples of other countries were used as a guide for the selection of the proper BESS subsidy levels. In Germany, the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety subsidizes 30% of the BESS initial investment cost for PV installations up to 30kWp (Renewable Energy Association (REA), 2016; Truong et al., 2016). In Southern Australia, the State Government's "Home battery" scheme subsidizes 600 Australian dollars per kWh of installed residential BESS (Department of Energy and Mining, 2018). This corresponds to almost 47% subsidization of the BESS initial investment cost. In Sweden, a support scheme introduced in November 2016 subsidizes 60% of the BESS initial investment cost (Hutchins, 2016; Steel, 2016). Finally, in Japan, the Ministry of Economy, Trade and Industry subsidizes 66% of the BESS initial investment cost, in both residential and business installations (Energy Storage Council, 2015).

Following these examples, three possible subsidy typologies were chosen for the BESS system: **(i)** a subsidy of 30%, **(ii)** a subsidy of 50%, and **(iii)** a subsidy of 65%. The uncertain parameters considered to affect the performance of the policies under study are social (i.e., propensity and resistance of consumers to invest), technological (i.e., cost of PV panels and BESS), and market-related (i.e., electricity retail price and electricity demand). As a result, the definition of success is the achievement of the Greek small-scale PV capacity targets under any evolution of the uncertain contextual future.

2.3.2. Step 2: Problem Analysis

In this step, it is assumed that no new policies are implemented. The NEM scheme, currently in operation, was evaluated on the entire uncertainty space, to identify any vulnerabilities under potential future contextual evolutions. This means that its performance, in terms of new small-scale PV capacity additions, was tested under a wide range of possible evolutions of the uncertain contextual parameters. To do so, ATOM was used, and all the contextual factors incorporated in ATOM simulations, were used for the evaluation of the scheme’s performance.

For the market related parameters, according to the European Commission, the average retail electricity price is expected to increase by 18% by 2030, with relevance to 2010 levels, stabilize at around 20% between 2030 and 2040, and then start decreasing (European Commission, 2016, 2011). This corresponds to an annual increase ranging from 0.9 - 1% until 2030. Furthermore, different scenarios for the evolution of the electricity demand in the residential sector, are mentioned in literature, predicting both slight decreases and moderate increases until and beyond 2030. These scenarios range from an annual decrease equal to -0.2% to an annual increase equal to 1.2%. This is mainly due to an expected shift to heating means powered by electricity, an increase of the electric appliances used and the electrification of the transport sector, while negative scenarios assume large implementation of energy efficiency measures (E3M-Lab et al., 2016; FME CenSES, 2015; Norwood et al., 2017; U.S. Energy Information Administration, 2018).

Finally, regarding the technological parameters, according to literature, the BESS cost could decrease between 30% and 66% until 2030 with relevance to 2017-2018 levels (IRENA, 2017; Tsiropoulos et al., 2018). This corresponds to an about 2.5-5.1% annual decrease. For the case of PV costs, various scenarios for PV system price reduction exist (Ardani et al., 2018; Fraunhofer ISE, 2015; IRENA, 2012), from which the minimum and maximum annual system price reductions were inferred equal to 1.8-4.53%. The values of the above parameters, as presented in **Table 2.2**, form the uncertainty (contextual) space, in which NEM's performance, as well as that of the alternative support schemes (see step 3), was evaluated.

Table 2.2. Interval of uncertain parameters used for scenario creation

	Electricity retail price (%/year)	Residential Electricity Demand (%/year)	BESS cost (%/year)	PV cost (%/per year)
Min	0.90	- 0.20	- 5.10	- 4.53
Max	1.00	+1.20	- 2.50	- 1.80

After the determination of the uncertainty intervals of the contextual parameters, 20 scenarios were generated using LHS. Twenty scenarios were found to be adequate for the calibration of STEEM which is performed in steps 5 and 6 of the DAPP methodology. These scenarios were simulated in ATOM to acquire the annual small-scale PV adoption by consumers for the period 2019-2030 and recognize any policy vulnerabilities. Those vulnerabilities are scenarios in which NEM fails to achieve the Greek PV capacity targets. It is assumed that a policy is successful if:

i. the PV capacity additions meet the milestones set by the EU (as mentioned in Step 1),
ii. for the years with a milestone, the maximum capacity achieved is not above 20% of the trajectory,
iii. for the years without a specific milestone, the PV capacity additions follow the capacity trajectory with an allowed deviation of ±20%.

The upper limitation is set to restrict excess policy costs, avoiding the legislative failure (exceeding of targets by almost 146%) that was observed under the effect of the FiT scheme in 2013 (Anagnostopoulos et al., 2017; Spyridaki et al., 2013). Furthermore, the upper limitation is set to avoid the distortion of the energy market owing to overcompensation of a specific technology (Batlle et al., 2012). This means that if solar PV is highly subsidized, and as such highly profitable, investments in other technologies (i.e., wind turbines) would decrease significantly, carrying losses for interested parties. For the case of NEM in Greece, policy costs are equal to zero due the fact that the prosumer is not remunerated for the excess electricity at the end of the three-year period during which netting is performed (step 1).

2.3.3. Steps 3 & 4: Identification and evaluation of alternative policy actions

Step 2 resulted in the identification of potential vulnerabilities that will probably emerge in the future, by a continuation of the NEM scheme, and which might impede the achievement of the Greek PV capacity targets. As such the evaluation of alterative policies was necessary to prevent situations of policy failure and keep options open towards the achievement of the definition of success. The alternative policies are three typologies of the presented SC with BESS scheme, namely: 30%, 50% and 65% subsidization of the BESS initial investment cost. No subsidy is given for the PV installation. All these typologies were simulated in ATOM, using the same 20 scenarios and the same simulation period as in step 2. Assuming that for every 1kWp of PV capacity addition, 1kWh of BESS is installed, the cost of subsidizing the BESS in each scenario, was calculated using Eq. (2.3):

$$Cost_i = Cost_{i-1} + (A_i - A_{i-1}) \cdot BC \cdot (1 - BDR_i) \cdot SL \tag{2.3}$$

where:

- i: the simulation year,
- $Cost_i$: the policy cost until year i,
- A_i: the PV capacity additions until year i,
- BC: the initial investment cost of BESS, equal to 800 €/kWh in 2017 (Goebel et al., 2017; Solar Choice, 2018),
- $1 - BDR_i$: the decrease rate of the BESS cost in year i relatively to 2017,
- SL: the subsidy level.

The aim of steps 3 and 4 was to identify any scenarios in which each of the three typologies, either failed to follow the target trajectory, or performed better than NEM. Failure is defined as deficiency to meet the requirements described in step 2, while better performance means an opportunity that could be exploited with a change from NEM to SC. Finally, if none of the SC typologies performs at least equally well as NEM, more alternative policies should be identified followed by their evaluation (i.e., re-implementation of steps 3 and 4).

2.3.4. Steps 5 & 6: Assembly and selection of preferred pathways

In the previous steps, a preliminary analysis of the effectiveness of the individual policies over a small number of scenarios has been performed. In steps 5 and 6, the timeframe until which each policy performed well, considering the constraints set was identified and a map of DAPP was visualized. To do so, 1000 scenarios were generated in which the candidate polices were evaluated. The 20 scenarios in which the candidate policies were evaluated in the previous steps (inputs), along with the respective policy outcomes (outputs), were used for training STEEM. The number of scenarios succeeded in calibrating STEEM in only a few seconds (~ 5 seconds), thus neither an increase of complexity in the calibration process of STEEM, nor additional time-consuming simulations in ATOM were required. Then, 1000 scenarios were emulated for each policy. In LHS, when choosing to generate N scenarios, each dimension's (i.e., uncertain parameter's) interval is divided by N and a random value is drawn from each one of the N partitions. This ensures that values from the entire interval are drawn when sampling. Then the N randomly selected numbers of each parameter are combined in N scenarios (Minasny and McBratney, 2006). Thus, 1000 scenarios were chosen in this research to achieve high resolution of each input parameter. The scenario inputs and outputs of STEEM were fed into AIM for the design of DAPP.

AIM: Module 1

Each policy outcome under all scenarios was evaluated in terms of small-scale PV capacity additions across every year of the simulation period. At this point, the initial conditions are the PV capacity achieved by former policies until the end of 2017.

Using PRIM, the clusters of the Greek context in each simulation year, which correspond to successful policy results, and the respective scenarios whose inputs belonged to at least one of those clusters were identified. Then, a decision on the policies which succeeded in a reasonable number of scenarios in each simulation year, thus they were valid options to visualize in an adaptation map, was made. For the case under study, a policy is assumed a valid option if it succeeds in more than 70% of the scenarios. As mentioned in **section 2.2.3**, this percentage is a user-defined input to AIM. In this work, a policy success of 70% reflects the definition of robustness and flexibility of the adaptive policy plan. More specifically, policy success requirement above 70% reduces contingency actions (i.e., flexibility of the policy plan) that could be implemented, if the basic plan fails due to contextual influences, thus resembling policymaking according to the best estimate of the future which is undesirable. On the other hand, policy success requirement below 70% means that policy pathways are not robust in most possible contextual evolutions. Following a binary search logic, 70% was chosen as the criterion for robustness and flexibility of the generated policy pathways. This percentage was validated during (i) the TRANSrisk project's stakeholder consultation process, (ii) a "hands-on" modelling session at the "TRANSrisk Policy Lunch: Paris in Practice-Understanding the Risks and Uncertainties" on November 2018, and (iii) the "TRANSrisk & SET-Nav Regional Workshop: Decarbonizing our energy system-Transformation pathways, policies and markets, with spotlight on Greece", on November 2018, during which experts in the field of policymaking participated. As a result, the adaptation map visualized the successful policies as straight lines until the simulation year they started to perform poorly. If a policy did not meet some milestone requirements or started to deviate from the target trajectory, a policy intervention was required. Please note that since the final choice for the success ratio is open to the modeler's judgement, deviations from the validated success percentage could be inserted to AIM by a researcher (when replicating this study), to test a strict (i.e., 75%) or a tolerant (i.e., 65%) policy success requirement.

AIM: Module 2

Considering the initial adaptation map produced by Module 1, a policy was selected for implementation, and the initial conditions for the evaluation of all the other policies were updated, so that their projected small-scale PV capacity additions are added to the capacity achieved by the implemented policy. Eq. (2.4) describes this functionality.

$$A_{alt,n} = A_{imp,m} + \sum_{i=m+1}^{n} \left(A_{alt,i} - A_{alt,i-1}\right) \tag{2.4}$$

where:

- i: simulation year,
- A_i: PV capacity achieved until year i,
- imp: implemented policy,
- alt: alternative policy,
- n: number of simulation years,
- m: simulation year until which the selected policy is implemented.

After updating the outcome of all the alternative policies, Module 1 run again to update the policy map, showing the implemented policy for the selected simulation years and the available alternatives thereafter. This iterative process was undertaken several times, considering several hypothetical end-users' perspectives, until the end of the simulation time was reached with respect to the definition of success. The result was an ensemble of maps, each one showing the selected sequence of actions under different perspectives, so that the final targets are achieved.

2.3.5. Steps 7 & 8: Setting up a monitoring system, determining contingency actions and making the plan dynamic – AIM: Module 3

In these steps, conditions (i.e., combinations of contextual parameters) under which each policy might fail were identified. As mentioned in steps 5 and 6, the adaptation map visualized sequences of actions which were successful in at least 70% of the potential future evolutions. However, if one of the remaining future evolutions comes up, the policies can fail, and an alternative pathway (i.e., contingency action) needs to be selected. For this reason, a monitoring system was prepared, informing end-users for imminent need for adaptation. At each simulation year, if the success percentage of the respective policy compiling the pathway was not 100%, AIM went back two simulation years and implemented PRIM to identify signpost variables (i.e., variables belonging in a cluster) and their trigger values (i.e., cluster limits).

The latter was assumed according to the following premise: policies are designed in year Y-1 to be implemented in year Y. If policy failure is expected to happen in year Y, a contingency action needs to be implemented before failure occurs (i.e., year Y-1). As such proper information for the initiation of the contingency action design should be available in year Y-2.

The conditions under which a policy failed to achieve the targets, were those contextual evolutions in which one or more contextual variables had values outside of their clusters. Those signpost variables and their trigger values compiled the monitoring system, which made the adaptive policy pathway dynamic, enabling real world monitoring and preparation for adaptation.

2.3.6. Steps 9 & 10: Implementing and initiating monitoring

The dynamic adaptive plan is implemented, and the signpost variables are monitored for trigger events. If a trigger event occurs, one of the alternative pathways needs to be chosen and steps 5-8 need to be repeated. If no trigger events occur, the selected policy pathway is implemented until the end of the simulation time. In the worst case that the context evolves extremely differently than expected, leading to no available pathways that can meet the definition of success, new actions need to be identified and the whole DAPP methodology must be repeated.

2.4. Results and discussion

All pathways presented in this section start from January 2020. Until December 2019, no shift from the currently implemented NEM scheme to a SC scheme is assumed. The PV capacity additions achieved by the NEM scheme form the initial conditions for the evaluation of all alternative policies. The initial pathway map at the beginning of 2020 is shown in **Fig. 2.7**. The vertical dashed lines in all the following figures show the date until which a policy is implemented. The textboxes in years 2022, 2025, 2027 and 2030 show performance information of the pathways at the milestone and final target years and the respective cost of subsidies the Greek government would be charged with.

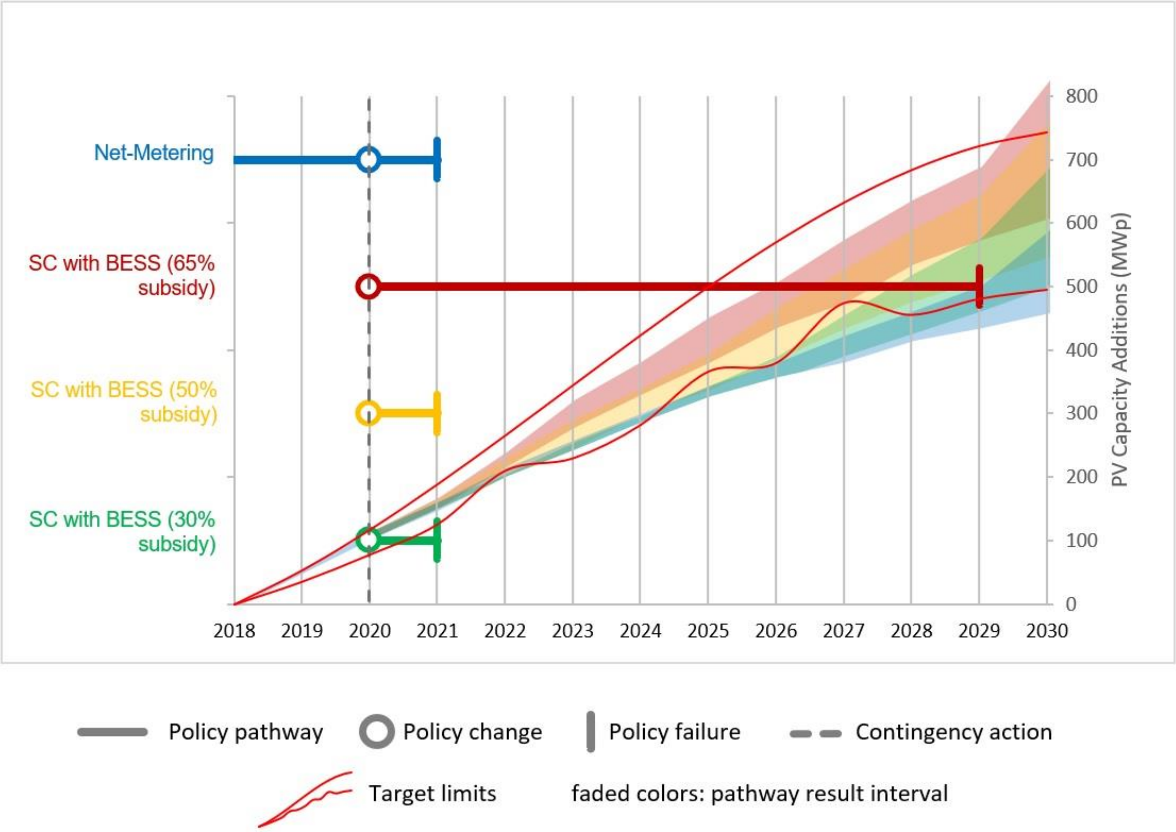


Fig. 2.7. Initial policy pathway map at the beginning of 2020

As presented in **Fig. 2.7**, NEM is capable of driving adequate investments that follow the targets trajectory only in the short term. All examined policy pathways showed that the scheme's effectiveness fell below threshold after 2021. On the other hand, a SC scheme with 30% and 50% BESS subsidies, is not capable of following the targets trajectory after December 2020 due to the strict milestone of 2022 and insufficient incentivization, considering the currently high investment costs of the BESS (De Boeck et al., 2016). As such, an initial change to SC with 65% subsidization of the BESS cost is required to incentivize more investments. However, high subsidization after December 2028 would attract many investors, causing significant deviation from the targets' trajectory with subsequent high subsidy costs for the government (**Fig. 2.8**).

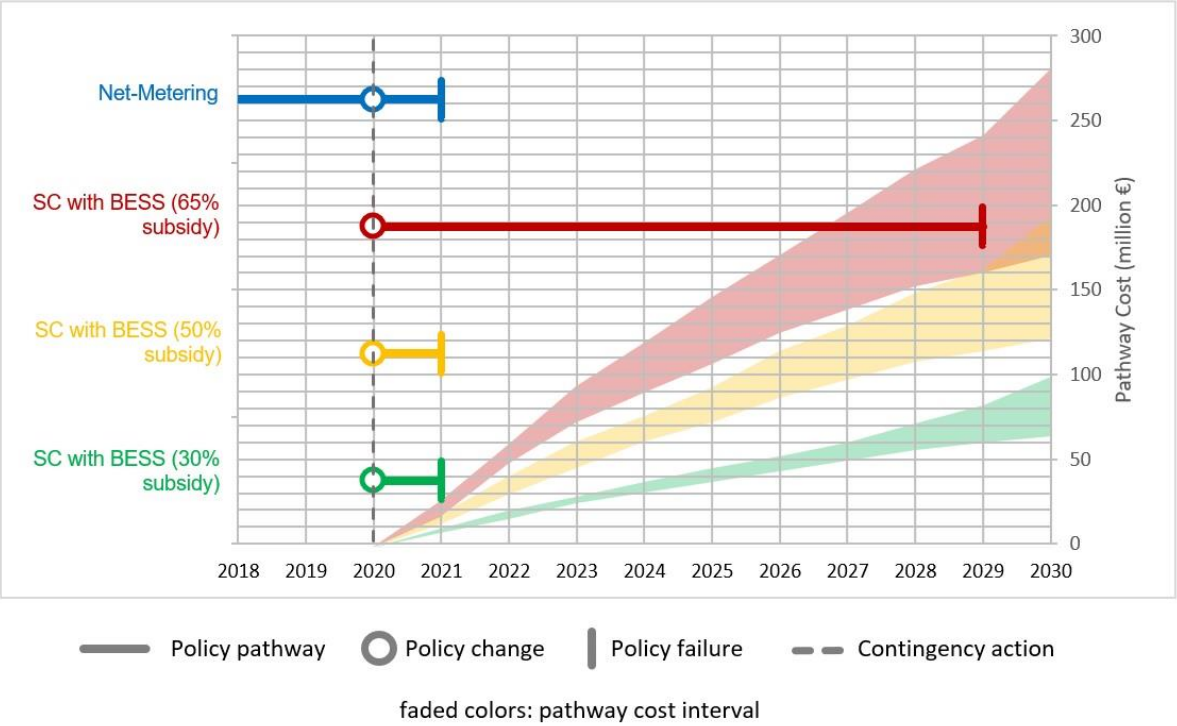


Fig. 2.8. Subsidy cost of individual policies after January 2020

Consequently, stepped subsidization is required to reach the 2030 capacity targets following the targets' trajectory. Note that the goal of this study is not to propose one optimal pathway towards the achievement of the Greek PV capacity targets, as the reality is that there is not one possible RES energy system of the future, but rather many possible ones. They differ in critical ways, average and marginal costs being only one among many, with diverse impacts on different stakeholder groups (Lilliestam and Hanger, 2016). As such, the author presents pathways using three realistic, stakeholders' perspectives, as derived from the consultation processes mentioned in **section 2.3.4**, demanding: **(i)** minimum policy changes, **(ii)** minimum policy costs, and **(iii)** maximum robustness until 2030.

2.4.1. Minimum policy changes pathways

Pathway 1

In this pathway (**Fig. 2.9**), two policy changes are required. Since NEM cannot follow the target trajectory after December 2020, a change to SC with 65% subsidization of the BESS cost is made early, in January 2020. This leads to the achievement of the 2022 milestone in 100% of the scenarios. Then, a reduction to 50% subsidization of the BESS cost is made in January 2022 and is kept in effect until the 2030. This shift leads to the achievement of the 2025, 2027 and 2030 milestones and targets in

100%, 85.22%, and 72.77% of the scenarios respectively. Since there is no 100% success in years 2027 and 2030, trigger values of signpost variables were calculated for the years 2025 and 2028 respectively.

For the year 2025, the clustering showed that the signpost variables are the BESS cost and the electricity retail price. If a total reduction of the BESS cost, lower than 19.6% or higher than 35.7% is observed in 2025, or if a total increase in the electricity retail price, less than 6.3% or more than 7% is observed in 2025, with relevance to 2017 levels, then a policy change will be required until January 2026 to avoid pathway failure. However, there are no available contingency actions to implement until January 2026. Simulations showed that if 65% subsidization is applied for one more year after January 2022, there would be no available pathway leading to the achievement of the 2030 targets in at least 70% of the scenarios, because the incentivization for small-scale PV installations would be high and the targets would be surpassed in unacceptable levels. Furthermore, 30% subsidization is not an option until January 2027 for the exact opposite reason; it does not create enough incentives to achieve the milestones and targets.

For the year 2028, the clustering showed that the signpost variable is the PV cost. If the PV cost decreases less than 18% or more than 37.6% in 2028 with relevance to 2017 levels, then a policy change is needed until January 2029. The available contingency action is a shift to 30% subsidization starting in January 2029. The implementation of this contingency action constructs the “Most robust policy pathway”, which is presented in **section 2.4.2**.

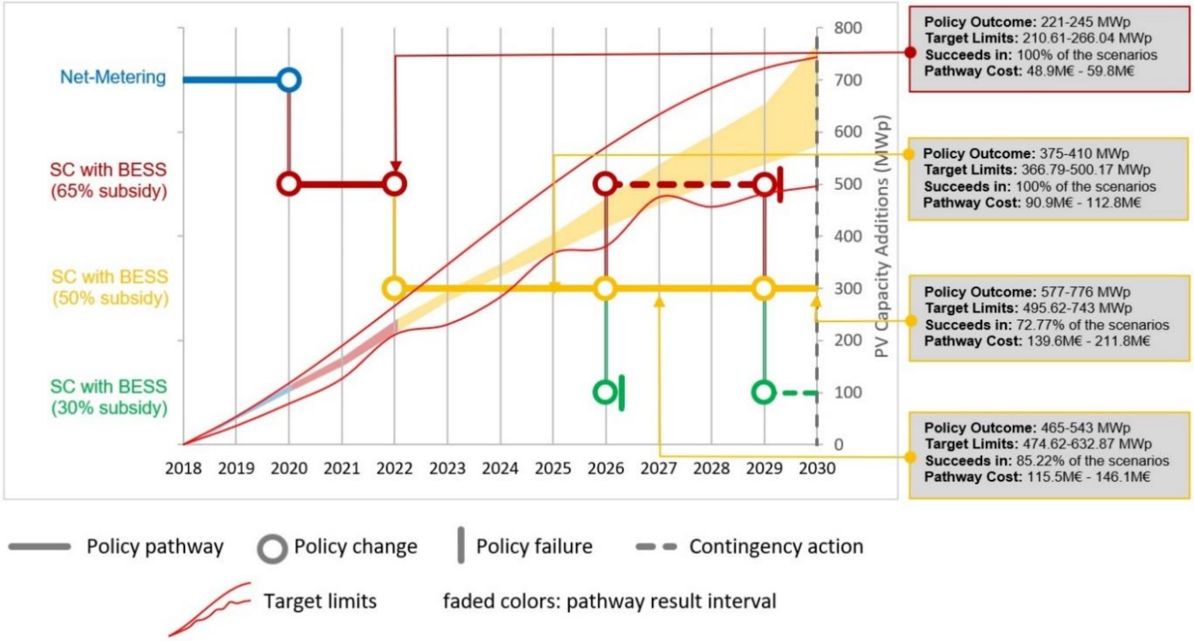


Fig. 2.9. Minimum policy changes pathway 1

The pathway's subsidy cost until 2030 is dependent on the evolution of the context (**Fig. 2.10**). From the 1000 scenarios, the one with the minimum subsidy costs (i.e., minimum PV installations) is equal to €139.5M, while the one with maximum subsidy costs (i.e., maximum PV installations) is equal to €211.8M. The respective contextual evolutions are shown in **Table 2.3**.

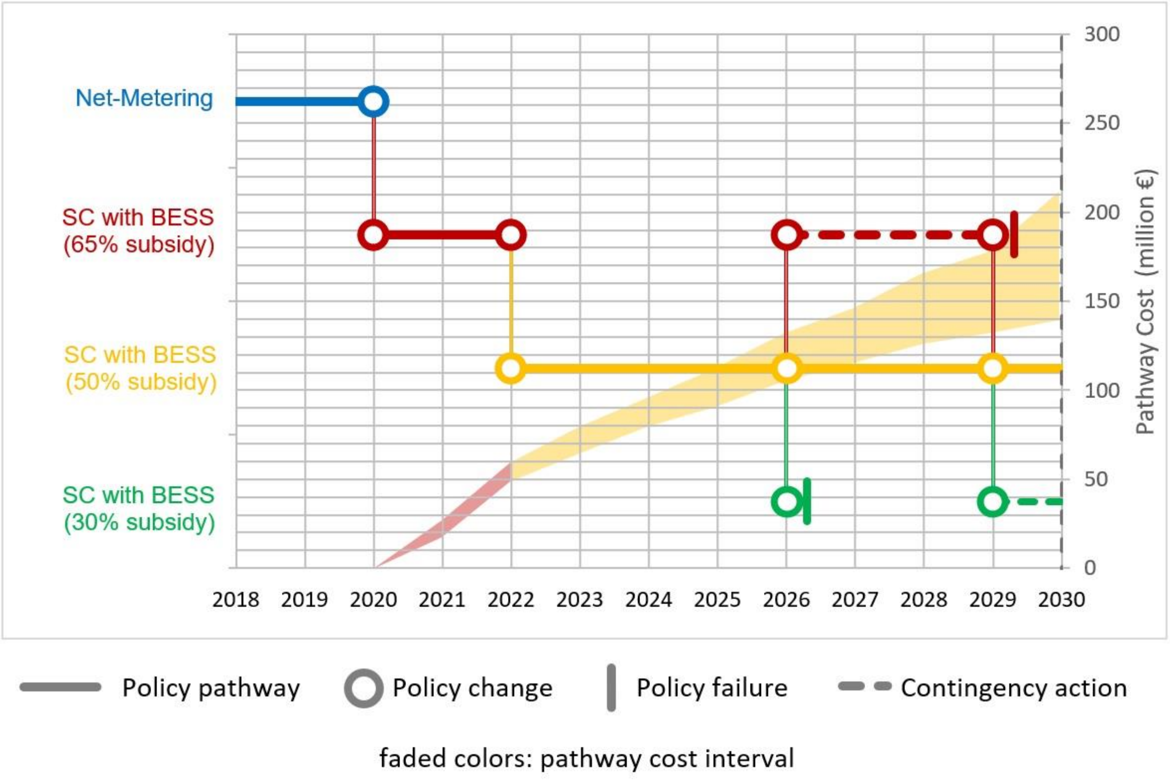


Fig. 2.10. Subsidy cost of the minimum policy changes pathway 1

Table 2.3. 2030 context corresponding to minimum and maximum subsidy costs of the "minimum policy changes pathway 1"

	Electricity retail price (% w.r.t 2017)	Residential Electricity Demand (% w.r.t 2017)	BESS cost (% w.r.t 2017)	PV cost (% w.r.t 2017)
Min Cost	11.00	3.91	- 59.80	- 22.20
Max Cost	11.10	10.5	- 30.70	- 45.10

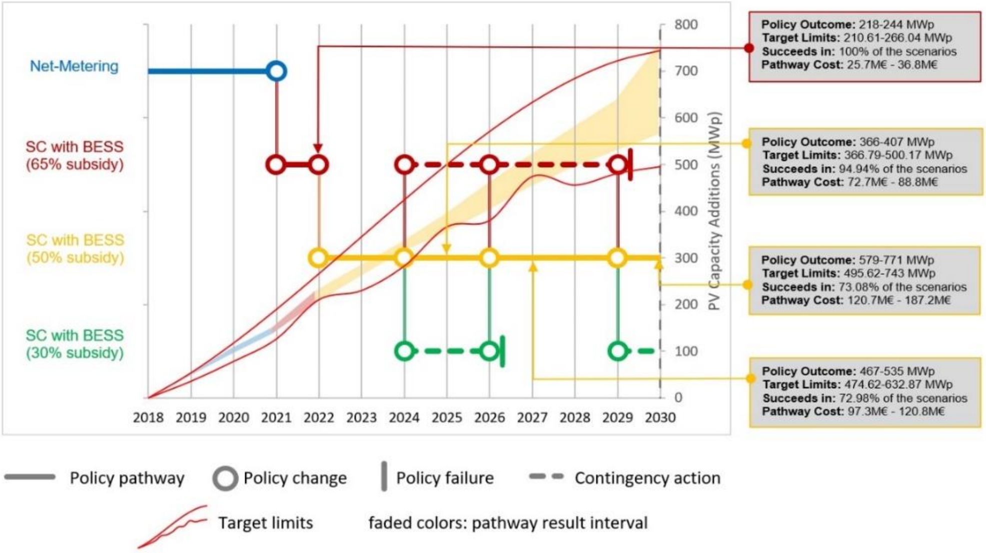
Pathway 2

This pathway (**Fig. 2.11**) is similar to the previous one, with the difference that NEM is implemented until December 2020, which is the last year that it performs well. Then a shift to SC with 65% subsidization of the BESS cost is made in January 2021 for one year, followed by a reduction of the subsidy to 50% for the rest of the years until 2030.This pathway achieves the 2022, 2025, 2027 and 2030 milestones and targets in 100%, 94.94%, 72.98%, and 73.08% of the scenarios respectively. While this pathway has a slightly higher success ratio in 2030 than the previous one, it performs worse in 2025 and 2027. For the years not succeeding in 100% of the scenarios, trigger values of signpost variables were calculated for two years earlier (i.e., for the years 2023, 2025 and 2028 respectively).

For the year 2023, the signpost variable is the PV cost. If the PV cost decreases less than 9.7% or more than 22.6% in 2023 with relevance to 2017 levels, then a policy change is needed until January 2024. However, no contingency actions capable of building a pathway towards the 2030 targets are available. Just like the “minimum policy changes pathway 1”, one more year of 65% subsidization would eliminate all pathways leading to the 2030 targets due to over-incentivization. On the other side, early implementation of a 30% subsidy would result in less PV installations than required to achieve the targets.

For the year 2025, the signpost variables are the PV cost, the BESS cost and the residential electricity demand. If in 2025, the PV cost decreases less than 15.6% or more than 31.7%, or the BESS cost decreases less than 19.6% or more than 35.7%, or the residential electricity demand decreases more than 1% or increases more than 8.4% with relevance to 2017 levels, then a policy change is needed until January 2026. However, for the same reasons as for the 2023 trigger point, there are no available contingency actions.

For the year 2028, the signpost variables are the PV cost and the residential electricity demand. If in 2028, the PV cost decreases less than 18% or more than 38.7%, or the residential electricity demand decreases more than 1.2% or increases more than 12% with relevance to 2017 levels, a policy change is needed until January 2029. The available contingency action is the reduction of the subsidy level to 30% in January 2029.



Policy Outcome: 218-244 MWp
Target Limits: 210.61-266.04 MWp
Succeeds in: 100% of the scenarios
Pathway Cost: 25.7M€ - 36.8M€

Policy Outcome: 366-407 MWp
Target Limits: 366.79-500.17 MWp
Succeeds in: 94.94% of the scenarios
Pathway Cost: 72.7M€ - 88.8M€

Policy Outcome: 579-771 MWp
Target Limits: 495.62-743 MWp
Succeeds in: 73.08% of the scenarios
Pathway Cost: 120.7M€ - 187.2M€

Policy Outcome: 467-535 MWp
Target Limits: 474.62-632.87 MWp
Succeeds in: 72.98% of the scenarios
Pathway Cost: 97.3M€ - 120.8M€

Fig. 2.11. Minimum policy changes pathway 2

Fig. 2.12 shows the pathway's subsidy cost until 2030 under different evolutions of the context. The minimum and maximum subsidy cost scenarios of the pathway until 2030 are equal to €120.7M and €187.2M respectively. Compared to the "minimum policy changes pathway 1", this pathway results in less subsidy costs owing to the implementation of the NEM scheme for one more year, and the implementation of 65% subsidization for one year less. The respective contextual evolutions are shown in **Table 2.4**.

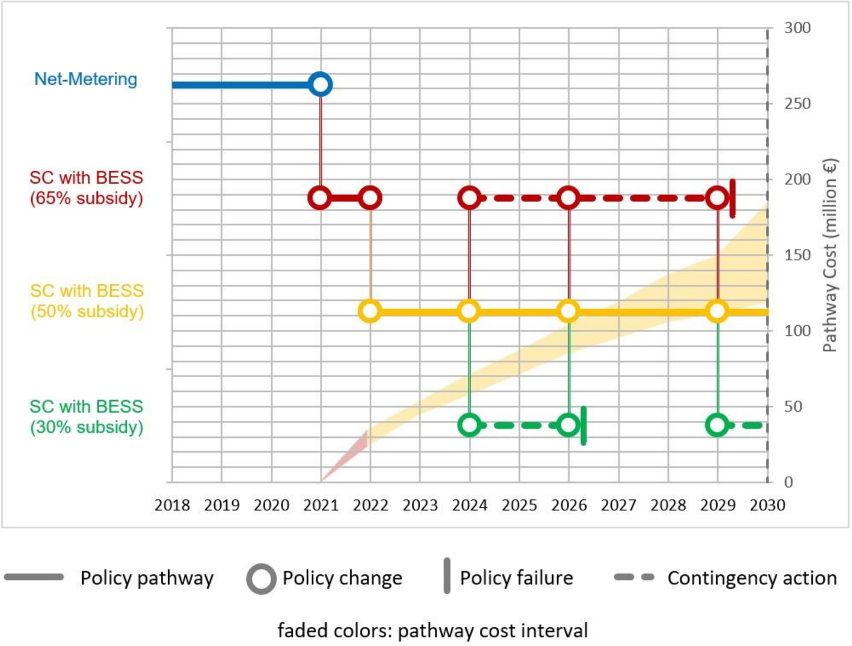


Fig. 2.12. Subsidy cost of the minimum policy changes pathway 2

Table 2.4. 2030 context corresponding to minimum and maximum subsidy costs of the "minimum policy changes pathway 2"

	Electricity retail price (% w.r.t 2017)	**Residential Electricity Demand (% w.r.t 2017)**	**BESS cost (% w.r.t 2017)**	**PV cost (% w.r.t 2017)**
Min Cost	11.60	- 2.05	- 61.20	- 24.60
Max Cost	11.30	+13.4	- 31.30	- 44.40

2.4.2. Most robust policy pathway

The "most robust policy pathway" (**Fig. 2.13**) is the same as the "minimum policy changes pathway 1", if the contingency action of 2029 is implemented. It consists of the NEM scheme until December 2019, a SC scheme with 65% subsidization of the BESS cost from January 2020 until December 2021, a reduction of the subsidy to 50% effective from January 2022 until December 2028, and then a further reduction of the subsidy level to 30% until 2030. The success percentages in the years 2022, 2025, 2027 and 2030 are 100%, 100%, 85.22% and 84,43% respectively.

The signpost variables are the same as in the "minimum policy changes pathway 1", apart from 2028, in which, if the PV cost decreases less than 18% or more than 40.9% with relevance to 2017 levels, a policy change is required until January 2029. The only contingency action would be to continue with the 50% subsidy until 2030, which is in essence the "minimum policy changes pathway 1". However, the 2028 trigger point of the "most robust policy pathway" is a superset of the 2028 trigger point in "minimum policy changes pathway 1", which means that if a trigger event occurs in the "most robust policy pathway", the "minimum policy changes pathway 1" is not available. The latter implies that while this pathway accomplished the highest success ratios in all years, in has no contingency actions.

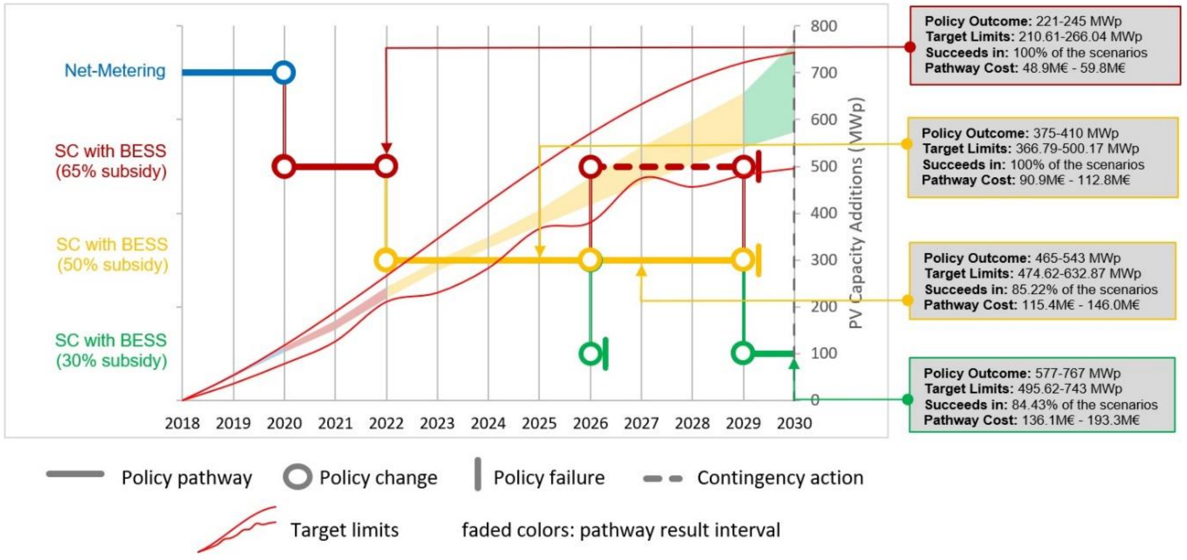


Fig. 2.13. Most robust policy pathway

Regarding costs, **Fig. 2.14** shows the pathway's subsidy cost until 2030 under different evolutions of the context. The minimum cost scenario is equal to €136.1M, while the maximum cost scenario is equal to €193.3M. The respective contextual evolutions are shown in **Table 2.5**.

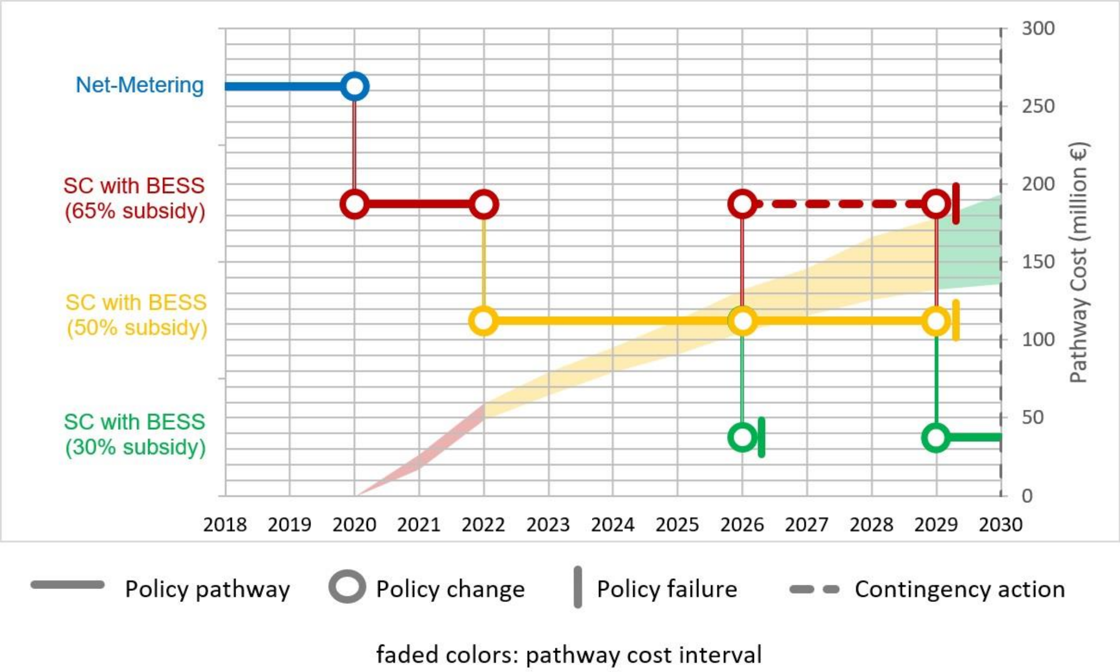


Fig. 2.14. Subsidy cost of the most robust policy pathway

Table 2.5. 2030 context corresponding to minimum and maximum subsidy costs of the "most robust policy pathway"

	Electricity retail price (% w.r.t 2017)	Residential Electricity Demand (% w.r.t 2017)	BESS cost (% w.r.t 2017)	PV cost (% w.r.t 2017)
Min Cost	11.00	3.91	- 59.80	- 22.20
Max Cost	11.10	10.50	- 30.70	- 45.10

2.4.3. Least cost policy pathway

To build the least cost policy pathway (**Fig. 2.15**), the NEM scheme, which has zero cost, is implemented until the date it starts to perform poorly; that is December 2020. Then, from January 2021 to December 2021, a switch to SC with 65% subsidization of the BESS is made, followed by a reduction of the subsidy level to 50%, effective from January 2022 until December 2026. Finally, from January 2027 until 2030, the subsidy level is decreased to 30%. In this pathway, the 2022 milestone is achieved in 100% of the scenarios, while the 2025 and 2027 milestones and the 2030 target are achieved in

94.94%, 72.98% and 76.82% of the scenarios respectively. Trigger values of signpost variables were calculated for the years 2023, 2025 and 2028 respectively.

For the years 2023 and 2025, the signpost variables and their trigger values are the same as in the “minimum policy changes pathway 2”, realization of which would require a policy change until January 2024 and January 2026 respectively. Similarly to the previous pathways, 65% subsidization of the BESS cost after January 2022 would lead to target surpassing, and the 30% subsidy alternative would not lead to success if implemented before January 2027. As such, for the 2023 and 2025 trigger points, no contingency actions exist.

For the year 2028, the signpost variable is the PV cost. If the reduction of the total PV cost in 2028 is less than 18% or more than 38.7% with relevance to 2017 levels, then a policy change is needed until January 2029. At this point, any subsidy level above 30% would lead to target surpassing, thus no contingency actions are available.

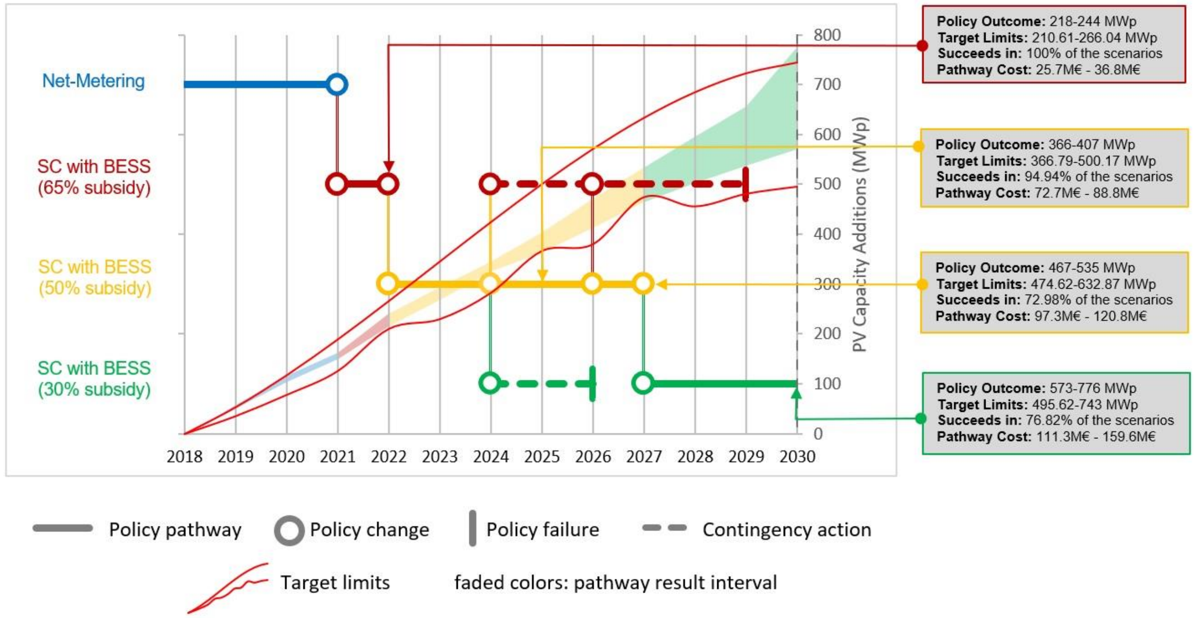


Fig. 2.15. Least cost policy pathway

Fig. 2.16 shows the pathway’s subsidy cost until 2030 under different evolutions of the context. The respective minimum and maximum subsidy cost scenarios until 2030 are equal to €111.3M and €159.6M. The contextual evolutions causing these costs are shown in **Table 2.6**. Note here that, while this pathway results in minimum policy costs, it lacks available contingency actions.

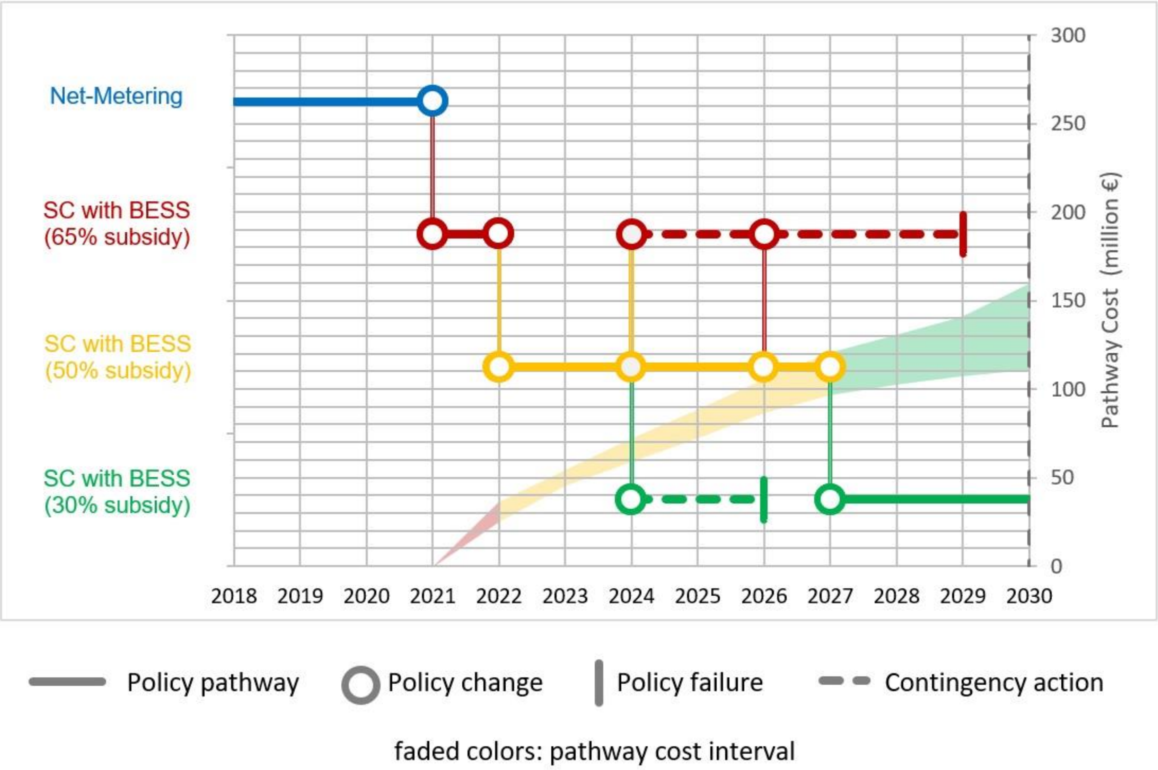


Fig. 2.16. Subsidy cost of the least cost policy pathway

Table 2.6. 2030 context corresponding to minimum and maximum subsidy costs of the "least cost policy pathway"

	Electricity retail price (% w.r.t 2017)	Residential Electricity Demand (% w.r.t 2017)	BESS cost (% w.r.t 2017)	PV cost (% w.r.t 2017)
Min Cost	11.00	3.91	- 59.80	- 22.20
Max Cost	11.50	14.20	- 34.00	- 48.00

2.5. Conclusions and policy implications

In this chapter, a transdisciplinary modeling framework consisting of an agent-based technology adoption model, and two model plugin toolboxes meant to facilitate participatory modeling approaches is presented. The suggested framework builds on the strengths of Exploratory Modeling and Analysis, and augments the Dynamic Adaptive Policy Pathways methodology, as originally introduced by Haasnoot et.al (2013). The presented work provided more technical details on the implementation of the Dynamic Adaptive Policy Pathways methodology and presented a complete modeling framework to assist end-users in applying the methodology to their benefit. The novelty of this study lies mainly in the presentation of the AIM plugin toolbox, demonstrating its potential for the participatory design of dynamic adaptive policy pathways, through real time visualizations and interactive stakeholder consultation.

To test the applicability of the presented framework, it was used to explore transition pathways for the support of the further diffusion of small-scale photovoltaics (i.e., up to 10kWp) in Greece, towards the achievement of the 2025 and 2030 capacity targets. More specifically, the effect of the net-metering scheme, currently in operation, and three potential typologies of a self-consumption scheme that subsidizes a Battery Energy Storage System, on photovoltaic investments was examined under several uncertain contextual evolutions. To the best of the author's knowledge, this is the first time that such a modeling exercise is attempted for the geographical and socioeconomic context of Greece.

The timing of this research chapter coincides with the recent update of the Greek National Energy and Climate Plan (NECP) (Ministry of Environment and Energy, 2019a), which mandates 1GW of cumulative small-scale RES to be installed in Greece until 2030, under net-metering and self-consumption schemes. The results of this study suggest that, given the new small-scale photovoltaic targets, net-metering is capable of driving adequate investments that follow the targets' trajectory only in the short term. While net-metering is considered to attract much prosumer attention (Gautier et al., 2018), the typology implemented in Greece is not so favorable for them. This is because grid charges for net-metered electricity burden the prosumers instead of being used to increase the value of locally generated electricity for their benefit as mentioned in Gautier et.al. (2018). Bill savings (i.e., prosumers' profits) are solely dependent on the electricity retail price and actually reduced by the grid charges burdening the prosumers. As a result, consumers' willingness to install a photovoltaic system is reduced. This finding is also validated by recent scientific literature acknowledging that the net-metering scheme's effectiveness, as it is currently implemented in Greece, is strongly related to the electricity retail price (Stavrakas et al., 2019). Additionally, regarding the price-dependency of net-metering, the recently updated NECP mentions a reduction in retail electricity prices until 2030 while in this work a slight increase is assumed. This implies that if the foreseen reductions by the NECP are indeed materialized, the performance of net-metering would be poorer than the one presented in this study. It is evident, thus, that the implementation of alternative schemes should be considered.

The introduction of a self-consumption scheme showed great potential in incentivizing investments. Unlike net-metering, where generation and consumption are not synchronized as there are no incentives for prosumers to do so (Gautier et al., 2019), the benefits of a self-consumption scheme that subsidizes battery storage is that prosumers consume more self-generated electricity since it can be stored for later direct use. Furthermore, grid charges are paid only for the electricity consumed from the grid. As such, there is less price-related uncertainty and prosumers' profits are higher. At the same time, apart from incentivizing consumers to invest, modeling outcomes suggest that the self-consumption scheme under study could also contribute to the achievement of the national battery storage capacity target (around 1.2 GW until 2030) mentioned in the Greek NECP. This is because it assumes that for every 1kWp of photovoltaic capacity addition, 1kWh of storage is installed. In particular, simulation results showed that up to 776 MWh of battery storage could be installed.

A study by Jin & Yu (2018) has shown that self-consumption with battery energy storage system for individuals could become profitable before 2030. The development of the appropriate regulatory framework for the uptake of storage systems seems a promising option to be considered by policymakers in Greece. Simulation outcomes showed that a high initial subsidy is required to attract investors' interest upon the introduction of a self-consumption scheme, due to the high battery storage investment cost, and the steep slope of the Greek photovoltaic targets trajectory. Smaller subsidies, while effective, fail to follow the steep targets' trajectory, if applied too early. On the other hand, high subsidies can cause rebound economic effects (i.e., public deficit), in the long-term, similar to the ones induced by the Feed-in Tariffs scheme over the period 2008 to 2013. Indicatively this is observed after 2028, where the trajectory's slope starts to decrease. As a result, a step subsidization is suggested. Such a suggestion is also implied by the expected reduction of the battery energy storage system's cost, driven by technological progress and learning effects. Regulatory efforts should envision subsidy reforms to benefit from these cost reductions, control the profit margin of prosumers, and limit public expenses.

Regarding the policy pathway to be followed, results highlighted a set of key performance indicators that can be considered by policymakers and decision-makers. These indicators are the success rate of policies, the pathway's subsidy cost (i.e., implementation cost of a policy), and the availability of contingency planning. Nevertheless, all parameters should be considered in a parallel planning process, and not individually, before concluding on a pathway. For example, the "least cost policy pathway" minimizes the public financial burden but succeeds in less scenarios than the "most robust policy pathway". Furthermore, the "most robust policy pathway", while achieving the highest success rates, is less flexible in terms of contingency planning than both "minimum policy changes pathways". Since short-term decisions influence long-term options, such differences should be ex-ante evaluated to eliminate the possibility of short-sightedness, providing policymakers with alternatives for future policy interventions.

Finally, the effect of contextual parameters should also be considered when identifying proper policy instruments to support the further diffusion of small-scale photovoltaics in Greece. In all pathways under study, the exceeding of a threshold value for the photovoltaics' cost appeared as a trigger point denoting potential imminent failure of policy pathways. Furthermore, pathways indicated that maximum photovoltaic capacity additions are driven mainly by a reduction of the photovoltaics' cost. This analogy is not the same when a reduction of the battery energy storage system's cost is observed. This is due to the fact that the storage system in the self-consumption scheme under assessment is subsidized, and as such the investment cost does not burden solely the consumer. On the other hand, a reduction of the battery energy storage system's cost affects directly the subsidy cost of the pathway. This implies that a policy mix, partly subsidizing both the photovoltaic and battery energy storage systems, could result in better consumer behavior expectations, larger availability of adaptation pathways and limitation of risk.

Regarding the applicability of the presented modeling framework, the case under study showed that while 100% success of a policy pathway, regardless the contextual evolution, cannot be achieved, opportunities and dead-ends can be highlighted and visualized in a stakeholder-friendly fashion. Highlighting risky situations without available contingency actions, showed that the modeling framework explicitly triggers the need for exploration of more policy options, and the re-application of the dynamic adaptive policy pathways methodology, which would help reduce uncertainty in potential pathways. This means that stakeholders using this framework can have sufficient information about the uncertainties they need to consider and make better-informed decisions on policy planning and implementation.

Considering the existing ambiguity of the photovoltaics market in Greece, the findings of this study signaling further research on measures that could counterbalance the phase out of the previous Feed-in Tariffs scheme, would be useful to government official and policymakers. The latter has already been validated during the consultation events mentioned in **section 2.3.4**. During these events, the potential of the modeling framework, as a useful decision support tool that provides fast answers to "What-if scenarios", has been acknowledged by policymakers, practitioners and other relevant experts from the field.

Given that small-scale PV installations contribute only partly to the cumulative renewable energy targets, further research on the applicability of the presented framework, for the determination of proper support measures for photovoltaic systems larger than 10kWp and other renewable energy technologies, would be purposeful. To this end, the author intends to upscale this analysis to a market-wide context, where the simultaneous implementation of renewable energy source support policies determine the electricity mix, which in turn affects the evolution of the wholesale electricity price and has economic implications for consumers. Furthermore, the AIM toolbox will be also linked with the Dynamic high-Resolution dEmand-sidE Management (DREEM) model (Stavrakas and Flamos, 2020) to visualize policy adaptation pathways towards the introduction of demand-flexibility (e.g., Demand-Response, price signals, etc.) to the Greek electricity market, identifying in parallel contextual factors that may affect the performance of the relevant policy measures required. Finally, note that although the applicability of the modeling framework presented herein was only demonstrated in a national case study, it can be applied to different geographic and socio-economic contexts, given that historical data-observations and market-related parameters are available.

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Nomenclature

Nomenclature			
Abbreviations			
AIM	Adaptive policImaking Model	PHS	Pumped Hydro Storage
BESS	Battery Energy Storage System	PV	Photovoltaics
BSAM	Business Strategy Assessment Model	RES	Renewable Energy Sources
EC	European Commission	SENTINEL	Sustainable Energy Transitions laboratory
EU	European Union	STREEM	STorage RequirEmEnts and dispatch Model
EAC	Equivalent Annual Cost	TEESlab	TechnoEconomics of Energy Systems laboratory
Li-Ion	Lithium Ion	TEEM	TEESlab Modelling
NECP	National Energy and Climate Plan	US	United States
O&M	Operation and Maintenance	WT	Wind Turbines
Indices and Sets			
i	iteration	t	Simulation period in hours
m	Number of years in the analysis horizon	$tech$	Technology assessed
n	Final year of analysis	y	Year of reference
p	Number of policies under investigation		
Parameters			
DoD	Depth of Discharge	$round\_trip$	Round-trip efficiency
$Duration$	Time required to fully charge/discharge a storage system at rated power capacity	$Target_{Curt}$	Targeted annual curtailment percentage
PV	Photovoltaics capacity	WT	Wind turbine capacity
Variables			
$Curt$	Yearly curtailment percentage	$PVOM$	O&M cost for each unit of photovoltaics
nc	Nominal capacity of the storage system	SC	Overnight investment costs for each unit of storage
$Ov.Cost$	Overnight investment cost	$slope$	Slope of curtailment decrease with storage capacity increase
$P.Cost$	Pathway cost	SOC	State of Charge
$P_{ch,t}$	Maximum charging power at simulation period t	$STOM$	O&M cost for each unit of storage
$P_{dis,t}$	Maximum discharging power at simulation period t	$WTOM$	O&M cost for each unit of wind turbines
PVC	Overnight investment costs for each unit of photovoltaics	WTC	Overnight investment costs for each unit of wind turbines

Are there preferable capacity combinations of renewables and storage? Exploratory quantifications along various technology deployment pathways

The decarbonization of the electricity sector is at the core of the European agenda, with renewable energy sources playing a leading role. A major challenge emerging with increasing shares of intermittent renewables is their efficient integration. To overcome this challenge, electricity storage systems are identified as components which will be inseparable from renewable generation in the following years. However, what are the available pathways for the capacity evolution of each generating technology? How do different capacity combinations perform in terms of pledged renewable penetration targets and investment costs? Is there an optimal capacity combination of renewables and storage? This chapter presents a modelling framework featuring detailed storage operation simulation and adaptive policy design, assessing these inquiries. To demonstrate its applicability, it is used to explore plausible wind, solar, and storage configurations in Greece. The results suggest that the proportions of wind and solar power is significantly affecting the timing and required capacity for storage, the potential for renewable electricity integration, as well as the costs needed for their achievement. Overall, the study demonstrates feasible pathways leading from the current status quo in Greece and towards the milestone horizon of 2030, concluding with key implications for policy and practice.

Keywords: Renewable Energy Sources, Battery Energy Storage System, RES Integration, Curtailment, Power System, Energy Transition

3.1. Introduction

The Green Deal published by the European Commission (EC) in late 2019, set the target for zero greenhouse gas emissions by 2050, pledging decoupling of economic growth from resource use. A critical component towards this direction is the decarbonization of the energy sector, which is reported to account for over 75% of the total greenhouse gas emissions in the European Union (EU). In this respect, the need to develop a power sector based on renewable energy sources (RES) is acknowledged (European Commission, 2019). Accordingly, member states, following also the Regulation on the Governance of the Energy Union and Climate Action (The European Parliament and the Council of the European Union, 2018), have already drafted their National Energy and Climate Plans (NECP), incorporating targets for renewable capacity expansion until 2030.

However, a major challenge emerging with high RES shares in the electricity mix is the intermittent nature of RES-generated electricity, which poses difficulties in their integration (Antweiler, 2021), potentially leading to curtailment (Jorgenson et al., 2018). While curtailment is an established method for managing excess RES generation and ensuring safe network operation (Michas et al., 2019), instances of curtailment enforcement should be limited, as its application reduces the amount of exploitable renewable electricity (electricity is wasted) (Chang and Phoumin, 2021), and entails financial losses for RES generators (Mayyas et al., 2022). In fact, the EU regulation 2019/943 on the internal market design (European Parliament and the Council, 2019), clearly states that curtailment should be held at a minimum and not exceed 5% of the annual RES electricity generation. Storage and demand response are two complementary technologies which can reduce the application of curtailment and increase the exploitable renewable generation. Demand response shifts demand to high generation hours, and storage shifts generation to high demand hours. The rollout of both technologies faces difficulties that need to be overcome, such as the high investment costs for storage, and the challenge of attracting participants to demand response programmes, as well as managing their loads (Denholm, 2015). With respect to the cost of storage, a sharp decrease is being reported in the recent years, with 70% reduction observed between 2015 and 2019 in utility-scale battery storage costs (EIA, 2020). On the other side, the participants response to demand response signals is highly random, adding uncertainty to the reliability of this technology in providing services to the grid. If reliability cannot be ensured, system operators, could limit demand response application to activities not interfering with system security, such as night-valley filling, which is already incentivised through time-of-use tariffs (Oconnell et al., 2014). While both technologies will have a role in the future, considering the above, and given that the REPowerEU plan (European Commission, 2022) published by the EU in 2022 gives special attention to energy storage as a means to provide flexibility to the system and facilitate RES integration, the focus of this chapter is placed on energy storage acting as a supplement to efficient renewable generation.

Many studies in the literature address the subject of up to 100% renewable energy systems, as thoroughly reviewed by Hansen et.al. (2019) and Breyer et.al. (2022), with solar photovoltaics (PV) and wind turbines (WT) mentioned as central pillars in most transition pathways, alongside energy efficiency measures. As PV and WT are identified as the most profitable among the RES options (Buonomano et al., 2018) which are likely to have increasing shares in the electricity generation mix in the future (Christoph Soini et al., 2019), it could be expected that storage will be largely used to store solar- and wind-generated electricity. In this respect, several studies in the scientific literature have focused on research combining PV, WT and storage. Cebula et.al. (2018) synthesize studies focusing on Germany, the United States (US) and the EU level, to investigate the storage requirements per share of variable renewable electricity, discussing also the effect of PV or WT preponderance and of the detail of grid modelling on storage needs. Johlas et.al. (2020) study the storage requirements for 100% and nearly 100% solar- and wind-powered systems, in the Midcontinent Independent System Operator energy market in the central US, under the effects of various PV and WT generation shares, geographical distribution of generation technologies, RES overcapacity and balancing power availability. Goteti et.al. (2019) study the potential of storage, operated for energy arbitrage (storing electricity when prices are low to supply it back to the grid when prices are high), to achieve carbon emissions reduction. They investigate the required wind and solar capacity to marginally achieve emission reductions, considering also the effect of natural gas prices, by performing case studies in a coal-heavy and a non-coal-heavy electricity region in the US. Budischak et.al (2013) simulate a wide range of PV, WT and storage configurations, to find least-cost electricity generation mixes, considering different storage technologies, geographical sitting expansion and RES technology diversification. Their simulations are constrained by the number of hours PV and WT need to cover demand, reaching up to 99.9% of the load hours (remaining demand is met by fossil back up plants), allowing for RES overcapacity to achieve such targets. Weitemeyer et al. (2015) investigate the effect of storage and its parameters (i.e., capacity and efficiency) on the renewable integration levels, by using Germany as case study. The study is performed, by analyzing in parallel optimal wind and solar generation shares, under the effect of overcapacity. Nayak-Luke et.al (2021) explore the storage magnitude (percentage of demand that needs to be met by stored electricity) and storage duration (short-/long-term) requirements, as a function of renewables penetration, wind and solar generation shares, and location, by considering a total of 37 locations in the United Kingdom and Australia. Heide et.al (2010) quantify optimal wind and solar generation mixes in Europe and their respective storage needs, considering a 100% wind-plus-solar only scenario and a transitional scenario allowing for fossil and nuclear power generation.

From the literature sources reviewed, several scientific gaps were identified, which are summarized subsequently:

- Research so far has mainly focused on analysing PV, WT and storage configurations, towards 100% RES electricity systems, without limitation in the total RES capacity, or reference to the implementation horizon of such electricity systems. This means that the focus is on studying an incremental increase of RES share, without answering **when** can this share be realized, **how** much RES capacity can realistically (or is planned to) be installed, and with **which** storage specifications. Therefore, the gap is in studying PV, WT and storage configurations, considering in parallel (i) a tangible time horizon (e.g., 2030), (ii) reported RES capacity expansion projections and (iii) established technical specifications of storage technologies.
- RES overcapacity is a usual parameter considered in literature, allowing curtailment to act as a means for managing excess generation and limiting the need for storage capacity. In fact, overcapacity is usually used as a parameter affecting the optimal PV and WT shares in the electricity mix, which in

turn limit the storage capacity required. While such a strategy is mentioned as a cost competitive alternative to deploying energy storage, especially considering the falling prices of RES (Perez et al., 2019), it can be restricted from the available land to deploy such a volume of renewable capacity. Indicatively, as literature suggests, in order to reach a fully renewable electricity system in Europe with a balanced technology portfolio, 2% of the total European land would need to be occupied, which is about the size of Portugal (Trondle, 2020). When considered in tandem with other constraints such as natural resource potential (e.g., solar irradiation), ground morphology, availability of transmission/distribution network, protected land (van de Ven et al., 2021), or barriers (Rai et al., 2016) and costs (Gao et al., 2022) to the installation of residential solutions, the sites available to install such a mass or renewables becomes notably narrower. Therefore, opting for a significant amount of overcapacity, would expand land use to many country sizes, could compete with other forms of land use, or could reveal injustices/dependencies among countries with different geographical, regulatory, or meteorological contexts. Taking also into account, the capacity density of WT and PV which is reported up to 19 W/m^2 and 100 W/m^2 respectively, when commercially available storage options offer a capacity density around 105 W/m^2 (Trondle, 2020), it becomes evident how much more hard-to-find European land would be required when considering overcapacity, and how much land use would be avoided by replacing PV or WT overcapacity with storage. Furthermore, overcapacity does not account for other issues, such as utilisation maximization of domestic resources, social acceptability issues, or investors' risk. For example, the REPowerEU plan (European Commission, 2022) published by the EC in response to the Russian invasion in Ukraine, aiming to reduce the dependency of the EU from Russian gas, mentions energy storage as a significant asset in providing flexibility to the grid and supporting security of supply, by facilitating RES integration and shifting generation to high demand times. While overcapacity with curtailment can reduce the residual demand (i.e., demand minus RES generation) during generation times, it cannot transfer electricity at times where it is most needed (e.g., peak demand, evening or night hours). That way the value of RES is reduced since they offset less fossil generation (Denholm, 2015). Finally, literature highlights that social acceptance of RES projects is a significant challenge in the EU (Kleanthis et al., 2022), and that financing as well as the design of policy support mechanisms are critical risk factors which could affect investment in RES (Angelopoulos et al., 2017). Therefore, aiming for underutilised systems might weaken the public and investors' trust towards the sustainability of RES systems. Considering the above, the gap in this case is in studying various PV, WT and storage configurations which minimize the application of curtailment towards utility maximization of domestically-generated electricity, without bias in allowing a specific technology to dominate the RES mix.

- Finally, usually the end-state of the electricity system is the focal point of research. Indicatively, most studies focus on a "future" electricity system and analyse the effects of its possible build-outs (e.g., shares of WT and PV, overcapacity and storage trade-offs, backup fossil generation, etc.). The current status quo of the electricity system, as well as its timewise intermediate buildouts (e.g., yearly PV, WT and storage configurations) leading to the materialization of a desired end-state, is usually neglected. This is in line with Hansen et.al (2019) whose extensive literature review highlighted that most studies do not analyse transition pathways (i.e., how to reach a target) and therefore do not provide information to policy-makers answering the “when’s” and “how’s” of the energy transition. In other words, the gap identified, can be expressed with the following four questions: (i) What is the current electricity generation portfolio? (ii) What RES plus storage configurations are feasible in a tangible time horizon (e.g., 2030), (iii) Which PV, WT and storage configurations can be implemented in the intermediate years, and (iv) What are their implications in terms of RES integration pace and timing of storage capacity requirements under various PV and WT shares?

This study aims to address the above research gaps by using a methodological framework consisting of two soft-linked models which: (i) enable the identification of storage capacity requirements, based on high-resolution storage operation simulation, and detailed technical specifications, such as round-trip efficiency, depth-of-discharge and energy-to-power ratio, and (ii) facilitate the interactive design of policy pathways, by providing an interface for simulated policy implementation. Greece is chosen as the testbed, as a country which has set ambitious RES capacity targets for 2030 and is currently characterized by limited capacity of interconnection transmission lines compared to its peak demand (i.e., about 20%), and high dependency on imported fuels for electricity generation. This makes the country a good example for assessing RES integration maximization in an effort to rely more on domestic resources. To make this chapter policy-relevant, actual market inquiries are addressed, which are either directly expressed by, or validated with, Greek stakeholders and market experts.

Overall, to the best of the author’s knowledge, the novel contribution of this chapter is twofold:

- The presentation of a modelling framework, which aggregates for the first time the merits of individual studies and evaluates RES plus storage configurations of electricity systems, considering simultaneously: (i) specific RES capacity targets, decomposed in various configurations of PV and WT shares without bias regarding the optimality of each configuration based on specific criteria (e.g., cost minimization), (ii) curtailment limitation under user-defined thresholds, using storage with detailed representation of its technical characteristics, (iii) RES integration percentages embedded in actual timewise implementation plans, and (iv) current status quos as well as the pathways towards diverse end-system configurations.

- The answering of inquiries expressed directly, or validated with, policymakers, aiming to support informed decision making. More precisely, taking into account actual RES capacity targets, and considering available technologies and a tangible time horizon, this study answers critical questions that still remain to be answered in the course of the energy transition in Greece. The timing of their answering coincides with the revision process of the Greek NECP, which is currently ongoing.

The remainder of the chapter is organized as follows: **Section 3.2** presents the modelling framework used. **Section 3.3** describes the Greek context in which the modelling framework is applied to. **Section 3.4** reports detailed simulation results. **Section 3.5** discusses key takeaways of the study accompanied with comparative analysis with relevant studies where possible. Finally, **section 3.6** summarizes key lessons learnt and provides implications for potential policymakers and end-users.

3.2. Modelling framework

The modelling framework used in this study consists of **(i)** the **ST**orage **R**equir**E**m**E**nts and dispatch **M**odel (STREEM), which enables the identification of the storage capacity requirements of a region, towards user defined curtailment levels, and **(ii)** the **A**daptive Pol**I**cymaking **M**odel (AIM) which performs exploratory analysis on a variety of policy options, and visualizes a map of diverse policy sequences, whose implementation lead to a desired outcome (Michas et al., 2020). The modelling framework is part of the **T**echno**E**conomics of **E**nergy **S**ystems **lab**oratory (**TEE**Slab) **M**odelling Suite (TEEM Suite[6]) and has been further developed in the context of the Sustainable Energy Transitions laboratory (SENTINEL[7]) project, based on consultations performed with relevant stakeholders (Süsser et al., 2022). **Fig. 3.1** shows a high-level overview of the modelling framework, while the following subsections present the models in more detail.

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[6] https://www.i2am-paris.eu/detailed_model_doc/teemsuite

[7] https://sentinel.energy

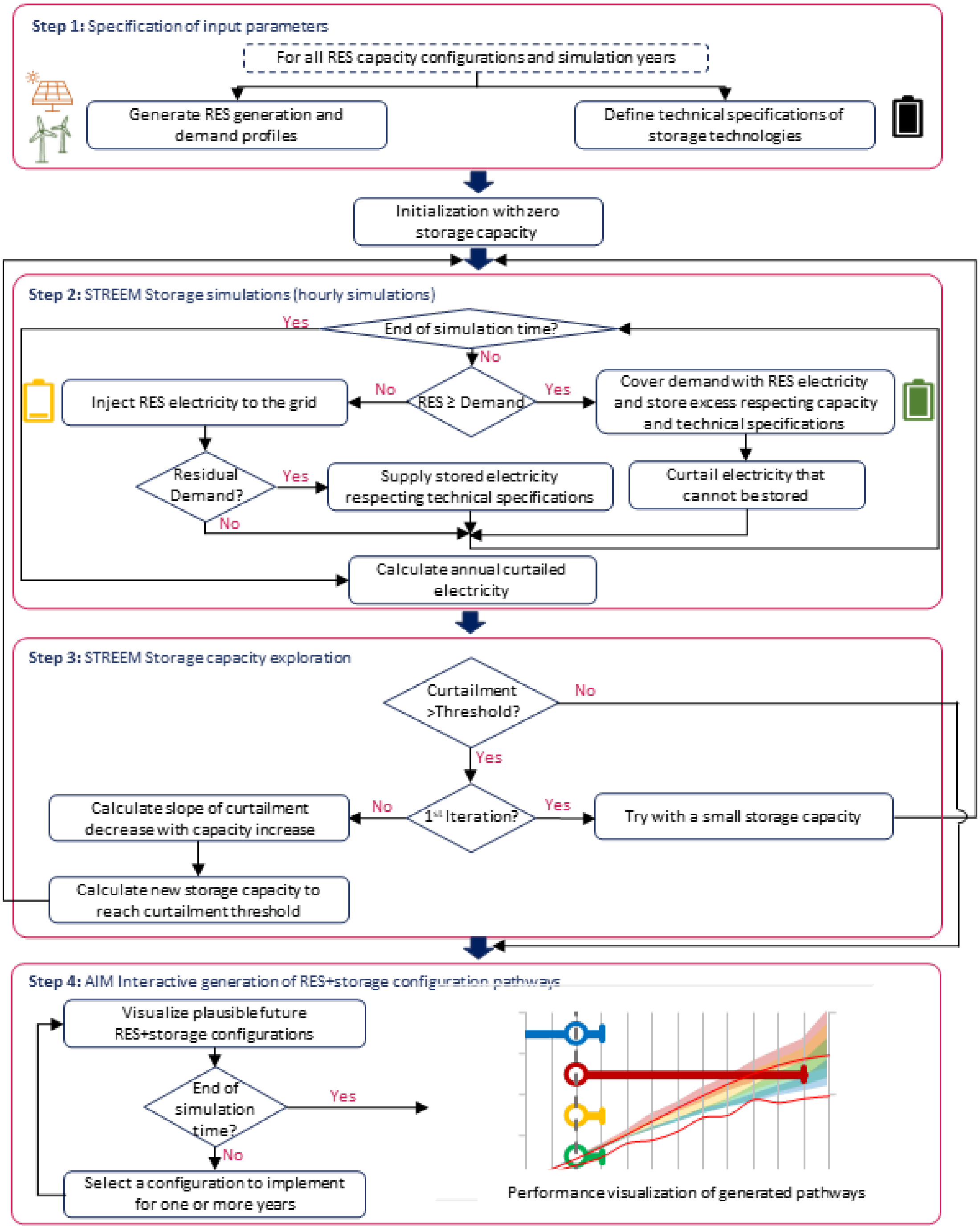


Fig. 3.1 Methodological Flowchart

3.2.1. STREEM

STREEM builds on the battery energy storage system (BESS) dispatch algorithm presented by Quoilin et.al. (2016), adapted to the temporal (i.e., hourly) and spatial (e.g., provincial, national, international) resolution of STREEM, and extended to account for storage capacity requirements investigation. The input parameters used by STREEM are summarized in **Table 3.1**, while the dispatch and storage capacity calculation algorithms are presented subsequently.

Table 3.1. STREEM inputs

Input Parameter	**Description**
Nominal Capacity	Maximum energy that can be stored in the storage system
Demand and RES generation timeseries	Projected electricity demand and generation from various RES sources in an hourly resolution for the entire simulation period
Duration	The time interval for which the storage system can charge/discharge at rated power capacity until full/emptied
Depth-of-Discharge (DoD)	The percentage of energy that can be discharged relatively to the nominal capacity of the storage system
Round-trip efficiency	The percentage of stored energy that can be retrieved during a full cycle of the storage system

Sources: (Cole et al., 2021; HOMER Energy, 2020; MIT Electric Vehicle Team, 2008)

Storage dispatch algorithm

The algorithm runs in an hourly resolution for each year of the simulation period. The initial state of the storage is set at minimum State of Charge (SOC), as described by Eq. (3.1).

$$SOC_{t=0} = nc * (100 - DoD) \tag{3.1}$$

where:

- t is the simulation period in hours,
- nc is the maximum energy that can be stored, and
- DoD is the depth-of-discharge of the storage system.

At each hour of the simulated period, the storage system stores electricity when RES generation is higher than demand, and supplies electricity to the grid when demand is higher than RES generation. If multiple storage technologies are used, the algorithm prioritizes short-term storage (e.g., battery energy storage systems) and uses the medium-/long-term storage technologies (e.g., pumped-hydro storage) after the short-term options have reached their storage capacity, or DoD. Excess generation that cannot be stored is curtailed. The hourly demand that could not be met either by directly feeding RES electricity to the grid or by discharging the storage systems, is saved as a residual demand timeseries.

At each simulation period t, the maximum charging power ($P_{ch,t}$), the maximum discharging power ($P_{dis,t}$), and the SOC of the battery are updated using Eq. (3.2)-(3.4)

$$P_{ch,t} = min\left(\frac{nc}{Duration}, nc - SOC_{t-1}\right) \tag{3.2}$$

$$P_{dis,t} = min\left\{\frac{nc}{Duration}, round\_trip \cdot [SOC_{t-1} - nc \cdot (1 - DoD)]\right\} \tag{3.3}$$

$$\begin{aligned} SOC_t &= SOC_{t-1} + P_{ch,t}\ , \text{ if storage is charging} \\ SOC_t &= SOC_{t-1} - \frac{P_{dis,t}}{round\_trip}, \text{ if storage is discharging} \end{aligned} \tag{3.4}$$

where:

- $Duration$ is the charge/discharge duration, and
- $round\_trip$ is the round-trip efficiency of the storage system

Storage losses are modelled during discharge of electricity, represented by the effect of the round trip efficiency in Eq.(3.3) and (3.4).

It should be noted that:

- Curtailment is calculated as the excess generation from RES that cannot be accommodated to the grid due to lack of demand. The model assumes that all generated electricity from the various RES technologies is aggregated and managed centrally, and that storage options are modelled as aggregated units per technology, representing an ideal "sum" of distributed systems. Therefore, restrictions related to grid-specific constraints (e.g., transformer availability, power flows, number of buses, etc.) are not considered. This enables a simplified representation of the power system allowing multi-spatial application of the model, spanning from cities to multi-country level analyses, aiming to provide high-level, policy relevant answers to challenges related to energy storage.
- The residual demand timeseries that results from the storage dispatch algorithm can be fed in a unit-commitment and economic dispatch model, to calculate the optimal dispatch of thermal units, imports, or other dispatchable units, for the demand not covered by RES. With this soft link technique of STREEM with unit commitment and economic dispatch models, RES generation (either direct or stored) is by priority injected to the grid, storage is used to store only RES electricity, and non-renewable generation is used to cover only the residual demand. The author has successfully attempted such a link with the Business Strategy Assessment Model (BSAM) (Kontochristopoulos et al., 2021). Relevant results for the residual demand are not in the scope of this study and therefore are not included.

Required storage capacity algorithm

The algorithm investigating the storage capacity requirements, identifies the correlation between storage volume and curtailment decrease. Initially the storage capacity is set at zero, representing a no storage energy system. The storage dispatch algorithm is run and the annual curtailment without storage is calculated. Following, a small capacity of storage is simulated, and the new annual curtailment is calculated. With these two initial iterations, the instantaneous slope of curtailment decrease with storage capacity increase is calculated using Eq. (3.5).

$$slope = \frac{nc_{i-1} - nc_{i-2}}{Curt_{i-2} - Curt_{i-1}} \tag{3.5}$$

where:

- i is the iteration of the algorithm
- nc is the nominal capacity of the storage system, and
- $Curt$ is the yearly curtailment as a percentage of total RES generation

Then, the new estimated storage capacity is calculated using Eq. (3.6).

$$nc_i = nc_{i-1} + slope \cdot (Curt_{i-1} - Target_{Curt}) \tag{3.6}$$

where:

- $Target_{Curt}$ is the target for curtailment

Considering that usually the correlation of curtailment with storage capacity is non-linear, the storage dispatch algorithm is run for the new estimated storage capacity and calculates the new instantaneous slope of curtailment decrease with storage capacity increase using Eq. (3.5). With this procedure, the actual curve of storage/curtailment correlation is approximated (example in **Fig. 3.2**), regardless of the storage technology or specifications simulated, while ensuring fast convergence. In fact, simulations suggest that the algorithm converges in 6-7 iterations. Furthermore, with this stepwise procedure, storage capacity overshooting is avoided, since the storage/curtailment slope gradually decreases towards the targeted curtailment levels.

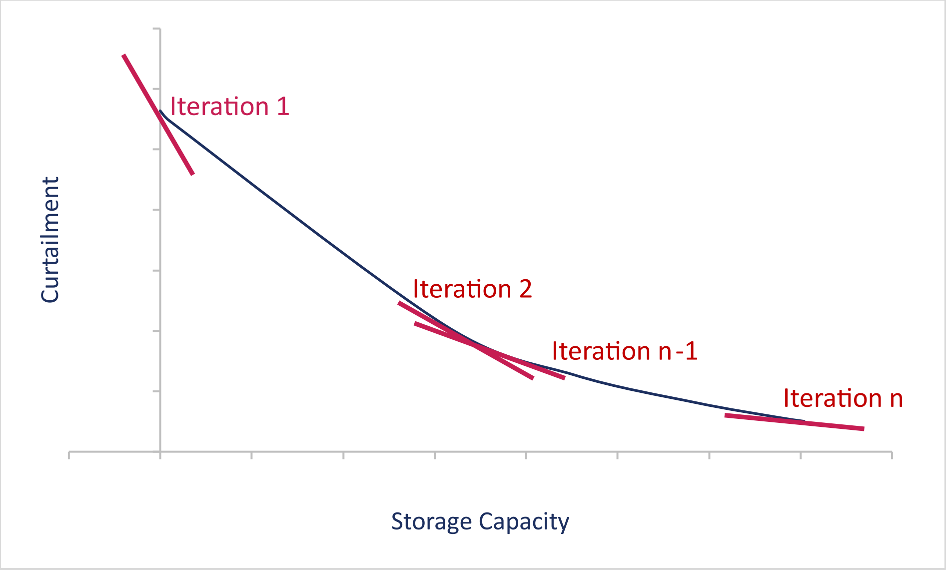


Fig. 3.2. Approximation of storage/curtailment curve

It is important to mention that the algorithm calculates the storage requirements of a single technology at a time, while keeping the other technologies at constant capacity. Such a simulation concept goes beyond classic optimization based on specific criteria (e.g., least investment cost, least operational cost, arbitrage maximization, etc.). Instead, the user is allowed to perform sensitivity analysis in terms of storage capacity requirements for different storage technologies, considering also the storage status quo of a region, or technology-specific constraints (e.g., long construction times and sites available for pumped hydro storage, maturity of technologies, etc.).

3.2.2. AIM

AIM is a decision support model which facilitates robust decision making under uncertainties and supports the development of policy pathways towards a desired target, based on simulated policy implementation and outcome assessment. It is a plug-in model, meaning that it requires as input, both the input parameters as well as the respective outputs, which are produced by a simulation model. In this respect it performs meta-analysis of simulation results. The main strength of AIM is that it enables fast assessment of a large number of scenarios along an analysis horizon, without mandating the same number of simulations to be performed by computational- and time-intensive simulation models. Specifically, it enables the assessment of $p^{m,}$ policy development scenarios with only p policy simulations performed by a simulation model, where p is the number of policies under investigation and m the number of years in the analysis horizon. The analytical formulation of AIM is presented in Michas et. al. (2020). In this chapter, AIM is adapted to match the scope of the herein presented modelling endeavor. Target is the generation of yearly adaptive pathways, comprising of changing RES plus storage configurations, towards higher RES integration levels with minimum curtailment.

Initially, AIM investigates if a specific PV-to-WT ratio (i.e., policy pathway), with relevance to the total RES capacity, is feasible from a stakeholder's "today" and onwards, considering the already installed capacities of each technology. Feasible pathways are those that do not result in less installed capacity of PV, WT or storage in a later year, than that installed in an earlier year, given that the lifespan of technologies has not been exceeded. Stakeholder's "today" is defined as the start of simulation time which coincides with the actual year of the problem analysis. Valid PV-to-WT ratios are depicted in an adaptive pathway map, showing which PV-to-WT ratios can be implemented starting from the stakeholder's "today", and which PV-to-WT ratios can be implemented in later years.

Then, with the simulated policy implementation functionality of AIM, PV-to-WT ratios are implemented in a stepwise manner. A feasible PV-to-WT ratio is implemented for a selected number of years, and the adaptive policy pathway map is updated within seconds, showing which PV-to-WT ratios are feasible for the years following the last year a PV-to-WT ratio was implemented. Policy implementation goes on until the end of simulation time is reached. During this process, the outcome of the implemented pathway (sequence of PV-to-WT ratios), as well as the outcome of "future" PV-to-WT ratios is displayed to the user. The outcomes along the pathway (or "future" pathways) comprise of: (i) the required storage capacity, (ii) the annual and peak curtailment levels with and without storage, (iii) the RES integration levels with and without storage, (iv) the peak residual demand that needs to be covered by thermal generating units, and (v) the pathway costs (i.e., capital cost and operation and maintenance (O&M)), decomposed to the cost of each technology (i.e., PV, WT and storage).

The outcomes (i)-(iv) result from simulations performed with STREEM. The pathway costs are the product of post-processing STREEM outputs with AIM. At each year of the pathway, the newly installed capacities per technology are calculated and multiplied with the discounted overnight investment costs and O&M costs at the same year as shown in Eq. (3.7) and Eq. (3.8) respectively, to derive the pathway's yearly overnight investment costs and O&M costs.

$$\begin{gathered} Cost\ of\ PV_y = \left(PV_y - PV_{y-1}\right) \cdot PVC_y \\ Cost\ of\ WT_y = \left(WT_y - WT_{y-1}\right) \cdot WTC_y \\ Cost\ of\ Storage_y = \left(nc_y - nc_{y-1}\right) \cdot SC_y \\ Ov.Cost_y = Cost\ of\ PV_y + Cost\ of\ WT_y + Cost\ of\ Storage_y \end{gathered} \tag{3.7}$$

$$\begin{gathered} O\&M\ cost\ for\ PV_y = PV_y \cdot PVOM_y \\ O\&M\ cost\ for\ WT_y = WT_y \cdot WTOM_y \end{gathered} \tag{3.8}$$

$$O\&M\ cost\ for\ ST_y = nc_y \cdot STOM_y$$

$$OM.Cost_y = O\&M\ cost\ for\ PV_y + O\&M\ cost\ for\ WT_y + O\&M\ cost\ for\ ST_y$$

where:

- y is the year of reference
- PV, WT, nc are the simulated PV, WT and storage capacities in the year referenced by the index,
- $PVC, WTC\ and\ SC$ are the overnight investment costs for each unit of PV, WT and storage in the year referenced by the index, and
- $PVOM, WTOM\ and\ STOM$ are the O&M costs for each unit of PV, WT and storage in the year referenced by the index.

Then, the Equivalent Annual Cost (EAC) of the yearly overnight investment costs of each technology are calculated using Eq. (3.9).

$$EAC_{y,tech} = \frac{Ov.Cost_{y,tech} \cdot i_{tech}}{1-(1+i_{tech})^{-k_{tech}}} \tag{3.9}$$

where:

- i is the interest rate,
- $tech$ is the technology assessed, and
- k is the lifetime of each technology

Finally, the pathways total cost is calculated as the sum of equivalent annual values and O&M costs until the pathway's horizon of analysis as shown in Eq. (3.10).

$$P.Cost = \sum_{y=1}^{n}\left[\left(\sum_{tech} EAC_{tech}\right)_y + OM.Cost_y\right] \tag{3.10}$$

where:

n is the final year of analysis.

It should be noted that Eq. (3.10) is not an objective function subject to minimizing. It only calculates the cost of each generated pathway. Cost minimization is possible, but it is out of the context of this work.

3.3. The case of Greece

Greece is chosen as the case study region, being a country which has set ambitious climate and policy goals for 2030, transitioning away from its current regime which is characterized by low interconnections' capacity, high dependency on fossil fuels and lately high dependency on imported fuels for electricity generation. The Greek NECP (Greek Ministry of Environment and Energy, 2019a) published in December 2019 describes the set targets, as well as, how they are intended to be achieved.

Among the targets is the decarbonization of the power sector, presenting ambitious renewable capacity expansion objectives, as well as projections about the evolution of the generation capacity mix (i.e., installed capacities of solar, wind, hydro, thermal, etc. generating units). Specifically, the gradual phase out of the highly polluting lignite power plants until 2023 is the starting point for the decarbonization of the power sector, with natural gas playing the role of the transition fuel. Target destination is a power sector dominated by RES technologies, mentioning a cumulative RES capacity in 2030 amounting to 14.7 GW, implying a growth rate equal to 153% with relevance to the installed capacity in 2020 (i.e., 5.8 GW). The 2022 Russian invasion to Ukraine and the consequent energy crisis might shortly delay the lignite phase out plan of Greece, but sooner or later Greece will be in a position where all dispatchable power plants operated with domestically produced fuels will be shut down, and Greece will rely only on gradually declining amounts of imported gas and gradually increasing amounts of intermittent RES to cover its electricity needs. Considering the above, the need for electricity storage has been identified in the Greek NECP, as the means for optimal integration of uncontrollable RES, avoiding the risk for significant curtailment which would make new RES projects unsustainable for investors (Aposporis, 2022). Specifically, storage capacity equal to 2.8 GW is foreseen until 2030, comprising mainly of pumped hydro and battery storage.

However, as stated in the official NECP, the amounts of installed capacity of the various generating and storage technologies, have been calculated based on simulations made under specific assumptions regarding the generation cost evolution for each technology. In this respect, the configuration of the electricity system presented in the NECP should be considered as possible but not binding (Greek Ministry of Environment and Energy, 2019a). This statement becomes even more relevant considering the 2022 energy crisis that followed the Russian invasion to Ukraine, which increases the uncertainty for natural gas availability, and implicitly mandates for maximization of utilization of RES-generated electricity.

In this respect, in this study, various configurations of PV, WT and storage configurations are analyzed, as potential buildouts of the Greek electricity system in 2030, providing implications for their renewable integration potential, the needs for storage capacity to maintain curtailment below 0.1%, the pathways towards their materialization, as well as, their overnight investment costs. The small curtailment window is left open to account for exceptional events, with concurrent high solar irradiation and wind speed, during which the storage systems may reach their capacity, or the hourly electricity to be stored may exceed the storage systems' rated charging power.

Important research questions tackled include:

i. How much storage is needed to reach the 2030 renewable integration targets in Greece without excessive curtailment, maximizing that way the utilisation of domestically produced electricity?

ii. How do the PV and WT capacity shares relate to RES integration and storage needs timing?

iii. Is there an optimal wind/ PV ratio to achieve efficient RES penetration with low curtailment, and how much storage does this configuration require?

iv. What is the cost of each additional percent of RES generation injected to the system?

These research questions have been either directly expressed by, or validated with, Greek stakeholders, during the stakeholder consultation workshops that were held in mid-2020 as part of the EC-funded SENTINEL project. Their answering aim to contribute to the work of policymakers, by providing implications for a wide range of electricity system configurations which are not a product of optimization based on specific criteria. Moreover, it contributes to the endeavors of the scientific community, by bridging the gap between scientific analyses and targeted policy inquiries. The following subsections present the assumptions of the study.

3.3.1. Demand, hydro, and RES generation

Historical demand, hydro generation and RES generation (i.e., PV and WT) timeseries in an hourly resolution for the period 2015-2020 were obtained from the ENTSO-e transparency platform (ENTSO-e Transparency Platform, 2021), and were scaled to their respective annual projections, as mentioned in the NECP for the period 2021-2030. Randomization in each projected timeseries was performed by drawing from a normal distribution with mean the average amounts (e.g., demand, hydro, wind and solar generation) for each hour of the historical calendar years (2016 – 2020), and standard deviation the standard deviation of each timeseries for each hour of the same period. **Fig. 3.3** shows the annual demand projections as well as a typical demand profile throughout a year.

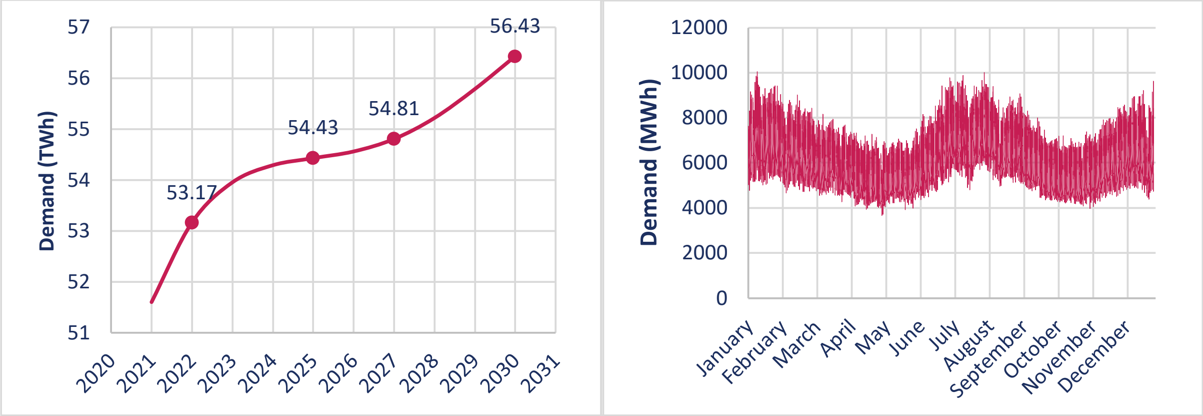


Fig. 3.3. Electricity demand in Greece

Hydro power plants' capacity (i.e., hydro run-of-river and hydro water reservoir) in Greece is not expected to change significantly by 2030. Therefore, the hourly hydro timeseries were only randomized according to the historical data obtained by ENTSO-e. **Fig. 3.4** shows a typical hydro generation profile throughout a year.

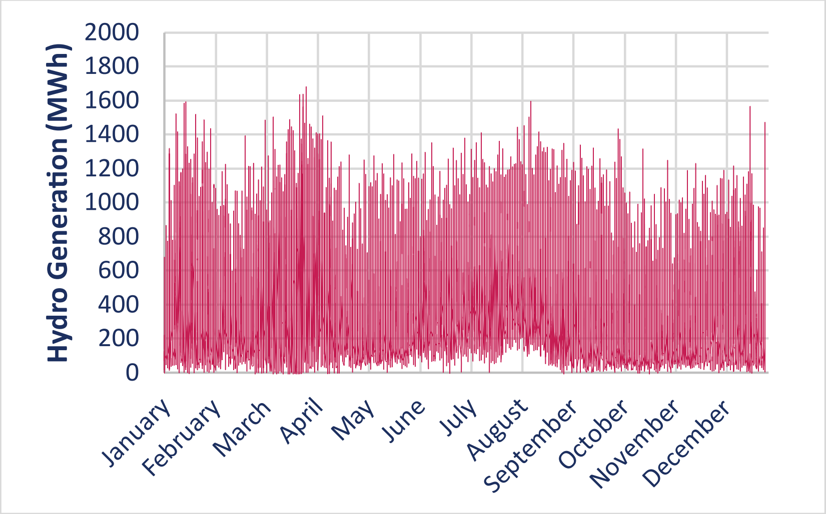


Fig. 3.4. Hydro generation in Greece

Finally, for the case of RES generation, as mentioned earlier in **section 3.3**, various PV-to-WT capacity configurations towards the aggregated RES capacity targets (i.e., 14.7 GW in 2030) are simulated. In fact, configurations featuring from 75% WT to 75% PV with 2.5% steps are included in the scenarios. Therefore, the generation profiles differ according to the shares of PV and WT in the RES capacity mix. **Fig. 3.5** shows the range of scenarios examined for RES (i.e., PV and WT) capacity and generation until 2030. The coloured capacities are the ones projected by the Greek NECP, while the grey ones are the maximum and minimum capacities that each technology can hold along the years in the assessed scenarios. The thick RES generation lines are the ones projected by the Greek NECP, while the shaded areas correspond to the generation range of each technology, depending on the capacity it holds within the maximum and minimum range of the assessed scenarios.

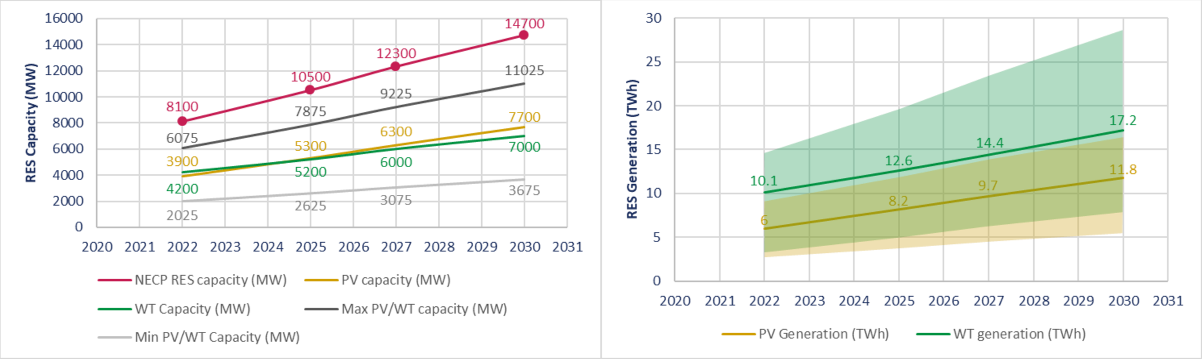


Fig. 3.5. Range of scenarios examined for RES capacity (left) and generation (right) in Greece

3.3.2. Storage Characteristics

Storage can provide a multitude of functions to the power grid and each storage technology is better suited for different applications as analytically presented by Palizban and Kauhaniemi (2016). This study does not intent to analyse the optimal storage technology mix for the services required by the power sector in Greece. Instead, the aim is to analyse the storage capacity needs under different RES generation configurations, considering current trends in Greek power storage, and an established and widely used storage technology as reference for future capacity expansion. As mentioned in the Greek NECP, storage capacity until 2030 will comprise mainly of pumped hydro and battery storage. Pumped hydro storage (PHS) is historically the most established method for storing and dispatching electricity, with main benefits being its almost infinite lifetime and high efficiency. PHS storage is suitable for bulk energy (i.e., energy arbitrage, peak shaving) and renewable energy integration applications (i.e., capacity firming, time shift), with potential for some ancillary services provision (e.g., secondary and tertiary frequency regulation or black start) (Palizban and Kauhaniemi, 2016). An important limitation of PHS, is the limited availability of sites for their geographical sitting in river-based applications (Lu et al., 2021). Nevertheless, the availability of sites for off-river, closed loop pumped hydro has been recently studied and the results were promising (Stocks et al., 2021). On the other hand, BESS, are increasingly attracting the attention of the scientific community (Gaspar et al., 2021; Kalkbrenner, 2019; Retna Kumar and Shrimali, 2021). The advantages of BESS, as identified by Hannan et. al (2021), include their fast and steady response, their adaptability and controllability, as well as their geographical sitting flexibility, which is a significant differentiation from PHS. BESS have the potential to contribute to a variety of ancillary services (e.g., voltage support, black start, primary/secondary/tertiary frequency regulation, etc.), customer energy management (i.e., power quality, power reliability) and renewable energy integration (IRENA, 2019; Palizban and Kauhaniemi, 2016), and is identified as the storage technology which is expected to provide much flexibility to the grid with increasing renewable generation (Seward et al., 2022).

Currently in Greece, there are two hydro power stations with installed pumping capacity (namely in the Sfikia and Thisavros power plants). According to consultations with stakeholders from the Public Power Corporation (owner of the power plants), there are plans to build two new PHS projects in Amfilohia and in Amari, however, due to high uncertainty regarding their delivery, they are not considered in this study. Therefore, the PHS capacity in the present study is kept constant. **Table 3.2** presents the technical specifications of PHS.

Table 3.2. PHS specifications

Power Plant Name	Sfikia	Thisavros

Nominal Capacity (MWh)	1320	3820
Nominal Power (MW)	315	372
Pumping rate (MWh/h)	220	250
Depth-of-Discharge (%)	95	95
Round-trip efficiency (%)	78	78
Duration (h)	6	10

Sources: (Kaldellis, 2015; Schmidt et al., 2019) and consultations with stakeholders from the Greek Public Power Corporation (owner of the plants)

BESS capacity is currently not installed in Greece, but it is mentioned in the political agenda (Greek Ministry of Environment and Energy, 2019a). While an estimation for the power capacity of BESS systems (in GW) until 2030 is provided in the NECP other technological specifications of BESS (e.g., technology, duration, round-trip efficiency, or depth of discharge) are not included. In this study utility-scale lithium ion (Li-Ion) electricity storage systems are assumed as the BESS option, and their required energy capacity (in GWh) to minimize curtailment is investigated. Li-Ion has lately been reported as the technology which is starting to be the dominant option for energy storage at grid-scale (Martins and Miles, 2021). It is a reliable storage technology with indicative strengths being its long lifecycle, its high round-trip efficiency and its low self-discharge rate (Killer et al., 2020). According to Schmidt et.al. (2019) the technology is expected to be the most cost-efficient in terms of levelized cost of storage in most electricity storage applications by 2030. Furthermore, stakeholders (i.e., utilities, regulators, system integrators, etc.) have been gaining working experience with the technology at grid-scale applications, as such it is expected to be the dominant technology for energy storage applications at grid-scale (Pellow et al., 2020). In fact, it has been reported that over 90% of large-scale BESS installations in 2017 were of the Li-Ion technology (IRENA, 2019). **Table 3.3** presents the technical specification of utility-scale Li-Ion BESS assumed in this study, for which capacity requirements are investigated.

Table 3.3. Li-Ion BESS specifications

Specification	**Metric**	**Justification**
Depth-of-Discharge (%)	88	Average optimal DoD of Li-Ion batteries for multiple applications until 2030 in terms of LCOS, as presented in Schmidt et.al. (2019)
Round-trip efficiency (%)	85	In agreement with values published in several studies reviewed by Cole et.al (2021)
Duration (h)	4	Wide application in the U.S. and cost-competitiveness with combustion turbines (Denholm et al., 2020)

3.3.3. Cost components

Projections for the overnight investment and O&M costs for PV and WT until 2030 were obtained from the Greek NECP and the Greek Long-term strategy (Greek Ministry of Environment and Energy, 2019b) respectively, performing linear interpolations for missing intermediate years. For the case of solar PV in Greece, it is assumed that for about every 7 MW of large-scale PV installations, 1 MW of small-scale PV (rooftop) installations occur, which is an assumption based on historical data (Michas et al., 2020). As such the average investment and O&M cost of PV was calculated using the same weights. For the case of 4-hour Li-Ion BESS, projections for the overnight investment costs for a complete 4-hour battery storage system, accounting for both energy (kWh) and power (kW) costs, were obtained from Cole et. al. (2021), after converting the prices from US Dollars ($\$_{2020}$) to Euros ($€_{2020}$) with the average exchange rate for 2020. O&M costs for batteries were obtained from the Greek Long-term strategy after performing linear interpolation for the missing years. **Table 3.4** presents the resulting cost values.

Table 3.4. Overnight investment and O&M costs of RES and storage

Year	Overnight Solar PV (€/MW)	O&M Solar PV (€/MW)	Overnight WT (€/MW)	O&M WT (€/MW)	Overnight Storage Min (€/MWh)	Overnight Storage Max (€/MWh)	O&M Storage (€/MW)
2021	591720	21550	1126040	21900	316000	333000	30300
2022	574080	20850	1092160	21800	290000	323000	28600
2023	557455	20150	1059360	21700	264000	315000	26900
2024	541845	19450	1027640	21600	238000	305000	25200
2025	527250	18750	997000	21500	212000	295000	23500
2026	513670	18050	967440	21400	199000	286000	21800
2027	501105	17350	938960	21300	184000	276000	20100
2028	489555	16650	911560	21200	170000	267000	18400
2029	479020	15950	885240	21100	157000	258000	16700
2030	469500	15250	860000	21000	143000	248000	15000

Sources: (Cole et al., 2021; Greek Ministry of Environment and Energy, 2019a, 2019b)

The effective lifetime of WT, PV and Li-Ion BESS is assumed to be equal to 20, 32.5 and 20 years respectively as obtained by NREL (2022) and Timmons et.al. (2020). Finally, the interest rate of new investments is assumed equal to 8.5% as obtained by the Greek Long-term strategy.

3.4. Results

The results of the study showed that towards the Greek RES capacity targets mentioned in the NECP until 2030, several configurations can be implemented, and various pathways can be followed for their achievement. The results do not imply optimal PV, WT and storage configurations or dominance of one option over another. Rather, the aim is to highlight the outcomes of each end-system configuration, providing insights to potential end-readers, such as policymakers, research practitioners, etc.

In all PV-to-WT configurations examined (see **section 3.3.1**), the annual curtailment levels until 2030 remain below the 5% threshold mandated by the EU, without any storage capacity (**Fig. 3.6**). This is due to the fact that the installed RES capacity until 2030 is still low, and the generated electricity can, by the largest part, be matched with demand.

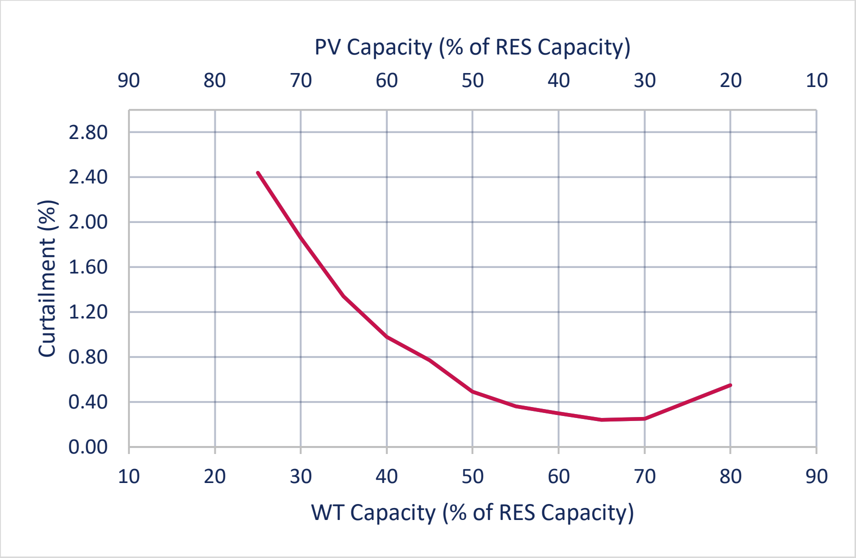


Fig. 3.6. Annual curtailment (%) without storage in 2030

Yet, even if curtailment remains low, it still highlights that instances of potential electricity loss will start to appear with increasing RES shares. The simulation results indicate that with BESS operating in parallel with the installed PHS capacity, curtailment could be minimized by 2030, paving the way for higher RES integration post the NECP horizon (i.e., post 2030), contributing that way to a decoupling of the energy transition of Greece from imported gas. At first glance, **Fig. 3.6**, suggests that with a WT share around 60-70% in the electricity system, the lowest curtailment levels can be achieved, thus low BESS capacity would be required. While this is true, the problem of RES integration is multifaced, and each PV, WT and BESS configuration in 2030 requires a more in-depth analysis. The following subsections present details for three end-system configuration scenarios and the pathways towards their achievement.

3.4.1. PV+ scenario

In the “PV+” scenario, the RES plus storage configuration features PV as the preponderant technology, holding 60-75% share with respect to the total RES capacity foreseen for 2030. This corresponds to 8820-11025 MW of PV capacity and 3675-5880 MW of WT capacity.

BESS requirements

In this scenario, curtailment levels without BESS capacity range between 0.98-2.44%, and the RES share in the electricity mix ranges between 48.5-54.5%. The required BESS capacity to reduce curtailment below 0.1% annually, ranges between 7.6-11.7 GWh, with respective power capacity ranging between 1.9-2.9 GW. The resulting RES share in the electricity mix with the use of BESS increases to 49.3-54.9%, which is mainly attributed to the contribution of BESS in matching generation and demand during the morning peak hours as shown in **Fig. 3.7**. Considering the PV shares examined, the correlation of PV share and RES integration implies a declining rate of -0.37% RES share per 1% additional PV share in the RES mix. The main drawback of such a configuration is that the mismatch between generation and demand remains high during the evening and night hours, resulting in a significant amount of peak residual demand (demand minus RES generation) that needs to be covered by thermal units, equal to 7.6-8.1GW. This also explains the low RES penetration levels observed.

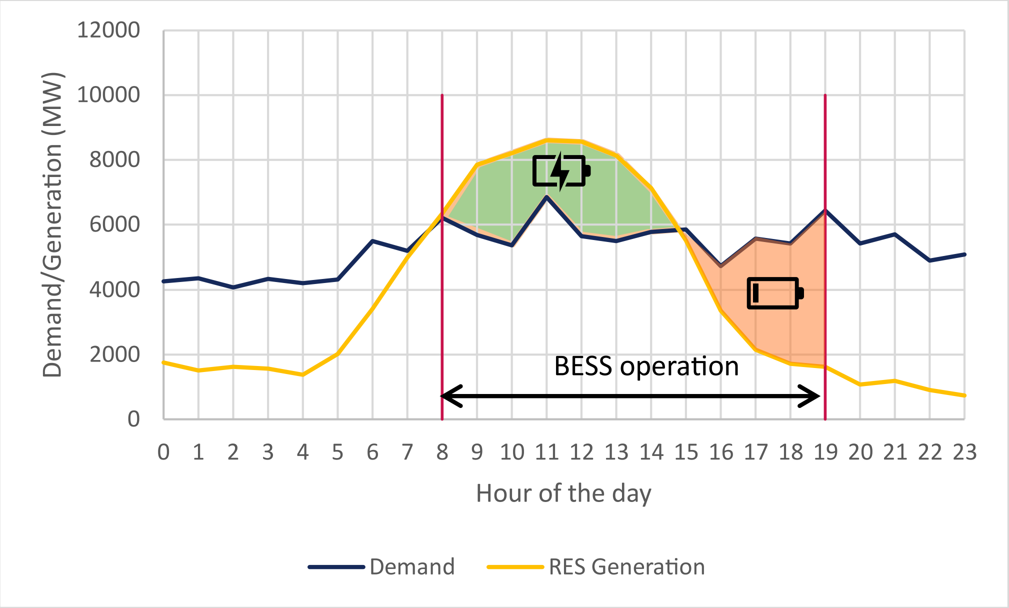
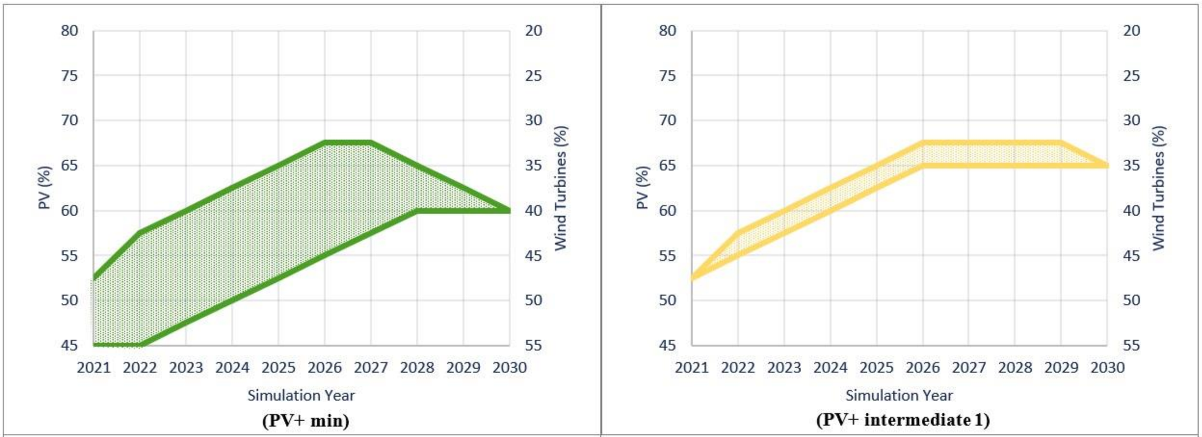


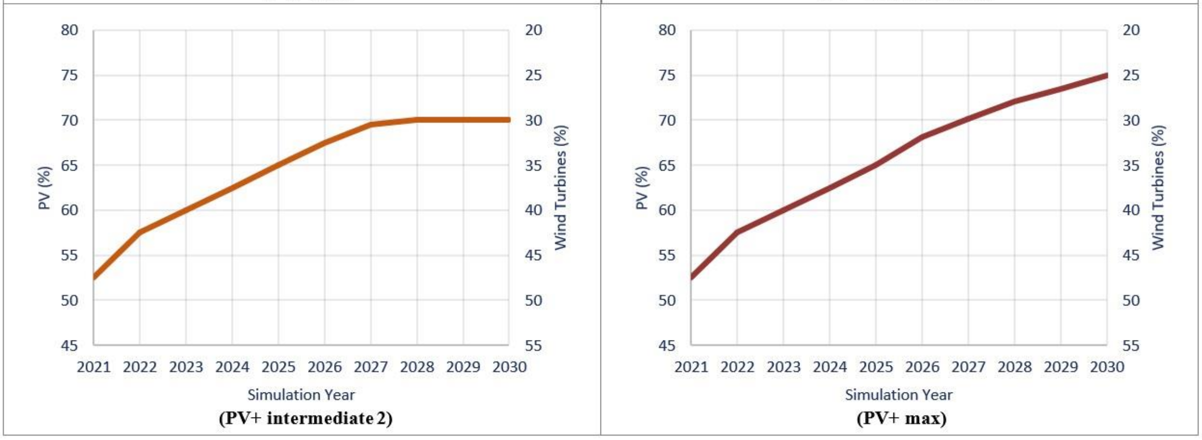
Fig. 3.7. BESS operation throughout a typical day with high generation in the “PV+” scenario

How to get there

In order to reach the end-system configuration described in the "PV+" scenario, multiple pathways exist as shown in **Fig. 3.8**. The thick lines in each subfigure represent the marginal pathways (percentage evolution of PV and WT) towards the 2030 configuration, restricted by the currently installed capacities per technology. This means that a percentage configuration above a thick line in a specific year cannot be materialized, because this would mean reduction in an already installed capacity (in this case WT), which is not desired. The shaded area within each subfigure indicates the feasible PV/WT percentages that can be followed, to generate intermediate pathways towards the final configuration target.



(PV+ min) **(PV+ intermediate 1)**



(PV+ intermediate 2) **(PV+ max)**

Fig. 3.8. Pathways towards the PV+ scenario. **(PV+ min):** Configuration in 2030 consisting of 60% PV and 40% WT. **(PV+ intermediate 1):** Configuration in 2030 consisting of 65% PV and 35% WT. **(PV+ intermediate 2):** Configuration in 2030 consisting of 70% PV and 30% WT. **(PV+ max):** Configuration in 2030 consisting of 75% PV and 25% WT.

Observing **Fig. 3.8**, it is easily deductible that with increasing PV shares in the end-system configuration, the pathway options towards their achievement decrease significantly, eventually, leading to the availability of only one pathway to follow (i.e., bottom subfigures of **Fig. 3.8**). Nevertheless, in order to reach an electricity system in 2030 with PV holding 60-75% of the RES capacity share, new PV installations should prevail as soon as possible in all cases of **Fig. 3.8**, in order to avoid capacity lock-ins. The choice of end-system configuration, as well as the pathway towards its materialization, can be informed by technological, as well as cost parameters.

The average BESS needs per additional RES share range between 1.1-1.3 GWh/%RES. Yet, due to the lower technological cost of PV with relevance to WT (**section 3.3.3**), the increased needs for BESS capacity with higher PV shares, increase only slightly the total annualised end-system configuration cost in 2030, and only if slow cost reductions are observed for BESS. This is graphically presented in **Fig. 3.9**, which illustrates the total annualised cost breakdown (i.e., capital cost plus O&M) in 2030, under various end-system configuration within the "PV+" scenario. WT and BESS reach cost parity by 2030, if WT hold a RES share ranging between about 32% and 36%, depending on the evolution of the BESS cost. Overall, the pathway's average annualised cost increase for every additional 1% RES share in the "PV+" scenario is equal to 27-33 million €, and the total budget spent until 2030 is equal to 4.7-5 billion €.

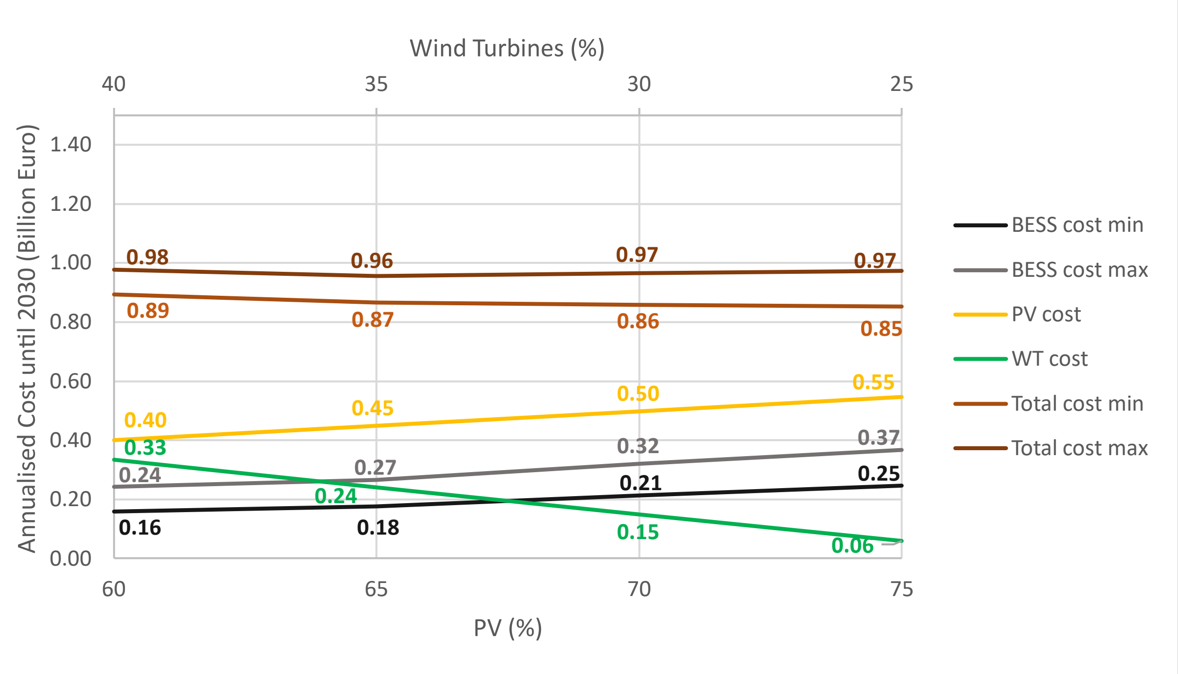


Fig. 3.9. "PV+" scenario investment cost breakdown until 2030

Finally, it is important to note that when multiple pathways towards the desired end-system configuration exist, the choice of pathway might affect the pace of RES integration in the electricity mix, or the timing and quantity of BESS capacity needs. This is graphically, illustrated in **Fig. 3.10** and **Fig. 3.11** which show the evolution of RES shares and BESS capacities, for the marginal pathways of the "PV+ min" and "PV+ intermediate 1" cases (see **Fig. 3.8)**. The choice of pathway affects both the RES integration percentage and the timing of BESS requirements. Specifically, in the "PV+ min" case

(**Fig. 3.10**), pathways appear to result in up to 3.4% RES integration difference until the 2030 end-system congifuration, while the timing of BESS capacity requirements initiate up to two years earlier with higher PV shares.

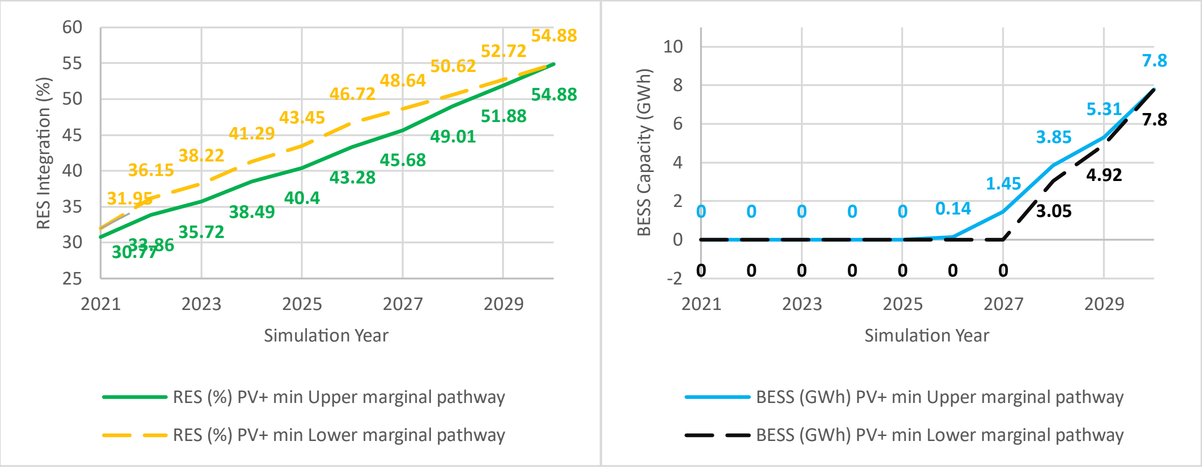


Fig. 3.10. RES integration and BESS capacity evolution for the marginal pathways of “PV+ min” case

Also, the effect on both metrics changes as the pathway option space becomes smaller (i.e. “PV+ intermediate” compared to “PV+ min”). Characteristically, as shown in **Fig. 3.11**, the maximum difference of RES integration among pathways is lower than 1%, while the timing of BESS capacity requirements remains practically the same among pathways, with small differences in the capacity slope of installed BESS.

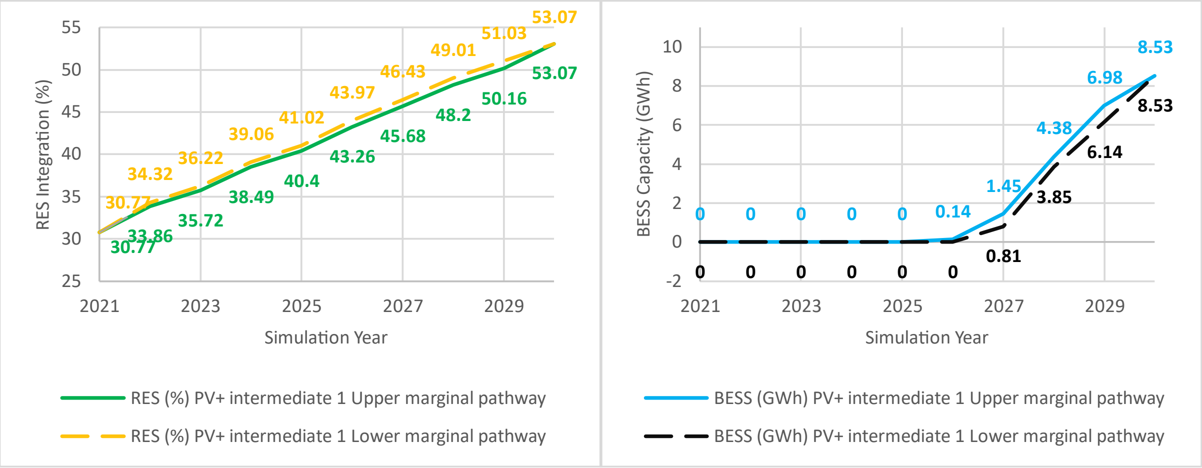


Fig. 3.11. RES integration and BESS capacity evolution for the marginal pathways of PV+ intermediate 1 case

3.4.2. Wind+ Scenario

The "Wind+" scenario, is the opposite of the "PV+" scenario, with WT being the preponderant technology, and holding 60-75% share with respect to the total RES capacity foreseen for 2030. This corresponds to 8820-11025 MW of WT capacity and 3675-5880 MW of PV capacity.

BESS requirements

In this scenario, curtailment levels without BESS capacity range between 0.24-0.40%, and the RES share in the electricity mix ranges between 61.6-66.3%. The required BESS capacity to reduce curtailment below 0.1% annually ranges between 2.4-6.5 GWh, with respective power capacity equal to 0.59-1.62 GW. The resulting RES share in the electricity mix with the use of BESS increases slightly, reaching to 61.7-66.5%. The correlation of WT share and RES integration in this case implies an increasing rate of +0.32% RES share per 1% additional WT share in the RES mix. **Fig. 3.12** shows a typical day where the BESS operates through the day. Residual demand that needs to be met by thermal units is also observed in this scenario, however, with smoother peaks (i.e., 6.4-7.1GW) and distributed during the morning and afternoon hours, compared to the case with high PV shares.

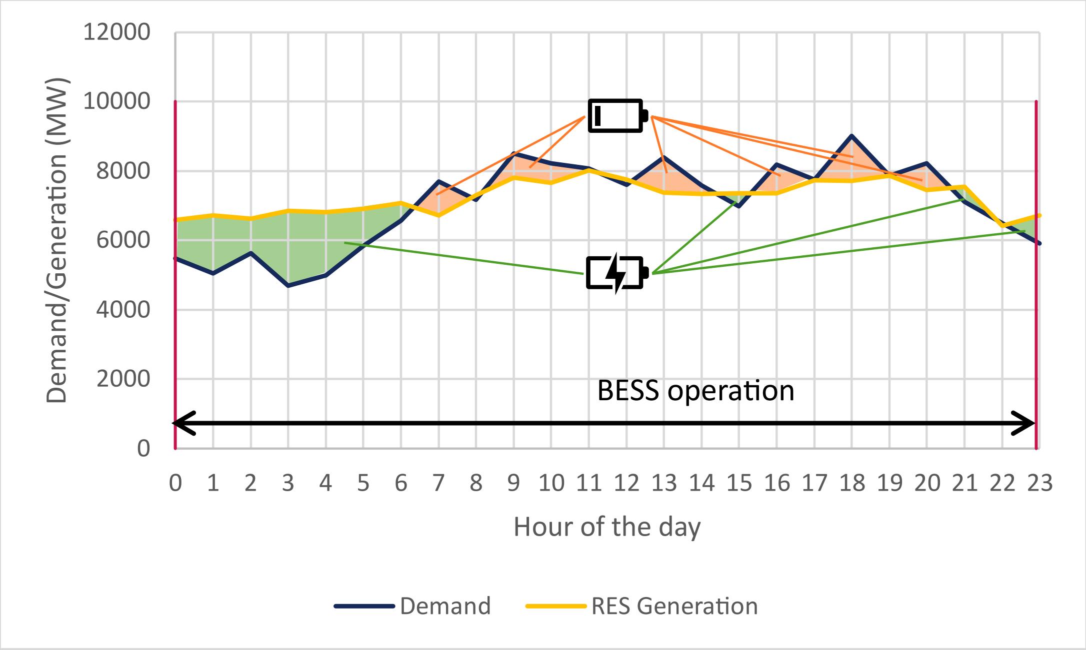
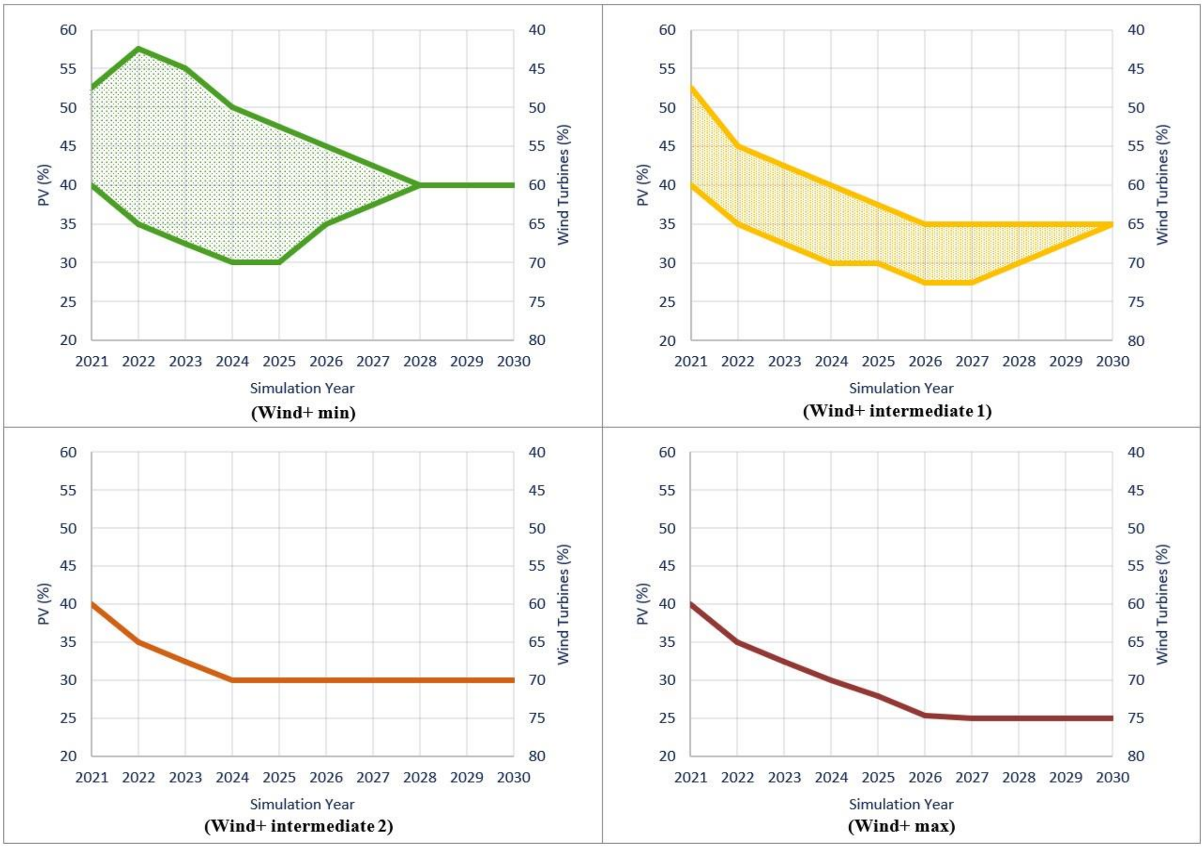


Fig. 3.12. BESS operation throughout a typical day with high generation in the "Wind+" scenario

How to get there

In the "Wind+" scenario too, there are multiple pathways in order to reach the desired end-system configuration. As shown in **Fig. 3.13**, when WT shares in the end-system configuration increase, the pathway options towards their achievement decrease significantly, leaving only one pathway to follow when high WT shares are aimed in 2030 (i.e., “Wind+ intermediate 2” and “Wind+ max” cases). PV can be the preponderant technology in the early years (e.g., upper marginal pathway of the “Wind+ min” case), but new WT installations will need to prevail early enough to avoid capacity lock-ins.



(Wind+ min)

(Wind+ intermediate 1)

(Wind+ intermediate 2)

(Wind+ max)

Fig. 3.13. Pathways towards the Wind+ scenario. **(Wind+ min)**: Configuration in 2030 consisting of 40% PV and 60% WT. **(Wind+ intermediate 1)**: Configuration in 2030 consisting of 35% PV and 65% WT. **(Wind+ intermediate 2)**: Configuration in 2030 consisting of 30% PV and 70% WT. **(Wind+ max):** Configuration in 2030 consisting of 75% PV and 25% WT.

In terms of BESS requirements to minimize curtailment, the average BESS needs per additional RES share range between 0.6-1.8 GWh/%RES. The smaller capacity from the range mentioned in the previous section (2.4-6.5 GWh) would be required in a configuration with about 62.5% WT. In fact, the results indicate that this configuration requires the minimum BESS capacity of all the scenarios examined. For every additional 1% of WT capacity, on average an additional 330MWh of BESS capacity would be required to ensure low curtailment, while for every additional 1% of PV capacity an additional 260MWh of BESS capacity would be required.

The average annualised cost increase, for every additional 1% RES integration in a “Wind+” system, ranges between 26-28 million €, and the total budget spent until 2030 is equal to 5.8-7.2 billion €. **Fig.**

3.14 illustrates the total annualised cost breakdown in 2030, under various end-system configurations within the “Wind+” scenario. The storage costs remain almost stable until the configuration consisting of 65% WT, with the minimum being observed at 62.5% WT. Then, the BESS cost gradually increases, with steeper slopes with higher WT shares. In terms of cost parity, PV and BESS require equal investment plus O&M costs by 2030, if WT hold about 70% and 72.5% of the RES share, depending on the evolution of the BESS cost.

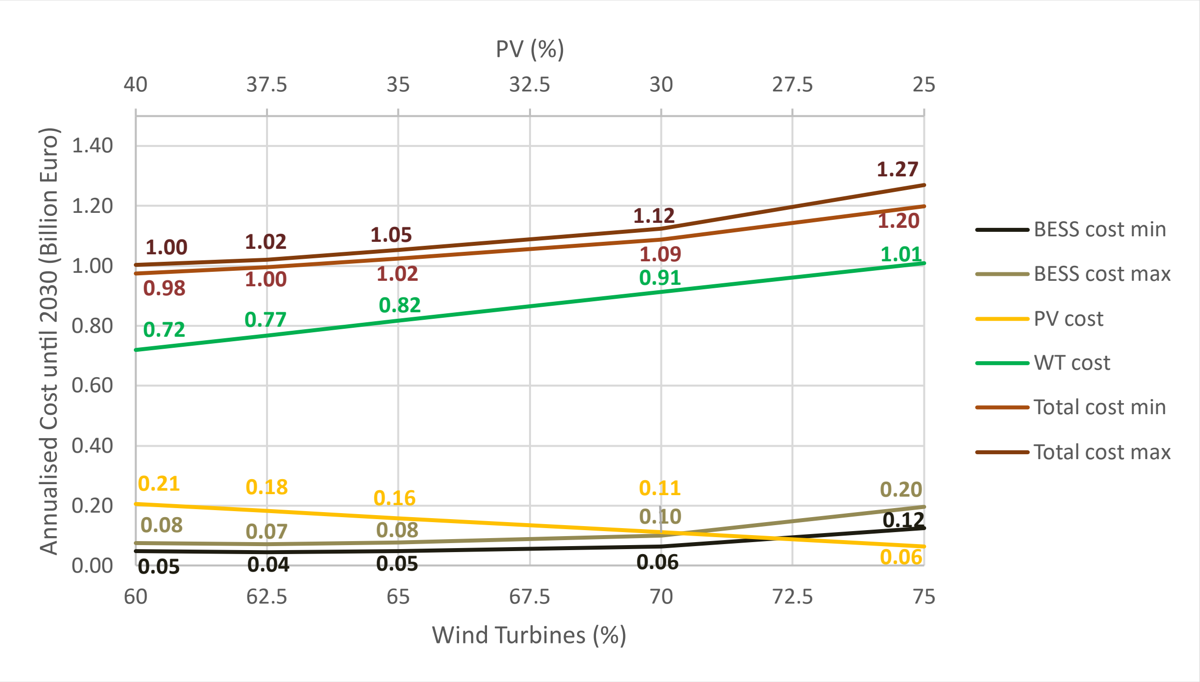


Fig. 3.14. “Wind+” scenario investment cost breakdown until 2030

Finally, for the “Wind+ min” and “Wind+ intermediate 1” cases, for which multiple pathways towards the end-system configuration exist, the choice of pathway affects the pace of RES integration, and the timing and quantity of BESS capacity needs (**Fig. 3.15** and **Fig. 3.16**). The effect on RES integration is more evident in the “Wind+ min” case, compared to the “Wind+ intermediate 1” case, due to the wider pathway space available towards the end-system configuration (see **Fig. 3.13**). In fact, as shown in **Fig. 3.15** pathways appear to result in up to 4.3% RES integration difference, until 2028 where all pathways lead to the same configuration.

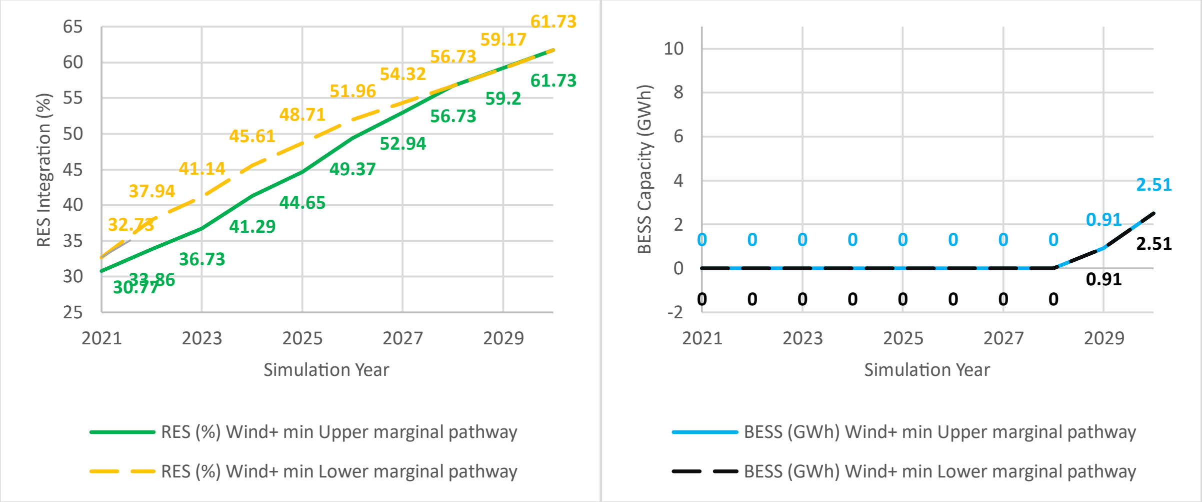


Fig. 3.15. RES integration and BESS capacity evolution for the marginal pathways of “Wind+ min” case

Contrary, the effect on the timing and quantity of BESS capacity needs is evident only in the “Wind+ intermediate 1” case (**Fig. 3.16**) where, BESS capacity requirements start to appear one year earlier, depending on the choice of pathway. This is because the lower pathways of the “Wind+ intermediate 1” case feature a relatively high WT share in 2029 (up to 67.5%), which leads to the need for BESS capacity to minimize curtailment.

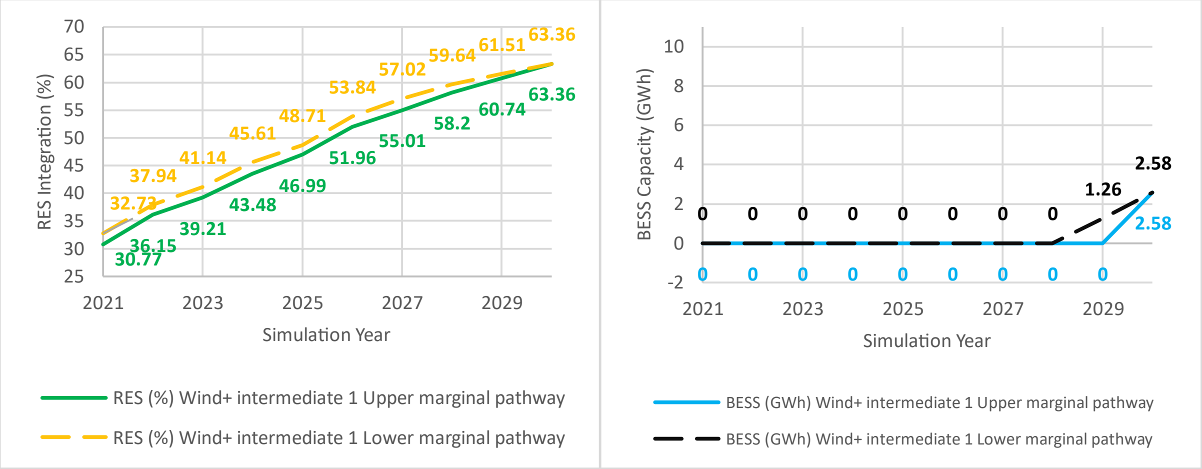


Fig. 3.16. RES integration and BESS capacity evolution for the marginal pathways of Wind+ intermediate 1 case

3.4.3. Balanced scenario

The “Balanced” scenario is an intermediate situation between the “PV+” and “Wind+” scenarios. PV and WT hold 42.5-57.5% share with respect to the total RES capacity foreseen for 2030. This corresponds to 6247.5-8452.5 MW of installed capacity for each technology, with each configuration summing up to a total of 14700MW of RES capacity.

BESS requirements

In this scenario, curtailment levels without BESS capacity range between 0.36-0.85%, and the RES share in the electricity mix ranges between 55.4-60.8%. In order to reduce curtailment levels below 0.1%, the required BESS capacity ranges between 3.0-6.4 GWh, with respective power capacity ranging in the interval 0.75-1.60 GW. The resulting RES share in the electricity mix increases to 55.8-60.9%, justified by the contribution of BESS to the combined generation profile of PV and WT, which is graphically illustrated in **Fig. 3.17**. The correlation of WT/PV share and RES integration in this case indicates a rate of +0.34% (-0.34%) RES share per 1% additional WT (PV) share respectively. In terms of residual demand, in such a configuration, there is uncertainty regarding the frequency and magnitude of generation and demand matching during the off-peak hours, which could make the operation planning of thermal units a challenging and costly task, considering also limitations imposed by their technical specifications (e.g., minimum uptimes, downtimes, start-up times and costs etc.). The peak residual demand events observed in this scenario range between 7.2-7.7GW.

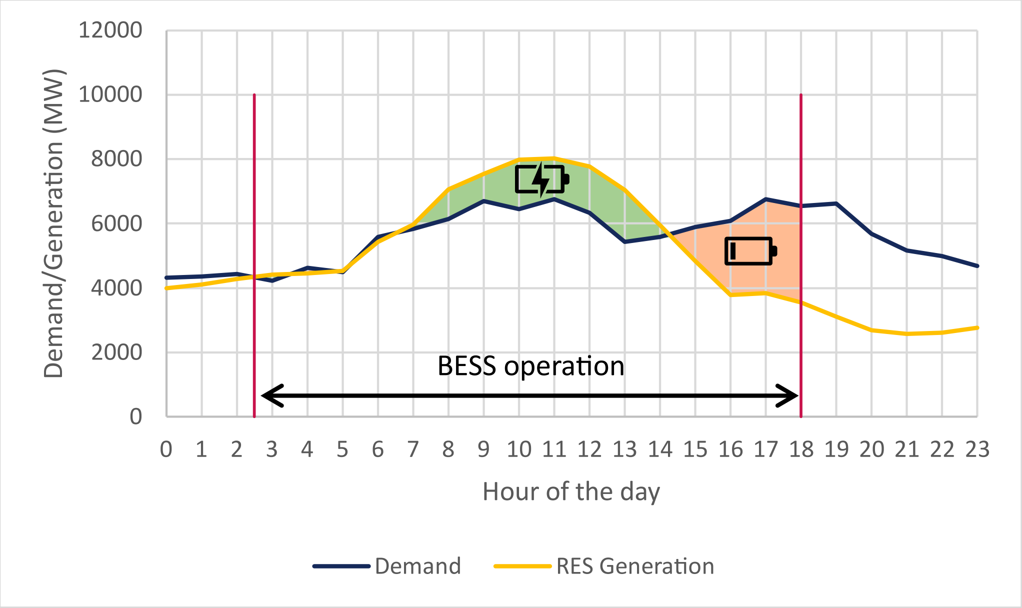
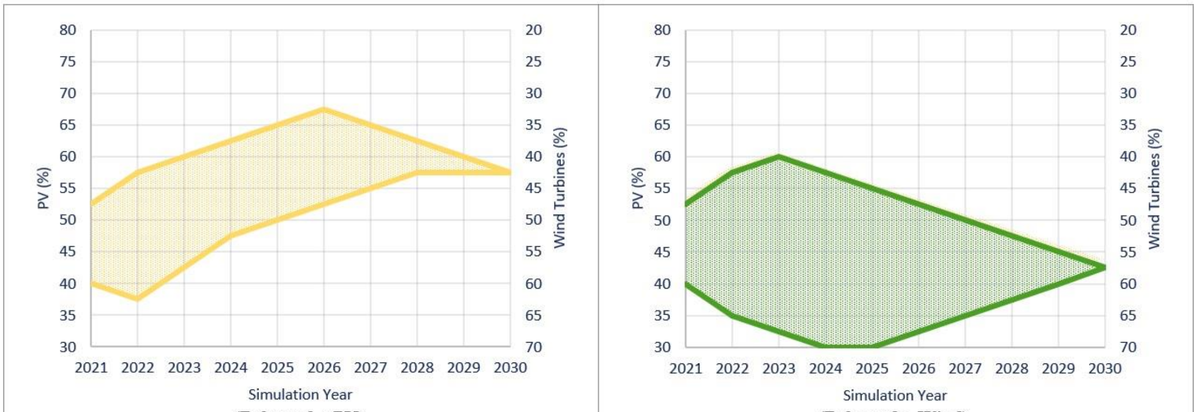


Fig. 3.17. BESS operation throughout a typical day with high generation in the balanced scenario

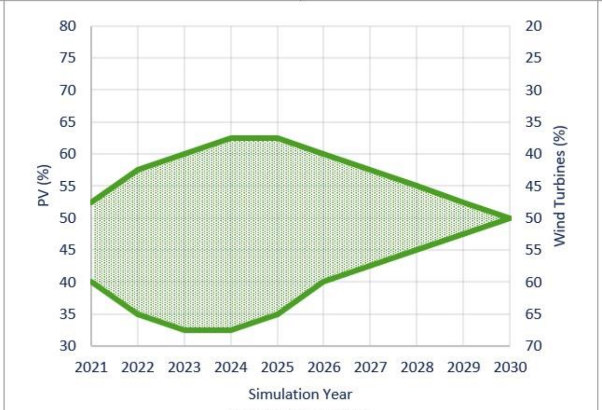
How to get there

This scenario features the highest flexibility in terms of pathways towards the end-system configuration, as shown in **Fig. 3.18**. This is due to the fact that the installed RES capacity in 2020 features 54.7% WT (3153 MW) and 45.3% PV (2606 MW), and a not very dissimilar percentage is aimed until 2030. Therefore, all pathways towards the 2030 configuration can feature either PV or WT as the preponderant technology for several years, until the end-system PV-to-WT configuration is achieved. Among the cases presented in **Fig. 3.18**, the “Balanced+Wind” and the “Balanced Equal” have the greatest flexibility, due to the initial conditions in 2020 which feature WT as the preponderant technology.



(Balanced + PV)

(Balanced + Wind)



(Balanced Equal)

Fig. 3.18. Pathways towards the Balanced scenario. **(Balanced+PV):** Configuration in 2030 consisting of 57.5% PV and 42.5% WT. **(Balanced+Wind):** Configuration in 2030 consisting of 42.5% PV and 57.5% WT. **(Balanced Equal):** Configuration in 2030 consisting of 50% PV and 50% WT.

Regarding BESS requirements, the average BESS needs per additional RES share range between 0.9-1 GWh/%RES. However, randomness can be observed in the required BESS capacity with changing PV/WT shares, indicating the effect of combined intermittency of the two technologies. The average annualised cost increase for every additional 1% of RES integration in a “Balanced” system in 2030 ranges between 26-31 million €, and the total budget spent until 2030 is equal to 4.8-5.7 billion €. The total annualised cost breakdown in 2030, under various end-system configurations in 2030 within the "Balanced" scenario is shown in **Fig. 3.19**. In general, the cost of WT is the higher above an about 42.5% WT share. The BESS cost is lower than that of both generating technologies, regardless of the end-system configuration.

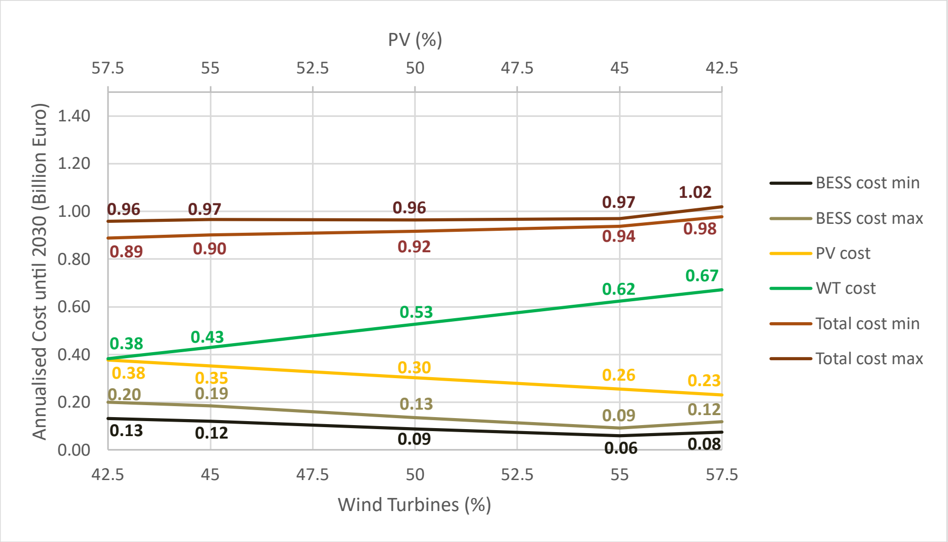


Fig. 3.19. "Balanced" scenario investment cost breakdown until 2030

Finally, like in the "PV+" and "Wind+" scenarios, the choice of pathway affects the pace of RES integration in the electricity mix, and the timing and quantity of BESS capacity needs. In the "Balanced+PV" case, the choice of pathway significantly affects the RES integration levels, and slightly the timing and quantity of BESS capacity needs (**Fig. 3.20**). Specifically, pathways appear to result in up to 4.1% RES integration difference until 2030. As for the BESS capacity requirements, their timing can differ up to one year, starting from 2026 or 2027, and the capacity deviation among pathways can be up to 800 MWh.

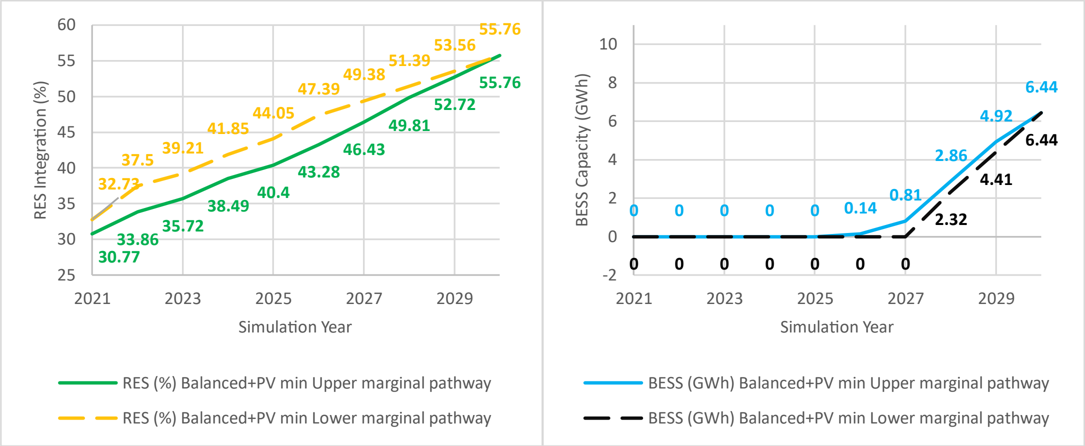


Fig. 3.20. RES integration and BESS capacity evolution for the marginal pathways of "Balanced+PV" case

In the "Balanced+Wind" case, the choice of pathway affects significantly mainly the RES integration levels, with barely noticeable effect on the timing and quantity of BESS capacity needs. As shown in **Fig. 3.21**, the RES integration difference among pathways can be up to 6% until the 2030 end-system configuration. The timing of BESS capacity requirements can differ up to one year, starting in 2028 or 2029, but the BESS capacity difference among pathways is minimal.

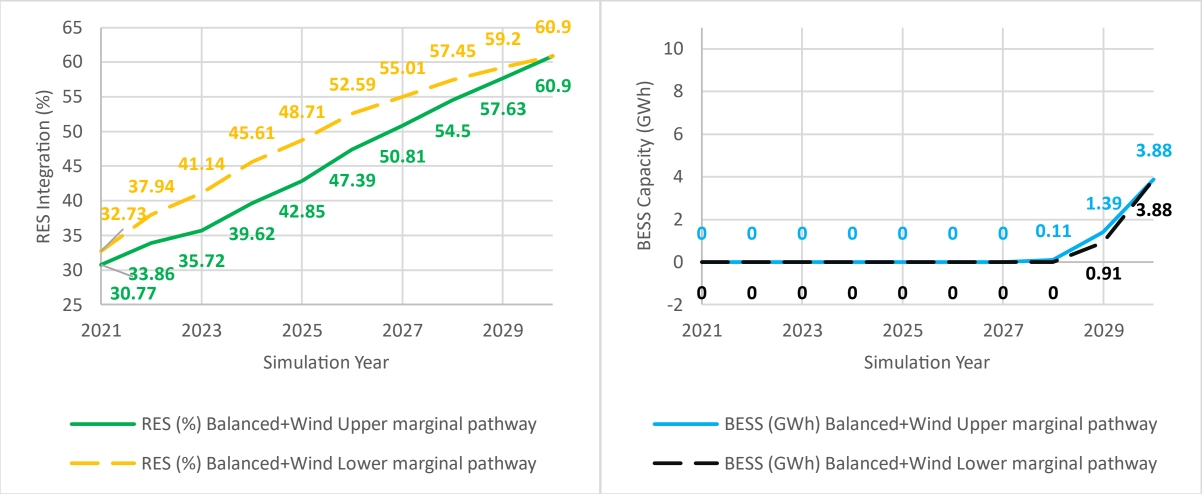


Fig. 3.21. RES integration and BESS capacity evolution for the marginal pathways of "Balanced+Wind" case

Finally, for the "Balanced Equal" case, the effect of pathway choice is evident mainly in the RES integration levels. Specifically, as shown in **Fig. 3.22**, the RES integration difference among pathways can be up to 6.6% until the 2030 end-system configuration, while the timing (starting in 2028) and quantity of BESS requirements is almost the same among the pathways.

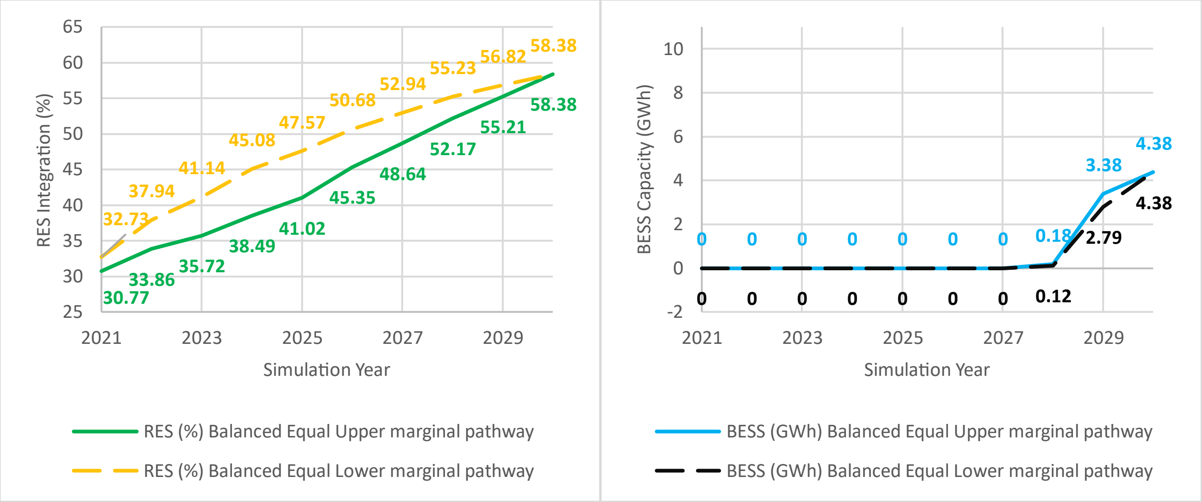


Fig. 3.22. RES integration and BESS capacity evolution for the marginal pathways of "Balanced Equal" case

3.5. Discussion

From the results presented in the previous section, it becomes apparent that the various end system configurations for 2030 can have significant impact on key performance metrics, such as RES integration level, optimal technology mix minimizing storage, or costs, as well as on the pathway flexibility towards their achievement. Minimum BESS configurations do not necessarily result in minimum costs, while minimum cost pathways seem to fail to meet the required RES integration levels in Greece. **Table 3.5** presents a comparative summary of the key findings.

Table 3.5. Key performance metrics and requirements for the materialization of the examined scenarios

Scenario	**PV+**	**Balanced**	**Wind+**
Pathways Availability towards 2030 (Flexibility)	+	+++	++
BESS Capacity in 2030 (GWh)	7.6-11.7	3.0-6.4	2.4-6.5
BESS capacity per additional % RES (GWh)	1.1-1.3	0.9-1.0	0.6-1.8
Timing of BESS capacity requirements (year)	2026-2028	2026-2029	2029-2030
RES Share in 2030 (%)	49.3-54.9	55.8-60.9	61.7-66.5
Residual Peak Demand (GW) – Probable occurrence	7.6-8.1 – night	7.2-7.7 – entire day	6.4-7.1 – morning
Annualised cost increase per additional 1% RES (M€)	27-33	26-31	26-28
Annualised costs in 2030 (B€)	0.85-0.98	0.89-1.02	0.98-1.27
Total budget spent until 2030 (B€)	4.7-5.0	4.8-5.7	5.8-7.2

A key takeaway is that the end system configurations featuring high PV shares, are less flexible in terms of pathways for their realization. This is because the installed capacity in 2020 is equal to 3153MW of WT and 2606MW of PV, which correspond to a RES portfolio consisting of 54.7% WT and 45.3% PV. The preponderance of WT in 2020 gives a flexibility to configurations featuring medium-to-high WT shares in 2030 to be achieved with a wide range of pathways. This in turn indicates that the selection of a 2030 end-system configuration needs to be made with long term planning in mind (e.g., 2050), as it will affect the pathways' availability towards long-term targets.

In terms of curtailment and required BESS to minimize it, in principle, both increase with greater preponderance of PV in the electricity mix, which is indicated by the almost double storage volume required in 2030 with relevance to the balanced and Wind-dominated scenarios. This can be attributed to the seasonal complementarity of WT and PV generation, which approaches better the seasonal demand profile in Greece with greater WT preponderance as shown in **Fig. 3.23** for 2030.

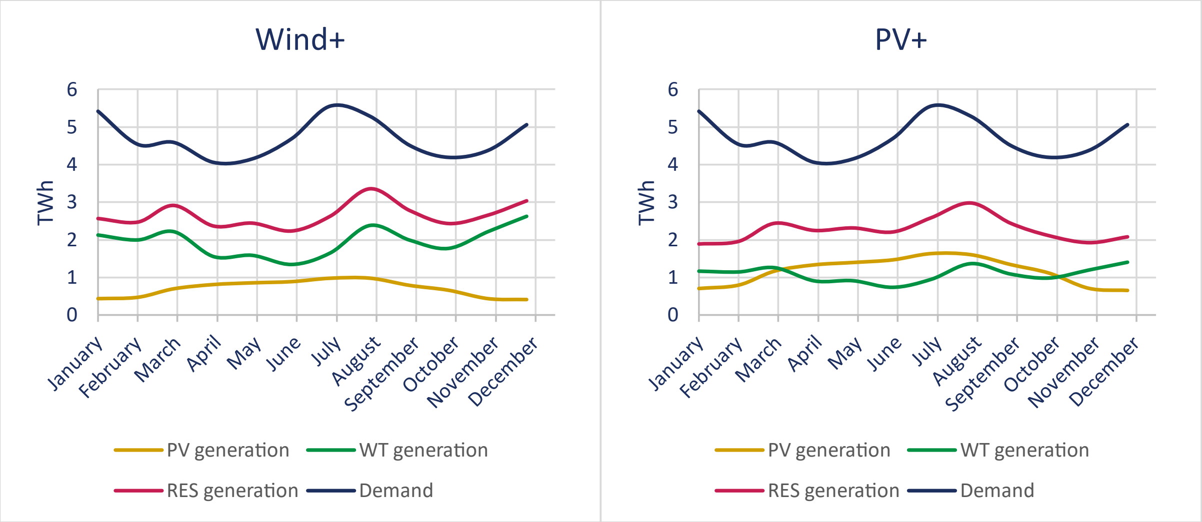


Fig. 3.23. Seasonal demand and RES generation profiles for 2030

This is in line with the results of other studies, who mention that the total storage size is significantly higher in solar dominated systems than in wind dominated systems (Cebulla et al., 2018; Nayak-Luke et al., 2021), with storage capacity and power requirements increasing with high solar penetration levels (Fattori et al., 2017). Consequently, also the timing of BESS capacity requirements occurs sooner in PV-dominated than in Wind-dominated systems.

An optimal combination of WT and PV is observed at capacities 62.5% and 37.5% respectively, requiring minimum BESS capacity to manage curtailment. This configuration is in line with the results of Komušanac et. al. (2016) who reported that minimum critical excess electricity production is achieved with higher WT capacity than PV capacity, and is within the range mentioned by Weitemeyer et. al. (2015) who found that optimal integration of RES share above 30% is achieved with a wind share ranging between 50-65%. Yet, beyond that minimum-BESS point and towards higher WT shares, BESS requirements start to increase rapidly. This is demonstrated by the high upper limit of BESS capacity requirements per additional percentage of RES integration (**Table 3.5**), compared to the other two scenarios.

The RES integration potential of each end-system configuration is also worth examining. Higher WT shares achieve higher RES shares in the electricity mix, which is expected taking into account the higher capacity factors of WT. What is interesting to highlight is the magnitude of residual demand as well as its timing. PV-dominated systems appear to contribute to covering demand during morning hours, with significant peak events of residual demand occurring at night. On the contrary, WT-dominated systems cover the largest part of the demand during night hours, with the peak residual demand events occurring at morning hours, but with lower magnitude. In any case, both systems appear to have a predictable pattern for residual demand instances that would need to be covered by thermal units. This is something that balanced systems lack of, since residual demand events may happen anytime, making the unit commitment problem of thermal units a challenging and potentially expensive task, if peaking units need to be dispatched frequently.

Finally, regarding the cost of the pathways, the results indicate that BESS is not the key cost component until 2030 due to the relatively low storage capacity required, in comparison to the planned generation capacity. In general, WT-dominated systems are expected to be more expensive than PV-dominated systems, driven by the higher investment cost of WT compared to the cost of PV. Nevertheless, the total cost alone is not a decisive parameter. When compared to what is achieved with the money spent, it is evident that WT-dominated systems, which also require less storage compared to PV-dominated systems, perform better in terms of RES integration due to their higher capacity factor, with balanced systems achieving intermediate results. This is easily deductible by comparing the annualised cost increase per additional 1% RES of **Table 3.5**.

3.6. Conclusions and policy implications

In this chapter, RES plus storage capacity configuration pathways towards utilization maximization of domestically produced RES-generated electricity with low curtailment in the Greek electricity system until 2030 have been investigated. The RES technologies considered are PV and WT, which are core technologies mentioned in the Greek NECP. The storage technology accounted for in this study to support the integration of RES is utility-scale Li-Ion BESS, operating in parallel with the installed capacity of PHS in Greece. The main endeavors of this chapter are to highlight what are the plausible PV, WT and BESS capacity configurations in 2030 with respect to the RES capacity targets mentioned in the Greek NECP, and what capacity configuration pathways can be followed towards their achievement, presenting the outcomes of each option.

To enable this, a modelling framework which treats policies as experiments and enables adaptive policy design based on dynamic information and experience acquired through simulated policy implementation, has been used. Such an experimental policy analysis method has been proposed almost a century ago by Dewey (1927), and is most relevant today considering the uncertainties and complexities encountered during the transformation of the electricity system from its dispatchable fossil-fueled regime to a RES-based intermittent one. The modeling framework consists of the STREEM and the AIM models. STREEM using its functionality to simulate in high temporal resolution the operation of storage technologies, enables the exploration of storage capacity requirements of a region, towards user defined curtailment levels. The main features of STREEM lie in its ability to model various storage technologies with simple parameterization of its input variables, as well as its capability of approximating the actual curve of storage/curtailment correlation, regardless of the storage technology modelled, achieving that way efficient computational performance. AIM on the other hand is a plug-in model, which using the inputs and outputs of simulation models visualizes adaptive policy maps, indicating alternative pathways which lead to desired policy outcomes. Main features of AIM lie in its intuitive simulated policy implementation functionality, and its ability to enable the assessment of a large number of policy development scenarios with only few simulations performed by a simulation model. Overall, the linking of the two models enable detailed exploration of RES plus storage transitions of electricity systems, considering specified technologies and actual timelines. Although in this chapter the modelling framework is applied to the case of Greece, it is capable of modelling any other country or region, given that the required data is available.

For the Greek case under study, the various PV, WT and BESS configurations are considered as policy options, and their stepwise implementation (changing configurations) are the pathways towards the achievement of targeted end-system configurations. From the overall analysis, it was found that the achievement of the Greek RES integration targets until 2030 (61% in gross electricity consumption) depends highly on the end-system configuration. Specifically, marginal achievement is feasible with a configuration with about 42.5% PV and 57.5% WT with respect to the total RES capacity (14700 MW) and 3.9 GWh of accompanying BESS capacity. Such shares are close to the current Greek RES mix (mid 2021), which consists of 55.1% WT (3755 MW) and 44.9% PV (3055 MW). Considering that on average with every additional 1% of WT in the electricity mix 0.34% additional RES integration share is achieved, and vice versa, the PV and WT shares mentioned in the Greek NECP (i.e., 52.4% PV and 47.6% WT) are expected to achieve about 92% of the Greek RES integration target. The remaining contribution would need to be provided either **(i)** by other RES technologies (e.g., biofuels, solar thermal, geothermal, etc.) or **(ii)** with configurations featuring higher WT shares, or **(iii)** with higher total RES capacity in order to reach the pledged RES integration levels.

BESS capacity is an important parameter to consider when deciding on specific PV and WT shares. Efficient RES integration with minimum BESS requirements could be achieved in a configuration with about 62.5% WT, 37.5% PV and 2.4 GWh of accompanying BESS capacity. Beyond that minimum, the sensitivity of BESS requirements is equal to 330 MWh for each additional 1% WT share, and 260 MWh for each additional 1% PV share. Such sensitivity is crucial when planning future capacity configurations, especially when presented with reference to RES integration levels, equal to 1.1-1.3 GWh/%RES in PV dominated systems, 0.6-1.8 GWh/%RES in wind dominated systems and 0.9-1 GWh/%RES in systems with balanced PV and WT shares. Considering this, the tendering procedure should be designed in a way that accounts for accompanying BESS capacity that would enable the optimal integration of the chosen RES configuration.

Investment plus O&M costs are also a crucial parameter for policymakers when deciding on PV, WT and BESS configurations. Until 2030, the cost intensity in Greece is mostly accounted to WT, followed by PV and then by BESS. However, given the weighted contribution of each technology in the plausible RES plus storage configurations, with similar amounts of investments, alternative configurations with PV or WT as the preponderant technology, or balanced configurations can be achieved. Specifically, considering that the average annualised cost increase for every additional 1% of RES is about 27-33 million € for PV dominated systems, 26-28 million € for wind dominated systems and 26-31 million € for balanced systems, the higher unit-costs of specific technologies, can be counterbalanced with appropriate combinations of technological investments. Opportunities for funding should also be considered, in order to leverage available funding for applicable technologies. Indicatively, the Greek recovery and sustainability plan (IEA, 2022) provides 450 million € for the installation of electricity storage systems. This implies that slightly wind-oriented systems, which require the lowest levels of BESS, can at a high degree be materialized by exploiting the available funding for storage technologies, while for systems with high preponderance of PV or WT, the available funding for storage can be exceeded.

Lastly, the timing of investments is a major factor affecting the success of planned configurations. When targeting for electricity system buildouts with high preponderance of one technology, investments in this technology should be prioritized early enough to avoid capacity lock-ins. The pathway of RES investments in turn affects the timing of BESS capacity requirements, which could also affect the pathways' cost based on projected technological cost reductions. Reportedly, with high PV shares, BESS in Greece would be needed when RES integration exceeds 41-48%, with high WT shares when RES integration exceeds 59-64%, and with balanced WT and PV shares, when RES integration exceeds 51-58%, depending on the installed PV and WT shares. Timewise, such integration levels could be expected in Greece in the period 2026-2029, implying that plans for BESS investment should be made for the second half of the NECP horizon.

Overall, this study's general conclusions are summarised as follows:

- WT-dominated systems are suitable for applications where ambitious renewable targets need to be reached with PV and WT as the main technologies, daytime demand peaks are moderate, or the solar potential is limited. The high (yet efficient) investment cost and the long licensing procedures of WT are the main challenges of such systems.
- PV-dominated systems could be an option when the wind potential is limited. Yet, such systems are less efficient in terms of output (i.e., %RES integration) per money spent and would require early and high investments in storage.
- Balanced systems are suitable option if long-term policy planning is not available and options towards future system buildout options need to remain open. These systems combine merits and drawbacks from both PV- and WT- dominated systems.

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Chapter 4 – Shielding the electricity system from external disruptions

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Nomenclature

Nomenclature

Abbreviations

AIM	Adaptive polIcymaking Model	PHS	Pumped Hydro Storage
BESS	Battery Energy Storage System	PRIM	Patient Rule Induction Method
BSAM	Business Strategy Assessment Model	PV	Photovoltaics
EC	European Commission	RES	Renewable Energy Sources
EU	European Union	VRES	Variable Renewable Energy Sources
NECP	National Energy and Climate Plan	STREEM	STorage RequirEmEnts and dispatch Model
O&M	Operation and Maintenance	WT	Wind Turbines

Indices and Sets

n	Targeted simulation year	$t.tech$	Thermal generation technology
ref	First year of simulation	y	Simulation year
$tech$	Referenced technology		

Parameters

CC	Capital cost	i	Interest rate
OMC	Operation and maintenance cost	k	Effective lifetime of technologies

Variables

CAC	Carbon Abatement Cost	EAC	Equivalent Annual Cost
CO_2	Carbon Dioxide emissions	$gen.cost$	power generation cost
CRF	Capital recovery factor		

Least-cost or sustainable? Exploring power sector transition pathways

The 2022 energy crisis augmented the European ambition for RES capacity expansion. However, beyond the issue of "how many" renewables, the research question that remains, is which capacity mixes achieve the emissions reduction, renewable integration, and energy autarky targets in a cost-effective way. This chapter tries to answer this inquiry supported by two energy models and one decision support model. The analysis focuses on Greece, as an example country which opted for lignite phase out, turning to temporary heavy reliance on natural gas for power generation. The results indicate that even though from the energy and environmental targets' perspective, more wind turbines in the RES capacity mix yield better results, when incorporating the economic point of view, balanced wind and solar mixes enable the achievement of targets in a cost-effective way. The most cost-efficient mixes consist of 50-55% wind and 45-50% solar capacity, with cost per additional percentage of RES share in the generation mix, equal to 40 million €. Nevertheless, in order to materialize them in a timely manner, and limit the short-term dependency on imported gas, permitting simplification, tenders for large-scale projects and incentives for small-scale projects are needed to facilitate accelerated RES deployment.

Keywords: Power system transformation, RES capacity mix, Energy crisis, Decarbonization cost, RES deployment pathways, Tipping point

4.1. Introduction

The "Fit for 55" package published by the European Commission (EC) in 2021 acknowledges that the current generation might be the last which can act in time, before irreversible climate tipping points occur (European Commission, 2021). This means that planning for transformations, instead of adapting to irreversible events is still possible. The energy sector has been acknowledged as the biggest greenhouse gas emitter in the European Union (EU), which reached an all-time peak in 2021 (Su et al., 2023), accounting for more than 75% of the total emissions (European Commission, 2019), with the power sector holding one third of the global CO_2 emissions (Michas et al., 2019).

The EU Green Deal emphasizes a transformation, towards renewable energy sources (RES), phasing out fossil fuels, and decarbonizing gas, while ensuring that the energy supply to consumers and businesses is affordable and secure (European Commission, 2019). Towards this direction, natural gas was selected as a temporary transition fuel, being a lower-carbon alternative to emission-intensive fossil fuels (Gürsan and de Gooyert, 2021). However, with the 2022 energy crisis natural gas has been transformed into an expensive and unreliable energy source (Osička and Černoch, 2022), diverging from the aspects of security, affordability and sustainability, as sought by the energy trilemma (Glasgow Science Centre, 2021). At the beginning of the introduction, the term tipping points was mentioned, which has received several understandings in literature, both negative and positive. Here the definition given by Tabara is found to be more relevant, describing tipping points, as those additional actions that trigger and accelerate substantial changes in a system of reference (Tàbara, 2023). Therefore, the 2022 energy crisis might be a tipping point, which triggers an acceleration of the already underway efforts towards RES-based electricity systems (Steffen and Patt, 2022).

4.1.1. Literature review

In scientific literature, many studies assess decarbonization strategies by focusing on the deployment of clean technologies. Bamisile et.al. (2022) analyse the techno-economic requirements to achieve net-zero emission in China, by considering the electricity, industry and transport sectors. They compare the transition scenario proposed by the Chinese government, with 3 alternative scenarios which focus on the additional use of biomass, pumped hydro storage (PHS), or clean electricity imports. Pastore et.al. (2022a) explore strategies for achieving 55% emissions reduction by 2030 in the Italian energy system. They form a sectors' implementation matrix, describing 3 levels of ambition in the energy transition strategies for each of the 8 sectors considered. They model all possible ambition combinations to evaluate their performance in terms of annual CO_2 emissions and annual cost for the Italian energy system. Aghahosseini et.al. (2018) study cost-optimal energy systems in Iran comprising of 100% RES by 2030. They examine two cases, one focusing only on the power sector, and one where the power sector is integrated with the water desalination and industrial gas sectors, to find optimal combinations of RES technologies, least-cost energy supply, and assess the role of storage.

Furthermore, many studies put their emphasis solely to the power sector, due to its high contribution to the global CO_2 emissions. A key theme of focus is on the proper capacity mixes of RES and storage (i.e., what share does each technology hold with respect to the total renewable energy or storage capacity), applied at various scales. For instance, Arévalo et.al. (2022) perform a feasibility study to assess the potential of supplying the Galapagos islands with 100% renewable energy, by examining many variations of wind turbine (WT), photovoltaic (PV) and battery storage capacity mixes. Katsaprakakis et.al. (2018) study the technical and economic feasibility of supplying the autonomous power system of the Greek island Sifnos, with 100% renewable energy, by combining WT, PV and a PHS facility. Li et.al. (2022) examine concurrent optimal mixes for WT and PV, and for long-term and short-term storage, accounting for the two-way interaction between renewables and energy storage. They focus on the UK to identify optimal strategies that maximize the usage of renewable generation and storage technologies. Similarly, several other studies focus on the proper combination of generation and storage technologies towards objectives, such as, minimization of levelized cost of energy (Yu et al., 2022), low storage requirements (Johlas et al., 2020), or curtailment minimization (Michas and Flamos, 2023). The list of available studies in carbon abatement, with energy systems featuring up to 100% RES is vast, and extends to over 20 years of research as evidenced by the 180 articles reviewed by Hansen et.al. (2019).

After the 2022 energy crisis, the objectives of relevant studies have been augmented with the target of minimizing natural gas use in all end-use sectors, through the accelerated expansion of RES. Indicatively, Belaïd et.al. (2023) focus on the reasons that resulted in natural gas price increase and highlight the role of green investments towards energy security and sustainability. Steffen and Patt (2022) assess the impact of the 2022 Russian invasion to Ukraine on the public support for clean energy policies in Switzerland, highlighting that the support has grown stronger, but this should be translated into policy action in order to take effect. Frilingou et.al (2023), use fuzzy cognitive maps to elicit knowledge and perceptions from experts in Italy, noting a strong preference for renewable energy uptake compared to contingency natural gas reserves planning. Pastore et.al. (2022b) investigate measures to reduce natural gas consumption in Italy, by combining variable renewable energy sources (VRES) capacity expansion, heat pump deployment, and renewable fuel production. Karamaneas et.al. (2023) perform a stakeholder informed modelling exercise to compare the energy transition scenarios of two policy documents in Greece (i.e., the 2019 National Energy and Climate Plan (NECP) (Greek Ministry of Environment and Energy, 2019a) and the 2022 Climate Law (Hellenic Parliament, 2022)) with an ambitious power generation portfolio, requiring 80% RES-generated electricity by 2030 and carbon neutrality by 2035.

4.1.2. Gap and scope of this study

In most of the analyses performed in the reviewed articles, energy models have been employed. Even though simulations take into consideration several combinations of policies and strategies towards decarbonization (e.g., sectoral clean energy ambitions, combinations of RES and storage portfolio), in order to identify those that perform best with respect to one or more objectives, they have been found to lack the incorporation of the uncertainty governing the context within which the policies and strategies are applied. This can be attributed to the fact that energy models need significant time to be calibrated and produce meaningful results in a constantly changing context (Frilingou et al., 2023). Nevertheless, the incorporation of uncertainty and unforeseen events in energy modelling has been acknowledged by stakeholders from the fields of academia, policymaking, industry and non-governmental organizations (Süsser et al., 2022), in order to support adaptive policymaking, which focuses on planning under normative circumstances, with concurrent identification of actions and strategies that are resilient even in the event of extreme context evolutions.

The price of natural gas is currently one of the main uncertain parameters in the energy markets, which is characterized by very high fluctuations (Trading Economics, 2023), especially in the event of geopolitical turbulence, such as the Russian invasion to Ukraine in 2022 and the middle east conflict in late 2023. Despite the efforts of the EU members states to reduce its use for power generation, natural gas will remain a significant contributor in the energy mix, as the deployment of clean energy generation and storage technologies takes time. In this respect, there is a need to identify RES capacity mixes and their deployment strategies which (i) ensure the achievement of member states' decarbonization targets, (ii) shorten the use of natural gas as an intermediate fuel, and (iii) achieve cost-effective transformation of the power system, even under the uncertainty of natural gas prices.

This study aims to address this need, by applying a modelling framework which supports fast simulations in an hourly resolution for (i) the identification of storage requirements of a region towards maximization of renewable energy exploitation under many scenarios of RES capacity mixes, (ii) the solution of the unit commitment and economic dispatch (UCED) problems in an electricity market with highly-volatile fuel prices and technical constraints on dispatchable generating resources, and (iii) the exploratory analysis of diverse capacity mixes and the pathways leading to them, correlating in parallel their performance to natural gas prices.

4.1.3. Context and research questions

The country chosen for the application of the modelling ensemble, is Greece. In 2019, with the publication of its first NECP (Greek Ministry of Environment and Energy, 2019a), Greece opted for a gradual phase out of lignite power plants by 2028 (Kleanthis et al., 2022), and an ambitious plan for 200% VRES capacity expansion compared to 2019, meaning a total VRES capacity equal to 14.7 GW in 2030, when in 2019 the total installed capacity was 4.8 GW. With this decision, all baseload power plants which operate with domestically extracted fossil fuels would be shut down. This would result in the country relying solely on natural gas power plants as the primary dispatchable thermal technology. Therefore, Greece would be locked in to imported natural gas until the transformation of the power system based on RES is completed.

However, with the 2022 energy crisis stemming from the Russian invasion to Ukraine, the use of natural gas as a transition fuel revealed challenges related to security of supply and turbulent energy prices. Therefore, in January 2023 the proposal for the 2024 update of the Greek NECP (from here on mentioned as "under revision NECP") was presented, mentioning a 400% increase in VRES capacity compared to 2019, reaching a total of 23.9 GW by 2030 (Greek Ministry of Environment and Energy, 2023). The current implementation stage of the NECP is at 65% with respect to the 2019 targets and at 40% with respect to the under-revision targets, with 9.6 GW of installed VRES capacity in 2023. Furthermore, the lignite phase-out is at 32% completion, with 2.7 GW still operating (ENTSO-e Transparency Platform, 2021).

Given that the update of the Greek NECP is still underway and the NECP capacity shares per generating technology, should be treated as indicative and possible but not binding (Greek Ministry of Environment and Energy, 2019a), this chapter addresses the following interrelated research questions:

- Which VRES and storage capacity mixes can reduce the dependency of Greece on imported gas for power generation, while achieving the emissions reduction and renewable integration targets by 2030?
- Are there capacity mixes which achieve the targets in a cost-effective[8] way, considering the uncertainty of natural gas prices?

4.1.4. Novel contributions and outline

To the best of our knowledge, the novel contributions of this work are twofold:

- **Methodological contribution**: The presentation of a modelling framework which performs exploratory analysis of policy and strategy options under uncertainty, facilitating the formulation of robust strategies, which can perform well across a wide range of conditions, and adapt to potential context evolution scenarios, thus stepping away from optimized solutions based on a limited set of projections.
- **Content/knowledge contribution**: The stress-test assessment of RES and storage capacity mixes, under a market framework with highly uncertain natural gas prices, which affects the composition of the electricity mix, and in turn affect the targets that aim to be achieved by the chosen RES and storage capacity mixes. Greece is a good example for such an analysis, as it is a country with high potential for RES, but also with no alternatives for baseload generation, apart from imported natural gas and highly emitting lignite, and with limited interconnection capacity with its neighboring countries (i.e. about 20% of its peak demand (Michas and Flamos, 2023)).

The remainder of the chapter is organized as follows: **Section 4.2** presents the modelling framework used. **Section 4.3** presents the scenario design, as well as key input assumptions for the Greek case

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[8] Cost-effectiveness is measured with the cost incurred to increase the renewable energy percentage in the electricity mix by 1%, as discussed in **section 4.4.4**. Cost-effective capacity mixes are those which reduce this cost compared to their alternatives.

under study. **Section 4.4** reports detailed simulation results. **Section 4.5** discusses key takeaways of the study and summarizes key lessons learnt, providing implications for policy and practice.

4.2. Methodological framework

The methodological framework used in this study employs two simulation models and one decision support model, which are soft-linked in a sequential manner. The simulation models comprise of (i) the **ST**orage **R**equir**E**m**E**nts and dispatch **M**odel (STREEM), which simulates the hourly operation of energy storage systems and calculates the required storage capacity towards maximization of the exploitable renewable electricity (Michas and Flamos, 2023), and (ii) the **B**usiness **S**trategy **A**ssessment **M**odel (BSAM) which is an agent-based model solving, in an hourly resolution, the merit-order UCED problems (Kontochristopoulos et al., 2021). The decision support model is the **A**daptive pol**I**cymaking **M**odel (AIM) which enables the exploratory analysis of policy/strategy pathways towards the achievement of one or multiple targets, identifying in parallel their conditions of success (Michas et al., 2020). The model integration is presented in the following subsections and is visually illustrated in **Fig. 4.1**. It should be noted that this section focuses on the soft-linking of the models, and reports only any model updates relevant to this study. For more details on the models' mathematical formulation, the reader is referred to Michas and Flamos (2023) for STREEM, Kontochristopoulos et al. (2021) for BSAM and Michas et al. (2020) for AIM.

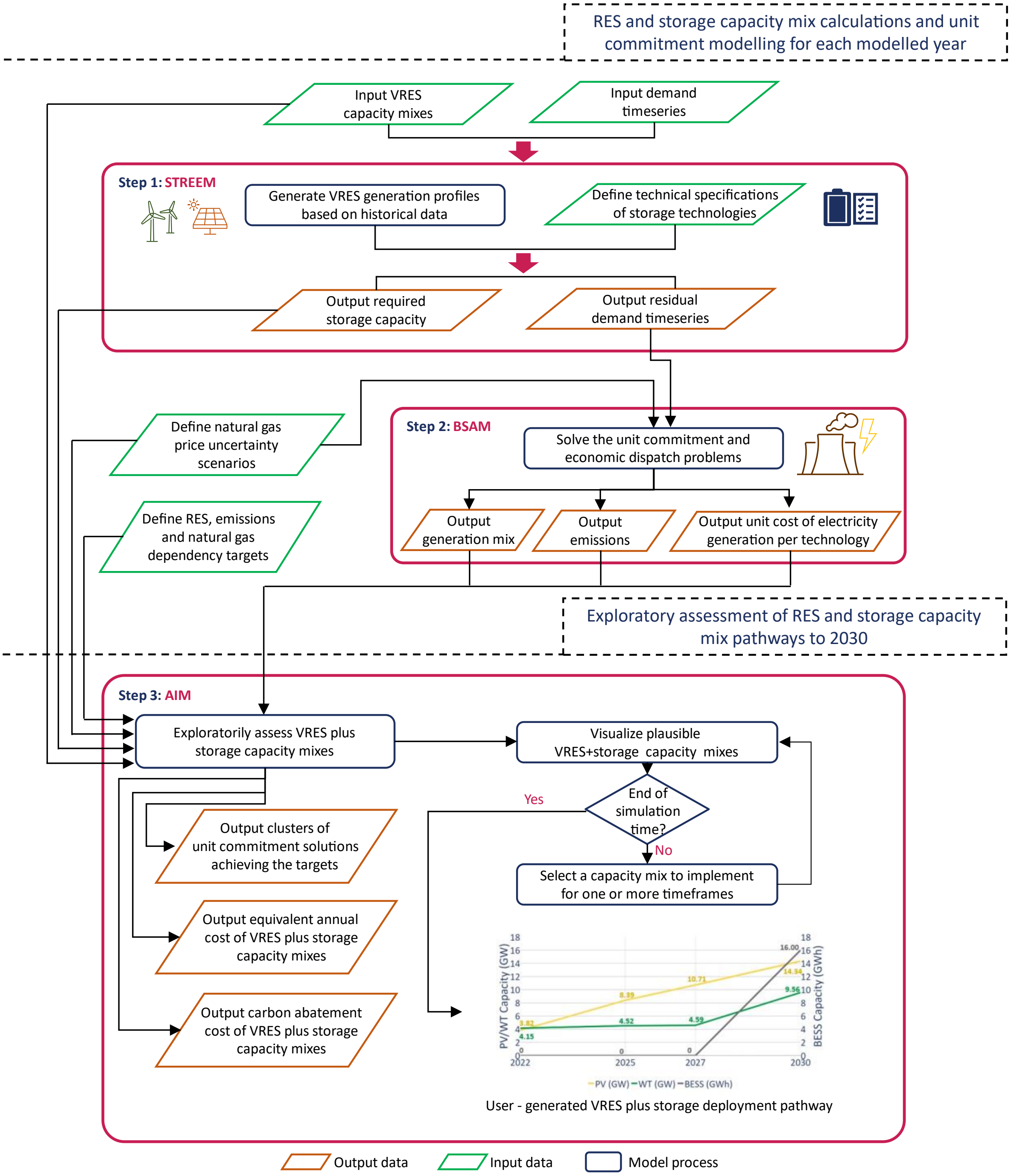

Fig. 4.1. STREEM, BSAM and AIM loose integration methodology.

4.2.1. Step 1: STREEM

Initially, STREEM takes as input the electricity demand time series and generation profile of various VRES capacity mixes and calculates the required storage capacity to reduce instances of curtailment. Consequently, for each VRES capacity mix, STREEM calculates a new demand timeseries which accounts for the shifting of excess VRES electricity generation to low generation periods, altering the residual demand profile that needs to be met by thermal generating resources.

4.2.2. Step 2: BSAM

The new demand timeseries are provided to BSAM to solve the UCED problems in an hourly resolution, respecting the technical constraints of dispatchable resources (e.g., minimum uptimes/downtimes, startup times, etc.), and considering a range of scenarios for the evolution of volatile natural gas prices, which affect the competition among the generation technologies. For each examined VRES capacity mix, BSAM outputs the contribution of each technology to the generation mix, the CO_2 emissions from electricity generation, and the unit cost of electricity generation per thermal technology.

4.2.3. Step 3: AIM

Finally, the outputs of STREEM and BSAM are provided to AIM for the exploratory assessment of the examined VRES capacity mixes, and the design of pathways leading to them. The exploratory assessment part entails the evaluation of the various VRES capacity mixes in terms of (i) renewable integration potential, (ii) emissions reduction, (iii) dependency on natural gas for electricity generation, and (iv) cost efficiency, under the effect of fluctuating natural gas prices.

Specifically, for the outputs (i)-(iii), the Patient Rule Induction Method (PRIM) is implemented within AIM, which identifies segments from the uncertainty space of the input assumptions, which correspond to outputs within acceptable limits (Michas et al., 2020). In the implementation of PRIM for this study, AIM takes as input all UCED solutions and power generation emissions, generated by BSAM for each examined VRES capacity mix, and outputs the clustered subset of those which contain PV, WT and hydro generation shares that enable the achievement of user-defined renewable generation, emissions reduction, and natural gas dependency targets.

For output (iv), two main indicators are calculated in AIM, the equivalent annual cost (EAC) of the various VRES capacity mixes, and the carbon abatement cost (CAC). The EAC is the sum of annualized capital costs and operation and maintenance (O&M) costs for PV, WT and storage, as adopted from Michas et.al. (2023) and presented in Eq. (4.1).

$$EAC_n = \sum_{tech}\left[\sum_{y=1}^{n}\left(CC_{tech,y}\cdot CRF_{tech}\right) + OMC_{tech,n}\right] \tag{4.1}$$

where:

- $tech$: the referenced technology,

- y: the simulation year,
- n: the targeted simulation year,
- CC: the capital cost of each technology for the newly installed capacity at year y,
- OMC: the O&M cost of each technology for the total installed capacity at year n, and
- CRF: the capital recovery factor for each technology as defined in Eq. (4.2)

$$CRF_{tech} = \frac{i_{tech}}{1-(1+i_{tech})^{-k_{tech}}} \tag{4.2}$$

with:

- k: the effective lifetime of each technology, and
- i: the interest rate for each technology

The CAC is a function of the EAC for VRES plus storage deployment, the avoided cost of displaced fossil fuel-generated electricity, and the respective avoided emissions. The original formula has been adopted from Pastore et.al. (2022b), and has been adjusted to the scope of this study, as presented in Eq. (4.3).

$$CAC_n = \frac{EAC_n - \sum_{t.tech}\left(gen.cost_{t.tech,ref} - gen.cost_{t.tech,n}\right)}{CO_{2,ref} - CO_{2,n}} \tag{4.3}$$

where:

- CAC_n: the carbon abatement cost at the targeted year n,
- $t.tech$: the thermal generation technology,
- $gen.cost_{t.tech,ref}$: the power generation cost of $t.tech$ without any new investments in RES,
- $gen.cost_{t.tech,n}$: the power generation cost of $t.tech$ at the targeted year n,
- $CO_{2,ref}$: the carbon emissions from electricity generation without any new investments in RES,
- $CO_{2,n}$: the carbon emissions for electricity generation at the targeted year n.

Finally, for the design of pathways towards the various examined VRES plus storage capacity mixes, AIM takes as input the case study's actual installed capacity for each assessed technology (i.e., PV, WT and storage), and sets it as the default capacity at the first simulation timestep. In each next simulation timestep, AIM checks which of the examined VRES plus storage capacity mixes result in at least equal or more capacity than the previous timestep for all technologies, and marks them as feasible for implementation. Then the user, can choose to implement one feasible VRES plus storage capacity mix for one or more timesteps, based on the exploratory assessment outputs (i)-(iv). Consequently, the installed capacities are updated with those of the last implemented VRES plus storage capacity mix. This iterative process continues until the end of the simulation timeframes, and the result is a user generated VRES plus storage deployment pathway.

4.3. Scenario design

4.3.1. Demand and generation portfolio

The scenario design builds upon the assumptions of the under revision NECP. **Table 4.1** shows the annual assumptions for the electricity demand, the VRES and the dispatchable portfolio. Specifically, for VRES, the capacity share of each technology across the years is assumed to range between 30-70% with respect to the total VRES capacity. In total 9 capacity share scenarios are formulated, with 5% share steps per technology in each scenario. With 60-70% PV/WT share, the system is characterized as "PV-/WT-preponderant" respectively, while intermediate shares are referred to as "balanced" systems.

To project hourly demand, PV, and WT generation quantities, average hourly historical data for the period 2016-2022 from the ENTSO-e transparency platform (2021) is used. First, the mean and standard deviations for each hour of the year is calculated, using the historical data years 2016-2022. Then, the mean values of the hourly normal distributions are scaled to the annual demand and VRES capacities shown in **Table 4.1.** Finally, values for each hour of the future modelled years are projected by drawing samples from the scaled normal distributions of each parameter (i.e., demand, PV generation, WT generation).

Regarding, the dispatchable generation portfolio of Greece, it comprises of lignite, natural gas and hydro generating power plants, with the lignite power plants planned for phase-out until 2028. The evolution of installed capacities is shown in **Table 4.1,** following the assumptions of the under revision NECP. The data shown in **Table 4.1** are for the years 2023, 2025 and 2027, as member states are required to report progress towards their NECP objectives, starting from 2023 and every two years thereafter, towards 2030 (European Commission, 2022c). 2029 is omitted as it is one year earlier than the NECP horizon, so the focus is on the target year.

Table 4.1
Scenario parameters

	scenario	2023	2025	2027	2030
Electricity demand (TWh)	-	61.1	62.5	60.1	71.5[9]
PV Capacity (GW)	30%	3.1	3.9	4.6	7.2
	35%	3.6	4.5	5.4	8.4
	40%	4.1	5.2	6.1	9.6
	45%	4.6	5.8	6.9	10.8
	50%	5.2	6.5	7.7	12.0
	55%	5.7	7.1	8.4	13.1
	60%	6.2	7.7	9.2	14.3
	65%	6.7	8.4	9.9	15.5
	70%	7.2	9.0	10.7	16.7
WT Capacity (GW)	70%	7.2	9.0	10.7	16.7
	65%	6.7	8.4	9.9	15.5
	60%	6.2	7.7	9.2	14.3
	55%	5.7	7.1	8.4	13.1
	50%	5.2	6.5	7.7	12.0
	45%	4.6	5.8	6.9	10.8
	40%	4.1	5.2	6.1	9.6
	35%	3.6	4.5	5.4	8.4
	30%	3.1	3.9	4.6	7.2
Lignite Capacity (GW)	-	2.6	1.5	0.6	0.0
Natural Gas Capacity (GW)	-	6.0	6.9	6.9	6.9
Hydro Capacity (GW)	-	3.2	3.4	3.4	4.0

4.3.2. Natural gas prices

Since natural gas prices significantly affect the thermal generation fleet, special attention is given to their assumptions. Initially, the average natural gas prices in Greece for 2021 (i.e., before the energy crisis) and for 2022 (i.e., within the energy crisis) is obtained from the Regulatory Authority for Energy (2023), to define the initial uncertainty range. Then, for each year until 2030, an increasing trend is applied to the initial uncertainty range, following relevant assumptions of the Greek independent power transmission operator (IPTO) (Greek IPTO, 2021). This means that both the upper and lower bounds of the uncertainty range are increased by the percentage increase in average natural gas prices implied by

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[9] The significant surge in electricity demand projected for 2030 can be attributed to the assumptions of the under revision NECP, which anticipates a gradual shift towards electrification in residential heating, coupled with a substantial increase in the adoption of electric vehicles beyond 2027, that is expected to account for 32% of new vehicle purchases in 2030, compared to an assumed 5% in 2025.

the IPTO. Finally, for each year until 2030, twenty scenarios are generated, resulting in the uncertainty space shown in **Fig. 4.2**. Twenty scenarios are adequate in order to allow the PRIM algorithm (as described in **section 4.2.3**), to identify solid clusters of UCED solutions containing PV, WT and hydro generation shares towards the achievement of the Greek NECP's targets for RES generation, emissions reduction, and natural gas dependency.

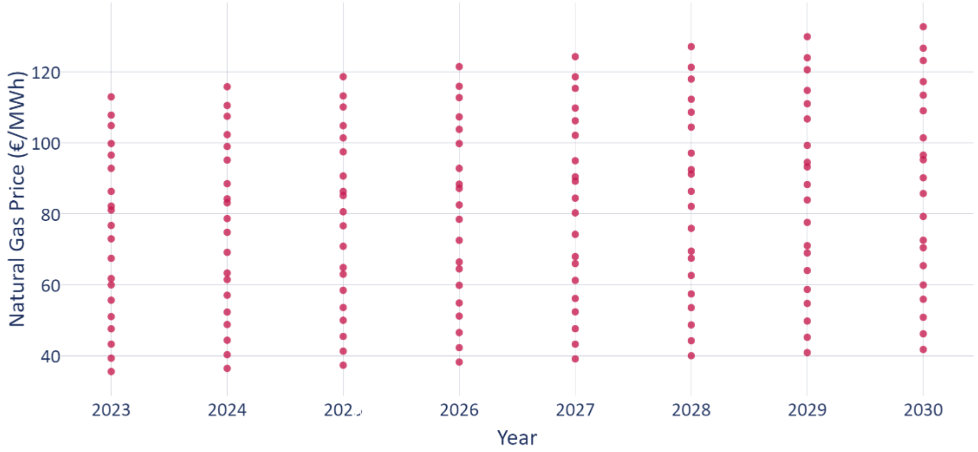

Fig. 4.2. Uncertainty space for the average annual natural gas price evolution in Greece until 2030.

4.3.3. Electricity import prices

Finally, Greece is also interconnected with Albania, Bulgaria, Italy, North Macedonia and Turkey. Historical data for import prices are collected from the ENTSO-e transparency platform (2021), and are scaled according to the assumed scenario for natural gas prices, presented in **Fig. 4.2**. For the countries that historical data are not available, average prices are assumed.

4.3.4. Technoeconomic assumptions

In addition to the scenario assumptions presented in the previous section, several technoeconomic assumptions are used, applicable to all the simulated scenarios. The storage technologies mentioned in the under revision NECP consist of PHS and battery energy storage systems (BESS). According to consultations with heads and experts of relevant departments from the Public Power Corporation, which were performed as part of the stakeholder engagement activities of the H2020 research and innovation projects SENTINEL[10] and TIPPING+[11], while there are plans for an extension of the PHS capacity, the

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[10] https://sentinel.energy
[11] https://tipping-plus.eu

delivery of new projects is highly uncertain. Therefore, the PHS portfolio used in STREEM, is kept constant until 2030, as shown in **Table 4.2**.

Table 4.2
Technical specifications of pumped hydro storage plants in Greece

Power Plant Name	PHS plant 1	PHS plant 2
Nominal Capacity (MWh)	1320	3820
Nominal Power (MW)	315	372
Pumping rate (MWh/h)	220	250
Depth-of-Discharge (%)	95	95
Round-trip efficiency (%)	78	78
Duration (h)	6	10

Sources: (Kaldellis, 2015; Schmidt et al., 2019) and consultations with stakeholders from the Greek Public Power Corporation (owner of the PHS plants)

For the case of BESS, the current capacity in Greece is zero. STREEM calculates the required capacity to minimize curtailment, as shown in **Fig. 4.1**. The assumed technical specifications of BESS are presented in **Table 4.3**.

Table 4.3 Assumed technical specifications of battery energy storage systems

Specification	Value	Justification
Technology	Lithium-Ion	- Popular at grid-scale applications (Martins and Miles, 2021) - Long lifecycle, high round-trip efficiency, low self-discharge rate (Killer et al., 2020) - Competitive levelized cost of storage in most applications by 2030 (Schmidt et al., 2019) - High energy density, mature technology (Yuan et al., 2022)
Depth-of-Discharge (%)	88	- Average optimal value in terms of levelized cost of storage (Schmidt et al., 2019)
Round-trip efficiency (%)	85	- Average value of published works reviewed by Ref. (Cole et al., 2021)
Duration (h)	4	- Wide application in the U.S. and cost-competitiveness to longer duration systems (Denholm et al., 2020)

In terms of costs (**Fig. 4.3**), overnight as well as O&M costs for PV and WT are based on projections from the 2019 Greek NECP and Long-term strategy to 2050 (Greek Ministry of Environment and Energy, 2019b), which are the latest publicly available official assumptions. For PV, the rooftop-to-ground mounted ratio, equal to 7:1 as implied by the 2019 NECP are used, since the draft under revision NECP does not differentiate between rooftop and ground-mounted systems. For WT, the assumptions included in the under revision NECP are used, implying onshore-to-offshore WT ratio after 2028, equal to 2.5:1. For the assumed BESS technology, the overnight costs (accounting both energy and power related costs) are derived from Cole et.al. (2021), after proper conversion to Euros (€$_{2020}$). BESS O&M costs are derived from the Greek Long-term strategy to 2050 (Greek Ministry of Environment and Energy, 2019b).

Fig. 4.3. Overnight (left) and O&M (right) costs for photovoltaics, wind turbines and battery energy storage systems.

Finally, the effective lifetime of each technology, as well as the interest rate assumed for new investments is presented in **Table 4.4**.

Table 4.4
Effective lifetime and interest rate of technologies

Technology	Lifetime (years)	Interest Rate (%)
Solar PV	32.5	8.5
Wind Turbines	20	8.5
BESS	20	8.5

Sources: (Greek Ministry of Environment and Energy, 2019b; NREL, 2022; Timmons et al., 2020)

4.4. Results and discussion

The analysis suggests that decoupling from natural gas, while ensuring achievement of the Greek power sector targets, in a cost-effective way, is feasible, if the VRES plus storage capacity mix is combined appropriately. Yet, in order to exploit the tipping point that emerged with the 2022 energy crisis and enable a positive development trajectory away from natural gas as soon as possible, proper planning is needed. All the figures presented in the following sections are produced by the modelling ensemble presented in **section 4.2**.

4.4.1. Renewable energy integration potential

The renewable integration potential depends on the generation output of PV, WT and hydro power plants. The blue shaded area of **Fig. 4.4** shows the clustered subset of simulated UCED solutions which contain at least the required hydro shares for RES target achievement, without surpassing the level of 10%. Moving on, the green shaded area shows the RES share achieved by PV and WT, under each examined VRES capacity mix, with the complementary generation of hydro contained in the blue shaded area. The 10% limit is set because water resources in Greek rivers and dams are limited, and hydro shares above 10% have not been observed in the available historical data (Kontochristopoulos et al., 2021). The hydro power plants' capacity is expected to increase by only 0.8 GW until 2030 (as shown in **Table 4.1**), and the PHS capacity is kept unchanged, following the consultations with stakeholders described in **section 4.3.4**. Therefore, considering the increase in electricity demand that is also expected until 2030 (**Table 4.1**), the share of hydro in the electricity mix is not expected to exceed 10% in the analysis horizon of this study.

The under revision NECP of Greece aims for 80% RES-generated electricity by 2030, mainly by PV, WT and hydro. 2.8% of this target is intended to be achieved by non-specified RES sources[12], which are not considered in this study. Therefore, the target for PV, WT and hydro is set at 77.2%. As shown in **Fig. 4.4**, the RES share increases with more WT in the VRES capacity mix, due to their higher capacity factor compared to PV. In this respect, WT-preponderant systems can overachieve the 2030 target, even with the minimum simulated hydro contribution. But, as the PV share increases, larger contribution from hydro is required in order to achieve the RES target, due to the smaller combined electricity output from PV and WT. Eventually, with more than about 57% PV in the VRES capacity mix, there is vulnerability to missing the target, since more than 10% contribution from hydro is required. Taking into account that the average hydro contribution for the 10-year period 2013-2022 in Greece was 7.4%, only systems with up to 47% PV can be considered robust for RES target achievement with the planned 23.9 GW of VRES capacity foreseen by 2030 in the under revision NECP.

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[12] In the presentation for the under update NECP, biomass is mentioned, but not explicitly for power generation, and these non-specified "other RES" are not further elaborated. Therefore, considering also the small percentage of "other RES", separate consideration of biomass or other RES is excluded from this study.

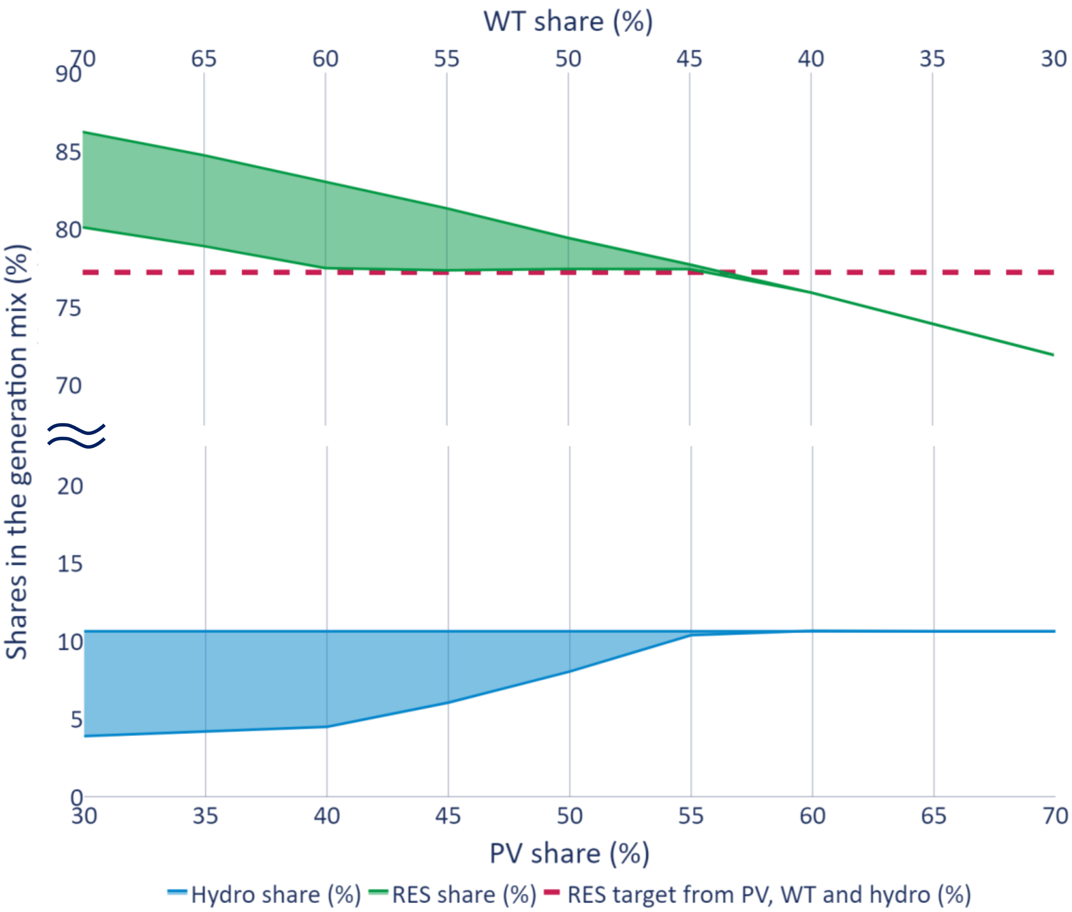

Fig. 4.4 RES electricity shares and required hydro contribution for the achievement of the Greek RES targets in 2030.

4.4.2. Emissions reduction

Emission-wise, the Greek 2030 target aligns with the European one and requires 55% reduction in emissions compared to 1990 levels. The 1990 emissions from electricity and heat production in Greece were equal to 40.77 Mt (Greek Ministry of Environment and Energy, 2021), implying a target for 2030 equal to 18.4Mt. **Fig. 4.5** illustrates the emissions range (grey shaded area) simulated for the examined VRES capacity mixes. The upper limit indicates the case of minimum simulated hydro generation, while the lower limit indicates the case of 10% hydro share. Although all cases can achieve the 2030 emissions target, an increasing trend in emissions is observed with increasing PV shares, due to the higher residual demand that needs to be covered by thermal units. Therefore, for the achievement of the ambitious result of 6.5 Mt emissions from power generation by 2030, as pursued by the under revision NECP scenario, the results suggest that the VRES capacity mix should consist of at least 53% WT when accounting for minimum hydro generation, and at least 40% when assuming 10% share of hydro generation. Notably, the 53% WT case coincides with the resilient configuration for RES target achievement presented in **Section 4.4.1**, while the 40% WT case approaches the under revision NECP, which projects 41% WT in the VRES capacity mix and about 10% hydro generation.

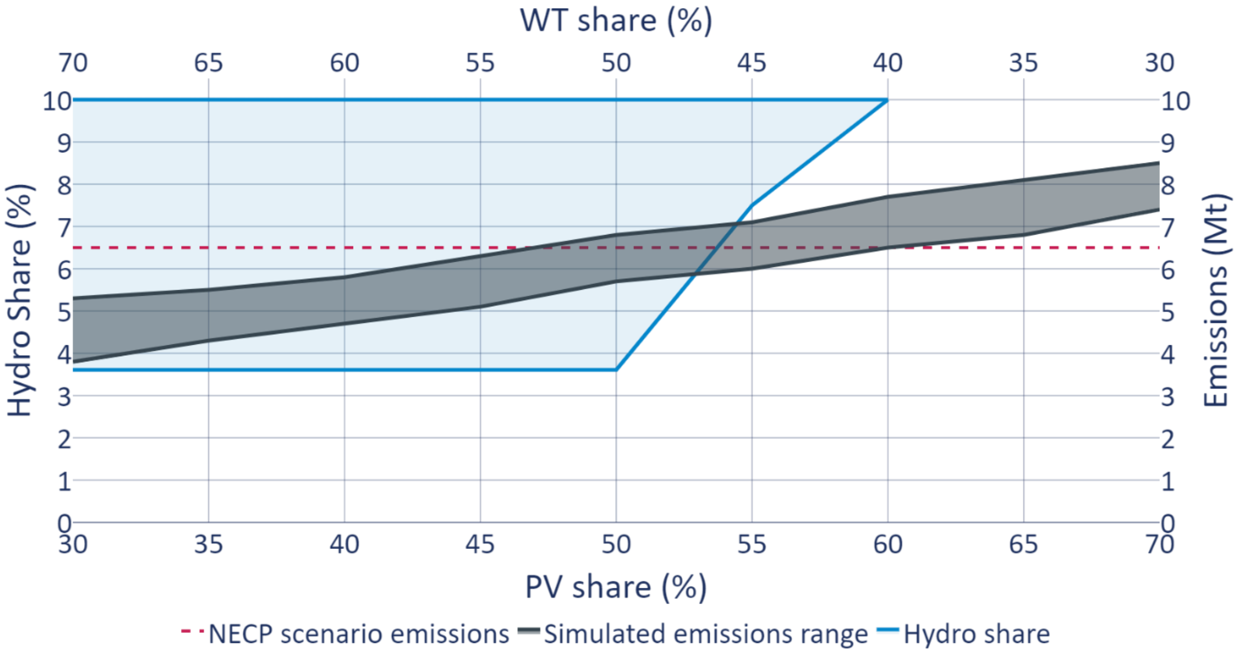

Fig. 4.5. Emissions range and hydro shares enabling the achievement of 6.5Mt emissions from power generation by 2030 under the examined VRES capacity mixes.

4.4.3. Dependency on natural gas

With respect to the subject of dependency on imported gas for power generation, **Fig. 4.6** suggests that for each additional percentage point of WT in the VRES capacity mix, the dependency of Greece is reduced on average by 0.3%. With relevance to the 2022 natural gas dependency levels (i.e., 37.2%), PV-preponderant systems achieve 7.2-16.2% reduction, and WT-preponderant systems 17.2-24.7% reduction until 2030, (with the lower bounds corresponding to 10% hydro share) showing the strength of WT-preponderance in this aspect.

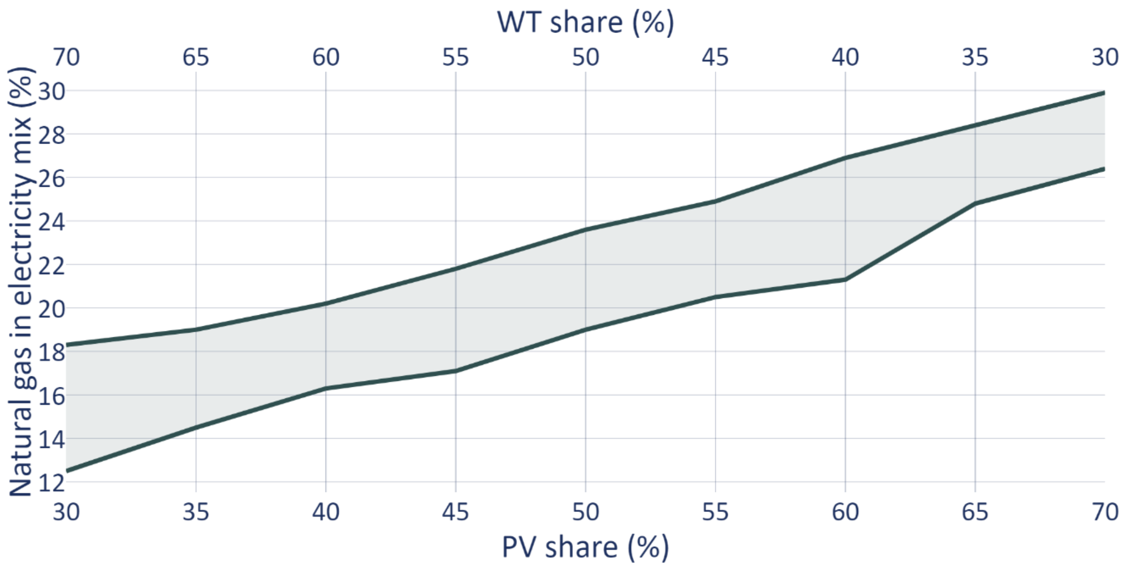

Fig. 4.6. Dependency range of Greece on imported natural gas for electricity generation under the examined VRES capacity mixes.

4.4.4. What about costs?

Despite the results advocating towards WT-preponderant systems from an energy and environmental point of view, when adding the economic perspective, the picture narrows down. As shown in **Fig. 4.7**, the EAC of the 2030 VRES capacity expansion mentioned in the under revision NECP decreases with increasing shares of PV in the VRES capacity mix.

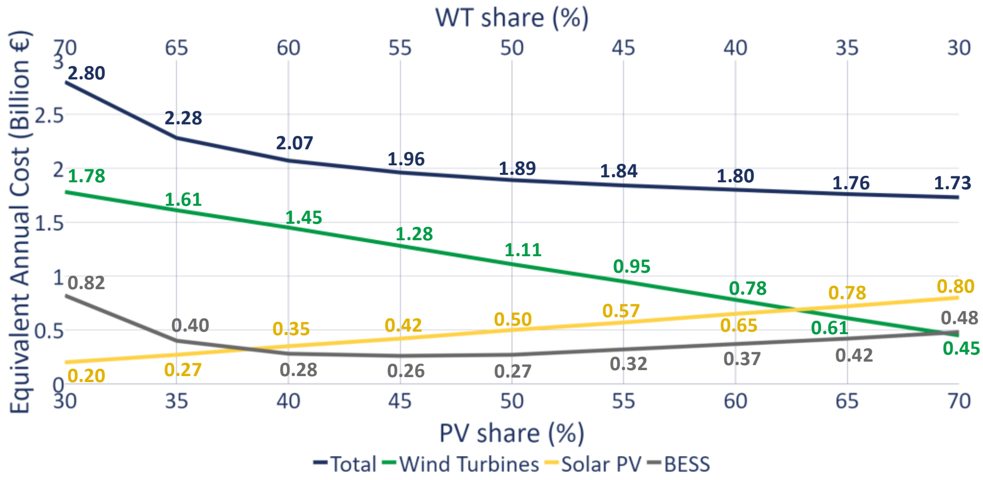

Fig. 4.7. Equivalent annual costs in 2030 of the examined VRES capacity mixes.

Despite the increasing needs for storage with higher PV shares in order to minimize curtailment, as shown in **Fig. 4.8**, the non-materialized investments in costly WT counterbalance and exceed the cost of storage, driving the total EAC towards a descending trend. On the opposite direction, with decreasing PV shares, even though the needs for storage become smaller due the generation complementarity of the two technologies approaching better the demand profile, the high investment and O&M cost of WT compared to PV, leads the EAC towards an increasing trend. Then, beyond the minimum storage requirements point (i.e., when the WT share exceeds 55% in this case), the generation complementarity of the two technologies starts to deviate significantly from the demand profile, and therefore requires much storage capacity to match generation and demand, as also argued by Michas and Flamos (2023). Consequently, the high cost of wind, along with the cost of storage (which is an additional cost to integrate the electricity that would otherwise be produced), drives the total EAC curve in an exponential increase.

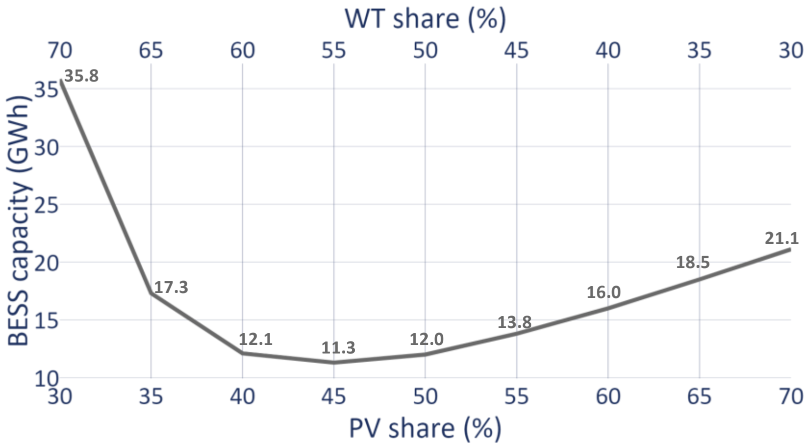

Fig. 4.8. Required BESS capacity to maximize RES integration.

However, when accounting also for the expected outcome in terms of renewable energy integration, the above observations change (**Fig. 4.9**). Both PV-preponderant and WT-preponderant systems indicate poorer cost-effectiveness (i.e., cost increase per additional 1% renewable energy in the electricity mix) compared to balanced systems, due to the additional cost of required storage to integrate their electricity production to the grid. Instead, the various balanced systems can achieve an additional 1% RES integration to the electricity mix with cost difference up to 3%, underpinning that balanced systems provide some investment flexibility. The most cost-effective VRES capacity mixes consist of 50-55% WT and 45-50% PV, with cost per additional percentage of RES share in the generation mix, equal to 40 million €.

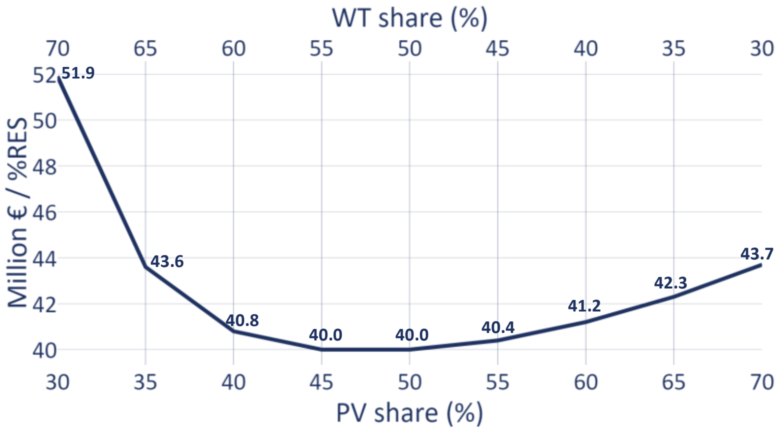

Fig. 4.9. Equivalent annual cost increase per additional 1% renewable energy share in the electricity mix.

Finally, while the above observations provide a comparative assessment of the examined VRES capacity mixes, they do not capture the effect of natural gas prices. The CAC, as defined in Eq. (4.3) and presented in **Fig. 4.10** shows this relation[13]. As the natural gas prices increase, the CAC becomes zero and even negative, showing that it is economically more sustainable to invest in new VRES plus storage infrastructure than maintaining the current thermal portfolio for electricity generation. The break-even point by balanced and moderately WT-preponderant mixes (i.e., 45-65% WT and 35-55% PV) is observed in the range 65-69 €/MWh. Higher PV shares (i.e., 35-40% WT and 60-65% PV) require natural gas prices in the range 72-77€/MWh to achieve zero CAC, while highly WT- or PV-preponderant systems (i.e., 70% PV or WT) achieve zero CAC at natural gas prices in the range 80-82 €/MWh. Even if the break-even price ranges seem to narrow, recent developments have shown that the price of natural gas ranged on average from about 33 €/MWh in 2021 (i.e., before the energy crisis), to 107 €/MWh in 2022 (i.e., within the energy crisis), and back to 50 €/MWh in 2023 (Regulatory Authority for Energy, 2023). Therefore, the proper combination of the VRES capacity expansion is necessary in order to optimize emissions abatement, as suggested by Belaïd et al. (2023), leading in this case towards negative decarbonization costs even at lower natural gas price scenarios (i.e., bold scenarios in **Fig. 4.10**).

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[13] Natural gas prices above 100€/MWh are not visualized, as this is the price limit up to which the simulated hydro generation share in the electricity mix did not exceed 10% for all the examined VRES capacity mixes, making the results comparable.

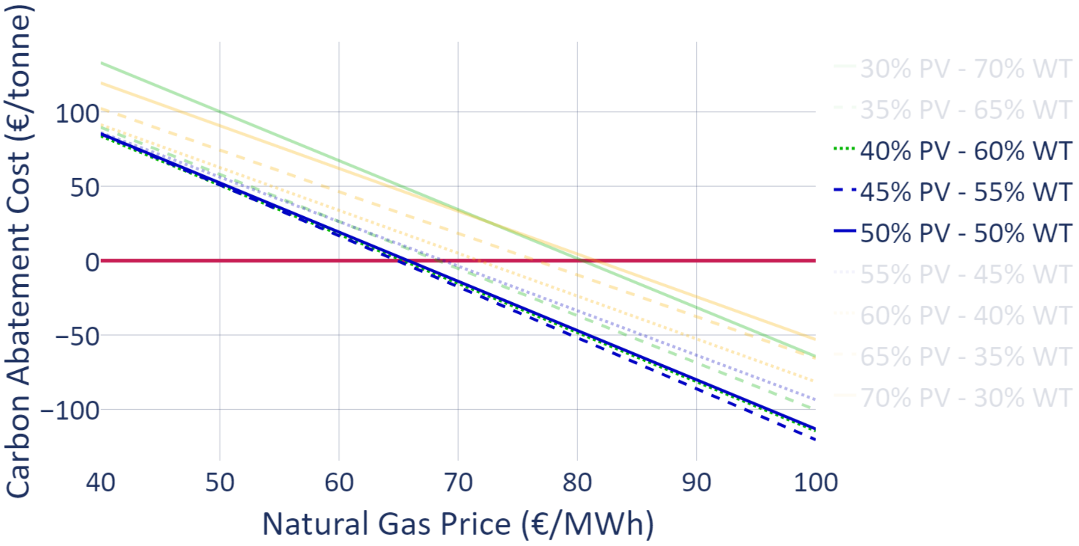


Fig. 4.10. Carbon abatement cost until 2030 for the examined VRES capacity mixes.

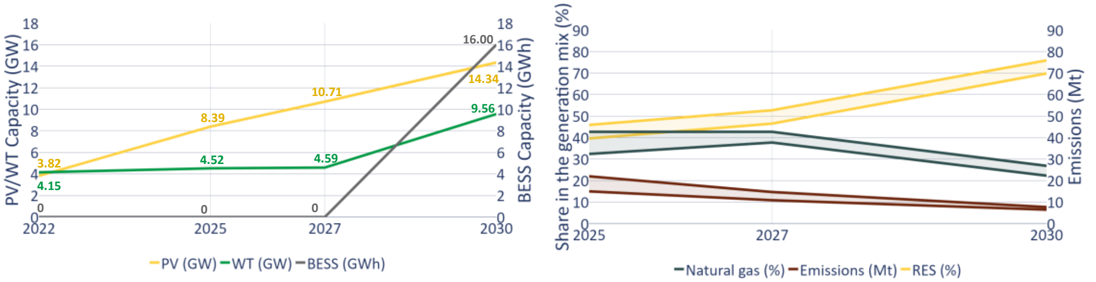
Table 4.5 presents a comparative summary of the results presented in sections **4.4.1-4.4.4**, highlighting how the appropriateness of each RES capacity mix differs according to the perspective of analysis.

Table 4.5
Comparative summary of the results for the various PV capacity mixes

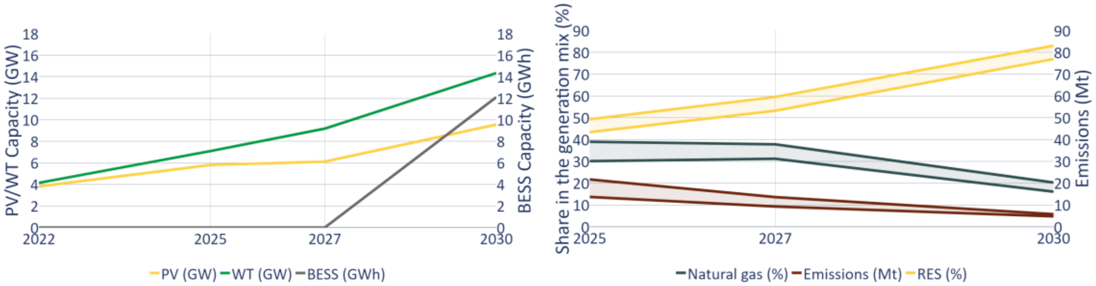
Perspective	System	PV-preponderant	Balanced	WT-preponderant
Energy and Environmental	Renewable energy from PV and WT in 2030 (%)	61.9-65.9	65.9-73.0	73.0-76.2
	Minimum hydro contribution for target achievement (%)	11.3-15.3	4.2-11.3	1.0-4.2
	Emissions in 2030 (Mt)	6.5-8.5	4.7-7.7	3.8-5.8
	Dependency on natural gas (%)	21.3-29.9	16.3-26.9	12.5-20.2
Economic	EAC in 2030 (billion €)	1.80-1.73	1.80-2.07	2.07-2.80
Combined	EAC increase per additional 1% RES (million € / %RES)	41.2-43.7	40.0-41.2	40.8-51.9
	Zero CAC natural gas price (€/MWh)	72-81	65-72	65-80

4.4.5. Pathways to 2030

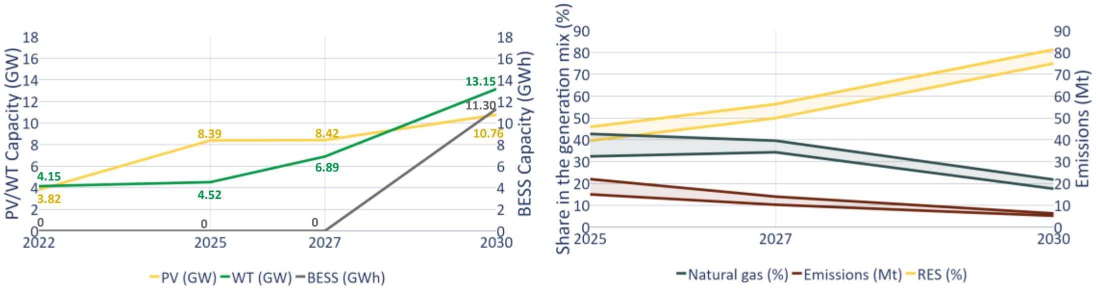
Driven by the analysis of the previous sections, three transition pathways of the Greek electricity system are presented in **Fig. 4.11** and discussed subsequently. These pathways do not imply optimality. Instead, they represent indicative routes that can be followed towards 2030, showcasing the main differences among perspectives.



(a) "Least-cost box ticking" pathway



(b) "Cost-effective resilience" pathway



(c) "Crossroads to equilibrium" pathway

Fig. 4.11. VRES and storage capacity mix deployment pathways (left) and their progress towards the Greek NECP targets for RES penetration, emissions reduction and dependency on natural gas (right).

The **"Least-cost box ticking"** pathway aims for the VRES capacity mix which costs less in 2030 and at the same time barely achieves the Greek targets. This capacity mix consists of 60% PV and 40% WT and accompanying 16 GWh of BESS. Such a 2030 VRES capacity mix, is within the cost-effective range presented in **Fig. 4.9**, and results in EAC by 2030 equal to 1.8 billion €, as presented in **Fig. 4.7**. Yet, it also entails uncertainty regarding the achievement of the RES target and the consequent dependency levels on natural gas, due to the requirements for ambitious hydro contribution, as presented in **sections 4.4.1** and **4.4.3**. For the intermediate years, as shown in the left panel of **Fig. 4.11a**, more time is given for the deployment of WT, which, according to the REPowerEU plan (European Commission, 2022a), can take up to 9 years to obtain a permit, when PV need half the time. In terms of progress towards the 2030 targets (right panel of **Fig. 4.11a**), the gradual phase-out of lignite power plants and the increase in VRES capacity, leads to a steady emissions reduction trajectory. However, due to PV-oriented investments until 2027, the renewable electricity share increase, barely compensates for the lignite phase-out, resulting in a temporary increase in the dependency of Greece on natural gas.

The **"Cost-effective resilience"** pathway goes beyond box ticking and aims for resilience in terms of achieving the Greek NECP targets. To achieve this the 2030 VRES capacity mix consists of 40% PV and 60% WT and accompanying 12.1 GWh of BESS, which, in line with the ambition of the under revision Greek NECP, achieves at most 20% dependency on natural gas-generated electricity, with reasonable hydro contribution. This pathway features slightly better cost-efficiency as presented in **Fig. 4.9**, yet, due to the higher shares of WT, the EAC by 2030 is 270 million € higher than that of the previous pathway, equal to 2.07 billion €. For the intermediate years (left panel of **Fig. 4.11b**), this pathway gives priority to WT deployment even from the milestone year 2025, to accelerate renewable energy integration in the generation mix. Consequently, the gradual phase-out of lignite power plants is better counterbalanced by renewable generation (right panel of **Fig. 4.11b**). Nevertheless, until 2027 the dependency levels do not decline with high speed, indicating that the lignite phase-out will challenge the power sector's autarky, even with ambitious WT deployment.

Finally, the **"Crossroads to equilibrium"** pathway is a combination of the previous pathways and aims for resilient achievement of the Greek 2030 targets in the most cost-effective way. The 2030 VRES capacity mix which achieves these objectives consists of 55% WT, 45% PV and 11.3GWh of BESS, with cost-to-benefit ratio equal to 40 million €/%RES, and EAC by 2030 equal to 1.96 billion €. For the early years of the transition, as shown in the left panel of **Fig. 4.11c**, PV investments are prioritized to allow some time for the permitting of WT. After 2025, WT investments are being accelerated, eventually holding the highest share in the 2030 VRES capacity mix. The gradual lignite phase-out is adequately compensated by the timely accelerated investments in WT (right panel of **Fig. 4.11c**), leading to 2030 RES integration and dependency levels, which on average align with the Greek NECP pledges.

Overall, acknowledging that many EU member states are in the process of transforming their power systems, the results presented in **section 4.4** are not restricted to the scope of Greece. Instead, they could provide an initial assessment supporting other member states' NECP updates. For example, Borasio & Moret (2022) mention that Italy aims to decarbonize its energy system, with high penetration of PV and WT being one of the pillars. They assess a deep decarbonization scenario, nevertheless its scope is on the target year and not on the transition pathway. In this respect, the pathway analysis performed with AIM, and the respective results, could promote research for Italy's energy transition pathway as well.

Bonilla et.al. (2022) explore electricity mixes leading to the decarbonization of Spain’s power system, in line with the 2030 NECP and beyond. Their results advocate for slightly WT-dominated systems, which coincide with the energy and environmental perspective presented in **Table 4.5**. Yet, the author marks further research in sustainability analysis. In this respect, the cost-effectiveness and carbon abatement cost analysis presented in **section 4.4.4**, could provide ideas for further expansion of relevant methodological frameworks and analyses. Also, beyond Mediterranean countries, Poland is aiming for coal phase-out by 2049 (Sokołowski et al., 2022) therefore, this study on VRES capacity mixes could provide some initial hints and ideas for further assessment of its clean energy transition

4.5. Conclusions and policy implications

In this chapter, VRES and storage capacity mixes in Greece, and their effect on emissions reduction, renewable energy increase in the generation mix, and decoupling from natural gas for power generation is explored. The economic performance of the various VRES capacity mixes is evaluated, discussing in parallel pathways towards their realization. The methodology used to perform this analysis combines two energy models and one decision support model, soft-linked in a stepwise manner.

The main extract of the analysis is summarized as follows:

- The transformation of the electricity system based on renewables, is not just a matter of “how many” RES, but also a matter of “how to combine” the available technologies. 6.5Mt of emissions from power generation in Greece could be materialized with a VRES capacity mix featuring at least 53% WT with respect to the total 23.9 GW VRES capacity, exploiting their high capacity factor, and decoupling ambitious emissions reductions from extensive hydro generation, which has resource limitations in Greece.
- Since Greece aims for 80% RES in the generation mix by 2030, the dependence of Greece on natural gas should be at most 20%, making WT-preponderant systems resilient towards this target. Nevertheless, accounting also for the average historical hydro shares in Greece (i.e., 7.5% in the generation mix), balanced VRES capacity mixes of at least 53% WT and at most 47% PV could achieve the same result in a resilient manner.
- Even though from the energy and environmental targets perspective, the analysis advocates for at least 53% WT in the VRES capacity mix, when incorporating the economic point of view, balanced VRES capacity mixes can yield more attractive results. The most cost-efficient VRES capacity mixes in Greece consist of 50-55% WT and 45-50% PV, with cost per additional percentage of RES share in the generation mix, equal to 40 million €. Higher preponderance of PV or WT could lead to costs up to 51.9 million € / %RES.

- The fast forwarding of the “Go-to-areas” measure (European Commission, 2022b) is of paramount importance to enable accelerated deployment of RES and storage, and therefore shorten the dependency period on natural gas. Furthermore, stakeholders engaged within the POLIZERO[14] project, funded by the Swiss Federal Office for Energy, highlighted the needs for organizing technology neutral tenders for the attraction of large-scale investments, as well as providing one-time subsidies for small-scale investments. Especially the latter, could re-initiate rooftop investments that have been stagnant in Greece for about a decade.

As a note for further research, it should be said that potential climate change impacts are not considered in this study. Therefore, solar irradiation, wind speeds as well as precipitation and water availability are considered to remain constant over time. In longer-horizon analyses, incorporating climate change impacts could provide a better overview on the efficiency of RES investments over their lifetime. Further research, augmenting the current analysis with a climate change model is underlined by the author.

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Nomenclature

Nomenclature

Abbreviations

AIM	Adaptive polIcymaking Model	PV	Photovoltaics
BESS	Battery Energy Storage System	RES	Renewable Energy Sources
DAPP	Dynamic Adaptive Policy Pathway	RQ	Research Question
EC	European Commission	VRES	Variable Renewable Energy Sources
EU	European Union	SFOE	Swiss Federal Office for Energy
IF	Impact Factor	STREEM	STorage RequirEmEnts and dispatch Model
NECP	National Energy and Climate Plan	WT	Wind Turbines
O&M	Operation and Maintenance		

5.1. Introduction

In this dissertation, the need for adaptive policymaking and planning has been elaborated. In classic decision making, a static plan was devised, based on the "most likely" future evolution of the context in which the plan would be implemented. However, this tactic has proven to be susceptible to unanticipated contextual evolutions, which might lead the once thought-optimal plan to failure. The decision of the European Union (EU) to rely heavily on imported gas as a transitional fossil fuel, in an effort to phase out coal and transition to renewable energy sources (RES), is a recent example of static policymaking, since it was decided on the premise that geopolitical relations would be turbulence-free, and the supply of gas would be uninterrupted. With the 2022 energy crisis stemming from the Russian war against Ukraine, this reliance on imported gas proved unsustainable, revealing a series of challenges, ranging from gas supply uncertainty and volatile energy prices (Council of the EU and the European Council, 2023), to decreased disposable income for households, and supply chain links between high gas prices and the production of goods and provision of services (Gunnella et al., 2023).

This dissertation builds on the premise that policy-and decision-making should be flexible to adapt to potential external disruptions of the context, being robust to negative impacts, while exploiting opportunities that emerge from positive contextual developments.

Continuing with the same example, the EU's ad-hoc response to the 2022 energy crisis and the failure of the previous static plan, is the publication of the REPowerEU plan (European Commission, 2022a), which aims to "*rapidly reduce EU's dependence on Russian fossil fuels by fast forwarding the clean transition and joining forces to achieve a more resilient energy system and a true Energy Union*", by providing a set of recommendations for accelerated RES deployment, energy efficiency interventions and energy saving measures application, as well as diversification of energy imports. For the aspect of RES uptake, the REPowerEU plan increases the ambition with respect to capacity deployment by 2030 to 1236 GW. Among the available technologies it identifies solar photovoltaics (PV) as the technology that can be rolled out most rapidly, and introduces the EU solar energy strategy (European Commission, 2022b) which lists outstanding hurdles and challenges in the solar energy sector, and outlines actions to address them and accelerate solar technology deployment. Furthermore, acknowledging the value of wind energy in providing abundant and more stable power supply, the REPowerEU plan stresses the need for accelerated permitting processes, which can take up to 9 years. The plan presents the commission recommendation on speeding up permit-granting procedures for renewable energy projects and facilitating Power Purchase Agreements (European Commission, 2022c), aiming to provide aid to

Member States in exploiting all RES deployment acceleration opportunities within the legislative framework.

Nonetheless, the manner in which these recommendations will be transposed into national legislation and the technological deployment pathways that will be followed by each member state until 2030 depends on the context of each country, including, but not limited to, spatial land-use restrictions, resource potential (e.g., wind speed and solar irradiation), funding opportunities, or the capacity to incentivize citizens to contribute to the energy transition by attracting their investment interest. To this end, energy models have historically improved the comprehension of the energy system's dynamics, have supported energy planning, and have facilitated the formulation of energy policy. Yet, the greatest obstacle is that energy models typically require significant time to be calibrated and produce meaningful results in a context that is constantly changing (Frilingou et al., 2023). In this respect, analyses are restricted to a limited set of energy system configuration scenarios and contextual variable assumptions, approaching the policymaking concept based on best estimates.

The key objective of this dissertation is to develop a methodological framework which moves away from short-sighted policymaking, towards outrightly informed, adaptive policymaking that explicitly accounts for context-specific uncertainties, and prescribes corrective actions to deal with unlikely contextual events from the design phase, rather than in an ad-hoc manner.

To enable this, a set of modeling tools has been developed which can be easily linked with existing simulation models, allowing for rapid simulations and the exploratory assessment of numerous policy/strategy pathways towards one or more overarching targets, allowing a tight loop between stakeholders and modeling teams to be established. The modelling tools consist of the decision support, plug-in model named Adaptive polIcymaking Model (AIM) and the energy simulation model named STorage RequirEmEnts and dispatch Model (STREEM). A key feature of the developed modeling framework is its capability to provide answers to multiple "What-if" scenarios, by identifying values of the uncontrollable context which enable or hinder the success of the evaluated policy/strategy pathways. In this respect, short-term planning is facilitated, with simultaneous description of potential future adaptive actions (from the design phase) that can be implemented in case that the future evolves unexpectedly, ensuring final target(s) achievement.

The entire work of this dissertation has been presented as a series of research chapters with the following structure:

- **Chapter 1**: Emphasis on the need for adaptive and participatory policymaking under uncertainty and the needs for model improvements towards this direction.

- **Chapter 2**: Development of the AIM model which **(i)** investigates the conditions under-, and the timeframe beyond- which a policy/strategy starts to deviate from the set targets, **(ii)** visualizes a map of dynamic adaptive policy pathways (DAPP), and **(iii)** sets up a monitoring system for real world policy adaptation. In this chapter AIM has been linked with the technology adoption model ATOM (Stavrakas et al., 2019) to investigate policy pathways incentivizing the uptake of rooftop PV in Greece.
- **Chapter 3**: Upgrade of AIM's applicability to account for multiple RES technologies, in order to facilitate national-wide analyses. Development of the STREEM model which simulates the hourly operation of energy storage systems and calculates the required storage capacity towards exploitation maximization of the renewable electricity potential. In this chapter, the upgraded AIM was linked with STREEM to investigate variable renewable energy sources (VRES) plus storage deployment pathways to 2030, limiting the enforcement of curtailment.
- **Chapter 4**: Upgrade of AIM's clustering functionality to account for multiple policy/strategy targets (i.e., emissions reduction, renewable energy penetration, dependency on natural gas), while decomposing the impact of each assessed contextual factor on the success or failure of a policy/strategy towards a specific target. In this chapter, AIM has been linked with STREEM and the wholesale electricity market simulation model BSAM (Kontochristopoulos et al., 2021), to investigate RES plus storage deployment pathways limiting the effects of the 2022 energy crisis, accounting for the operation of both VRES and dispatchable thermal units.

Considered jointly, the aforementioned research chapters represent independent but sequential stages of an integrated methodological framework, as presented in **Chapter 1.3**, which demonstrates how adaptive policymaking can be applied at different governance scales, technological assessments and policy evaluation ranges, supporting robust energy system transformation planning. This integrated methodological framework has been applied for the case of Greece, which is an example country which opted for lignite phase-out towards a RES-based electricity system, turning to large dependency on imported gas for the transition period, and therefore being prone to the uncertainties of the 2022 energy crisis. The aim was to showcase the support that the methodological framework can provide, in designing more resilient energy transition pathways which: **(i)** attract consumer engagement in the energy transition, **(ii)** ensure cost-efficient RES integration, minimizing instances of electricity waste due to mismatches with demand, and **(iii)** identifying VRES plus storage deployment pathways that can limit the adverse effects of the 2022 energy crisis, shielding the electricity system from external disruptions.

This rest of this chapter summarizes the dissertation's findings and examines its major conclusions. Specifically, it provides implications for end users in the disciplines of policy and practice, and summarizes the dissertation's contributions to the scientific and energy modelling communities. Limitations of the dissertation and specific recommendations for additional research are also provided.

5.2. Summary of results and key findings

The primary focus of this doctoral dissertation is on model-informed, exploratory and participatory policy/strategy assessment, applied to the energy transition topic. Its main goal is to support decision-making in a way that differs from traditional design approaches that are based on best estimates of the contextual future in which policies and plans are implemented, by focusing instead on short-term planning while pre-designing potential coping actions that can be implemented if deviations from the best contextual future estimates occur. The overarching research question (RQ) is:

> *How could energy models support the exploratory assessment of adaptive policies towards the design of electricity systems based on renewables, which are resilient to contextual uncertainties?*

To answer the overarching RQ, three thematic pillars were formulated, which aim for outrightly informed, robust and adaptive decision-making towards decentralized RES-based power systems, namely **(i)** consumer engagement in the energy transition, **(ii)** minimum waste of renewable energy, and **(iii)** shielding the electricity system from external disruptions. The respective thematic RQs that were formulated are the following:

RQ1. Which policy pathways could re-initiate small-scale PV investments (i.e., ⩽ 10kWp) in Greece without leading to the RES market failure that was observed in the past?

RQ2. Assuming an increase in overall RES capacity, which RES plus storage deployment pathways to 2030 enable least electricity curtailment and what criteria can be used for their selection?

RQ3. Which RES plus storage deployment pathways enable decoupling from imported gas, while achieving the emissions reduction and renewable integration targets in an economically efficient way, despite contextual uncertainties?

These RQs have been analytically answered in **Chapters 2-4**. The following sub-chapters summarize the results and key findings in relation to the three thematic RQs and the overarching RQ that governs them.

5.2.1. Summary per thematic research question

As mentioned in **section 5.1**, Greece was chosen as the testbed for the application of the methodological framework of this dissertation. It is a country that has set ambitious energy and climate targets for 2030, in order to transition away from its current regime, which is characterized by high reliance on fossil fuels and poor interconnection capacity with neighboring countries. The 2019 National Energy and Climate Plan (NECP) (Greek Ministry of Environment and Energy, 2019) laid the groundwork for a more sustainable energy system, by setting ambitious renewable capacity expansion targets by 2030 (i.e., 200% increase compared to 2019), phasing out highly polluting lignite power plants, and positioning imported natural gas as the transition fuel. However, the Russian invasion to Ukraine revealed that using natural gas as a transition fuel, would lock in Greece to the uncertainty and adverse effects of the energy crisis for many years. The governmental response in early 2023 was the proposal for an updated NECP, which doubles the ambition for RES deployment until 2030. Furthermore, considering that effort that is needed to reach this target, Greece immediately announced the "Rooftop PV" programme (govgr, 2023), which subsidizes the installation of PV and battery energy storage systems (BESS) in households, in order to re-initiate investments in rooftop PV systems, which have been stagnant since 2013. Nevertheless, in the proposal for the NECP update, only a couple of scenarios for the power production portfolio were provided, which are a product of optimization based on specific criteria, resembling an approach of decision-making based on best estimates. Considering also that Greece has already experienced a RES market failure in the period 2008-2013 due to over-subsidization, the answering of the thematic RQs of this dissertation aim to provide concrete recommendations for sustainable planning, achieving the ambition of Greece for a transformation of its energy systems, without risking financial deficits and by managing external uncertainties during the transition phase.

RQ1. Which policy pathways could re-initiate small-scale PV investments (i.e., ⩽10kWp) in Greece without leading to the RES market failure that was observed in the past?

The results indicate that net-metering, which is the current market framework for small-scale PV integration in Greece, cannot drive adequate investments in line with the Greek small-scale PV capacity targets and milestones by 2030 (i.e., 1 GW of installed capacity by 2030 when the installed capacity in 2020 was 0.35 GW), because the typology implemented in Greece is not favorable for prosumers. Grid charges placed on net-metered electricity end up burdening prosumers instead of increasing the value of locally generated electricity for their benefit. Consequently, prosumers' profits (i.e., bill savings), solely depend on the retail electricity price, which are further reduced by the grid charges, leading to decreased consumer motivation to install photovoltaic systems. On the other hand, implementing a self-consumption scheme featuring PV coupled with a partly subsidized BESS of equal scale (i.e., 1kWh of BESS per 1kWp of PV) has significant potential to motivate investments. Unlike net-metering, a self-consumption scheme, allows prosumers to consume more of their self-generated electricity by storing it for future use. That way, grid charges are only applied to the electricity drawn from the grid, price-related uncertainties for bill savings are reduced and prosumers' profits are increased.

Regarding the subsidy pathway to be followed for the BESS, the simulation results indicate that a high subsidy is required at the beginning, to attract adequate investor interest, considering the currently high cost of BESS and the ambitious trajectory that needs to be followed towards the 2030 Greek PV capacity target. However, offering prolonged high subsidies can lead to public deficits, similar to those experienced during the Feed-in Tariff period between 2008 to 2013. On the other hand, applying smaller subsidies too early may not align with the steep trajectory of the PV capacity target. Therefore, a stepwise approach to subsidization is advised. The level of subsidization should be determined considering the effect of contextual factors. Indicatively, the results of the analysis highlighted that the level of investments in small-scale PV is counter-proportional to the cost of PV, since the self-consumption scheme does not subsidize the installation of PV panels. On the other hand, despite BESS still being relatively expensive, there is no such observed correlation between the investment level in small-scale PV plus storage and the cost of BESS. This is because the storage system in the evaluated self-consumption scheme is subsidized, meaning that the investment cost is not solely borne by the prosumer. However, a strong correlation between the cost of BESS and the public policy cost is evident. In this respect, a combination of subsidies for both PV and BESS could lead to an improved balance between prosumer expectations and public expenses. Overall, the analysis highlights that the design of relevant policies should envision adaptation to market signals, in order to avoid prosumer's excess profits at the cost of public expenses, while still providing adequate incentive towards the set targets.

RQ2. Assuming an increase in overall RES capacity, which RES plus storage deployment pathways to 2030 enable least electricity curtailment and what criteria can be used for their selection?

The requirements for BESS capacity in order to minimize curtailment, depend on the generation profile complementarity of PV and wind turbines (WT), which are the renewable energy technologies with the highest potential in Greece. Optimal complementarity was found to be achieved with 62.5% WT and 37.5% PV, resulting in the minimum required BESS capacity, equal to 2.4 GWh, and achieving 62.5% share of renewable electricity to the generation mix. Beyond this optimum, BESS requirements increase on average by 330 MWh per 1% additional WT share and 260 MWh per 1% additional PV share. Taking also into account that increasing the PV share by 1% leads to about 0.34% less renewable energy integration in the electricity mix, and vice versa, marginal achievement of the 2019 NECP target for 61% RES in gross electricity consumption by 2030, is possible with approximately 42.5% PV and 57.5% WT in relation to the total RES capacity foreseen in the 2019 Greek NECP for 2030 (i.e., 14.7 GW) and 3.9 GWh of accompanying BESS capacity. This indicates that the tendering procedure should be designed in a way that accounts for both the capacity needs per technology which satisfy the set targets, and the accompanying storage capacity that maximizes the renewable energy yield. For example, the PV and WT capacity mix that was calculated for the 2019 NECP, featuring 52.4% PV and 47.6% WT, is expected to contribute in achieving up to 92% of the Greek RES integration target with the aid of 5.5 GWh of BESS. To meet the remaining 8%, other RES technologies, higher WT shares or increased total RES capacity would be required.

Beyond technological planning, it is important to also take into account the available funding opportunities to make the most efficient use of financial resources for eligible technologies. In the case of Greece, there is a budget of 450 million € in the country's recovery and sustainability plan (IEA, 2022) specifically allocated for the installation of electricity storage. This implies that systems with a high concentration of PV or wind projects may exceed the available funding for storage technologies. On the other hand, systems with a slight emphasis on wind projects, which require smaller volumes of BESS capacity, can be effectively realized by mostly utilizing the allocated funds for storage technologies.

Additionally, the timing of investments is crucial when determining the deployment pathways for RES combined with storage. As expected, each additional 1% of RES electricity in the generation mix leads to increased annual costs for deploying, operating, and maintaining RES and storage projects. The cost increase ranges from 27-33 million € for PV-rich systems, 26-28 million € for wind-rich systems, and 26-31 million € for balanced systems. BESS is expected to start contributing to these costs between 2026-2029, when the RES integration levels exceed certain thresholds (i.e., 41-48% for PV-rich systems, 51-58% for balanced systems, and 59-64% for wind-dominated systems). Therefore, funding and tendering mechanisms should proactively consider the timing of calls for eligible technologies, leveraging their combined financial efficiency and potential cost reductions driven by technological advancements.

RQ3. Which RES plus storage deployment pathways enable decoupling from imported gas, while achieving the emissions reduction and renewable integration targets in an economically efficient way, despite contextual uncertainties?

The analysis indicates that VRES (i.e., PV and WT) mixes with a high prevalence of WT are more effective in achieving or surpassing energy and environmental targets. However, when incorporating the economic aspect, balanced VRES capacity mixes offer more beneficial outcomes. Specifically, to achieve the power generation emissions level of 6.5Mt by 2030, as outlined in the under revision 2024 NECP of Greece, WT should hold a minimum of 53% with respect to the total projected VRES capacity of 23.9 GW. This would capitalize on their high capacity factor, enabling ambitious emissions reductions to be achieved, without heavily relying on hydro generation, which may be constrained by water resource availability in Greek rivers and dams. Moreover, this minimum WT share, when combined with historical hydro generation, could achieve an 80% renewable energy share in the generation mix. This aligns with the desired objective of limiting natural gas dependency in power generation to a maximum of 20% as stated in the under revision NECP.

Nevertheless, not every WT share above 53% is economically efficient. Indicatively, in order to increase the renewable energy share in the generation mix by 1% with WT-preponderant systems (i.e., 60-70% WT share in the VRES capacity mix), would cause an increase in equivalent annual costs for investment and operation and maintenance (O&M) equal to 40.8-51.9 million €, with the minimum range corresponding to 60% WT and the maximum to 70% WT share. This is because, the storage needs in order to ensure maximum RES integration increase significantly with high WT preponderance, increasing the respective annual cost. Similarly, PV-preponderant systems (i.e., 60-70% PV share in the VRES capacity mix), would cost an additional 41.2-43.7 million € per year, on the one hand due to their lower capacity factor compared to WT, and on the other hand, due the significant storage capacity needed in order to smoothen the daily generation peaks of solar PV. Balanced systems manage to tackle these challenges, by providing an aggregated generation profile that better matches the electricity demand profile in Greece, minimising the needs for storage capacity. Therefore, the relevant annual cost increase ranges between 40-41.2 million €, with the lowest cost corresponding to 50-55% WT and the highest cost to 60% PV share. The above observations highlight that in order to achieve the Greek targets for renewable integration, emissions reduction, and dependency levels in an economically efficient manner, VRES capacity mixes should feature a minimum of 53% and a maximum of 60% WT, and 40% to 47% PV. It is important to mention that the cost increases presented in this thematic RQ are higher and differently allocated to the examined VRES capacity mixes, compared to the ones described in the previous RQ. This is because the 2019 NECP (i.e., the focus of RQ2) considers only onshore WT installations, while the under revision NECP (i.e., the focus of RQ3) foresees both onshore and offshore installations. This differentiation of the under revision NECP leads to:

- higher combined capacity factor of the wind technology, enabling the achievement of minimum BESS capacity with slightly more balanced WT/PV systems compared to the 2019 NECP, and
- increased annual costs, due to the higher investment and O&M costs associated with off-shore projects.

Finally, the pathway analysis highlighted that depending on the perspective, different routes can be considered when deploying VRES in Greece, including least-cost marginal target achievement, cost-effectiveness for resilient target achievement, or combinations. The least-cost perspective features more PV investments, while the cost-effectiveness perspective aims for slightly WT-prevalent investments along the years until 2030. A potential combination of the above promotes PV investments for some years, and then WT investments are accelerated, leading to a balanced system by 2030. However, regardless of the perspective, despite the increased ambition for VRES capacity expansion by 2030, the loss of lignite-fuelled power production can only partially be offset until 2027, resulting in a continued dependency on natural gas. This emphasizes the urgent need for the transformation of the power system without further delay. Towards this direction, the "Go-to-areas" measure becomes crucial for accelerated permitting processes, which will shorten the dependency period on natural gas.

5.2.2. Summary with respect to the overarching research question

After consolidating the key findings from the thematic RQs, the overall contribution of the methodological framework applied in this dissertation, to answer the overarching RQ is summarised.

How could energy models support the exploratory assessment of adaptive policies towards the design of electricity systems based on renewables, which are resilient to contextual uncertainties?

Looking at the overarching RQ, the methodological framework applied, answers to several challenges that policymakers face when designing policies:

- **Which** national energy system transformation strategies aligned with EU policy are available and how do they perform?
- **When** to deploy the available clean energy technologies?
- **What** should be monitored to trigger policy/strategy change, ensuring target achievement despite contextual uncertainties?

EU regulation/strategy is usually the main motivator for policymaking decisions, which member states need to transpose into national legislation/strategies at various governance levels. However, EU plans and regulations are speedy and complex, creating difficulties to member states in keeping up (as elaborated in **section 1.1**). Taking this into account, the developed modelling framework supports the design of effective policies and strategies, supporting the transition to a low-carbon, sustainable energy system, by providing quick answers to multiple "What-if" scenarios, regarding **which** policy/strategy pathways perform well given the context of the country in which they are applied. Towards this direction, AIM's model agnostic nature, and STREEM's parametric configuration, as presented in **Chapters 2** and **3** respectively, enable the modelling framework to be applied at various governance levels and scales, supporting both horizontal and vertical coordination. This becomes evident when comparing the work presented in **Chapter 2**, where the focus is on the assessment of support measure pathways for the installation of rooftop PV and residential storage systems, when in **Chapters 3** and **4**, the focus is on national VRES plus storage deployment pathways. This means that the modelling framework can inform about the effectiveness of sectoral policies, which can be taken into account when designing nation-wide plans, such as technology-neutral tenders, in order to avoid unnecessary incentivisation towards target over-achievement, which can be expensive.

The time component is also a crucial parameter that often challenges energy policymakers, as the investment decisions taken at the short-term, have long-term impacts (Morris et al., 2017). This boils down to answering **when** to deploy the necessary technologies in order to achieve long-term goals sustainably, without risking over-deployment or suboptimal technological combinations. The modelling framework presented in this dissertation answers this inquiry. First of all, STREEM quantifies the required volume of storage technologies in order to maximize the grid integration of energy yield, without investing in underutilized BESS systems, given various RES generation portfolios, as presented in **Chapter 3**. Then, in combination with AIM, it can investigate which investment pathways for RES combined with storage can be followed towards a renewable-powered electricity system, ensuring financial effectiveness, and specifying the yearly timing of investments for each technology. On top, as presented in **Chapter 4**, both models can be linked with an electricity market simulation model, which can provide further insight regarding the timewise potential for emissions reduction, fossil fuel use, or response to coal phase-out decisions, assessing that way the a multitude of impact factors that can drive the choice of a specific investment pathway.

Finally, the performance and impact of energy policies and strategies depend on the context within which they are applied. Identifying which contextual parameters are the most impactful on the outcome of a policy or strategy, and which threshold should be considered as a trigger for policy/strategy change, is necessary in order to enable robust policymaking under uncertainty. As presented in **Chapter 2**, AIM is capable of supporting such a kind of policymaking by quickly simulating many contextual scenarios, and clustering segments of the uncertainty space, highlighting **what** should be monitored during the implementation of a selected policy/strategy pathway, in order to identify imminent deviation from the set targets. In parallel, alternative policy strategy pathways that perform well under the new contextual realities can be identified. That way, based on its participatory functionality, AIM can facilitate the establishment of a tight loop between stakeholders and modeling teams for the timely identification of opportunities and dead-ends, even from the policy design phase. Finally, since policies usually aim to achieve multiple inter-related targets, as presented in **Chapter 4**, AIM identifies clusters of contextual evolutions under the effect of which a policy/strategy performs well with respect to all targets. This also gives the opportunity, on the one hand, to identify the contextual space under the effect of which a policy/strategy performs well with respect to each target individually, and on the other hand, identify potential contradicting performance indicators, making a trade-off analysis possible.

These merits of the applied methodological framework and the modelling ensemble that comprise it, have been validated during consultations with various stakeholders and policymakers during the last five years, in events such as the "TRANSrisk Policy Lunch: Paris in Practice-Understanding the Risks and Uncertainties", in Brussels and the "TRANSrisk & SET-Nav Regional Workshop: Decarbonizing our energy system-Transformation pathways, policies and markets, with spotlight on Greece", in Athens, as well as during discussions with experts from the Greek Public Power Corporation as part of the SENTINEL project. Finally, the usefulness of the AIM model has been acknowledged by the Swiss Federal Office for Energy (SFOE), and is being linked with the JRC EU TIMES model, as part of the POLIZERO project, in order to explore Swiss policies towards zero CO_2 emissions compatible with European decarbonisation pathways.

5.3. Contribution of the dissertation

The overall contribution of this dissertation is summarised in the following categories: **1.** energy modelling, **2.** policymaking, and **3.** research community.

5.3.1. Contribution to the field of energy modelling

While energy models have been acknowledged as supporting elements in decision-making and energy planning processes (Doukas, 2013), there are still needs expressed by model users that need to be addressed by model developers, as elaborated in **Chapter 1.1.3**. The focus of this dissertation was on three structural elements of energy modelling (**Fig. 5.1**), which can facilitate model-informed, adaptive and participatory decision-making, namely: (i) simulations resolution, (ii) computational efficiency, and (iii) consideration of uncertainty and unforeseen events.

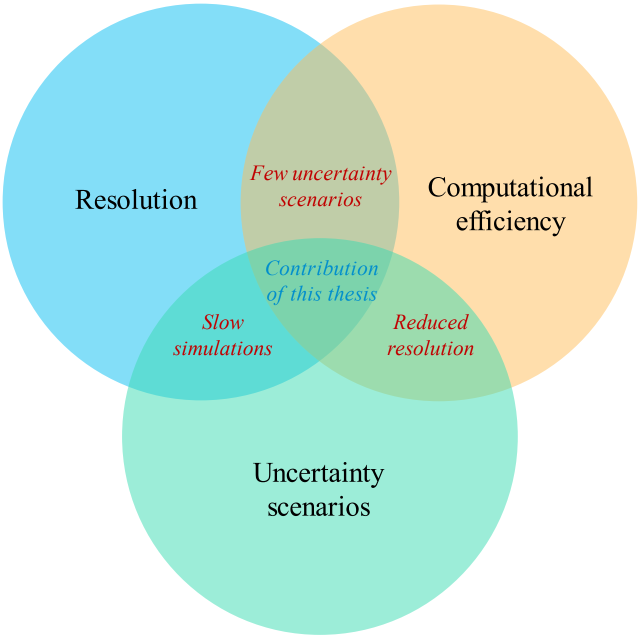

Fig. 5.1. Trade-offs in energy modelling and contribution of this dissertation

Acknowledging the impeccable value of each of these elements in supporting robust policymaking, the modelling framework applied in this dissertation, aims to find a balance among them, as described subsequently. Both AIM and STREEM, as presented in **chapters 2-4** have been developed with the Python language, in the context of the H2020 projects TRANSrisk[15], SENTINEL[16] and Tipping+[17] funded by the European Commission (EC), and the POLIZERO[18] project funded by the SFOE.

Simulations resolution

Both AIM and STREEM support high temporal and spatial resolution, as well as detailed representation of the modelled technologies. Specifically, STREEM runs in an hourly resolution in order to capture the contribution of storage technologies in shifting intermittent renewable generation to high demand and low generation hours. Furthermore, its ability to simulate different storage technologies by simply parameterizing technical details, such as nominal capacity, duration, depth-of-discharge and round-trip efficiency, allow the model to simulate the simultaneous operation of short-term (e.g., batteries) and long-term storage (e.g., pumped hydro storage), applying priority rules, and explore the suitability of each technology in different application contexts and scales. In this respect,

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[15] https://cordis.europa.eu/project/id/642260
[16] https://sentinel.energy
[17] https://tipping-plus.eu
[18] https://www.polizero.ch

given the availability of datasets for the demand and renewable generation profiles, STREEM can identify the storage volume requirements from a household level to a national level, exploring the optimal technology, or technological mix, for the application under study. STREEM has already been applied at the national level to explore how much storage is needed in order to minimize electricity curtailment, under different combinations of WT and PV capacity. Apart from storage requirements, the analysis with STREEM enabled the identification of renewables plus storage combinations which perform best in terms of cost of renewable energy integration.

On the other hand, AIM is a plug-in model, which can be linked to different energy system models, enabling the assessment of policy/strategy pathway through **transdisciplinary modelling approaches.** Plug-in means that it requires as input, both the input parameters as well as the respective outputs, which are produced by a simulation model. In this respect it performs meta-analysis of simulation results, supporting the same temporal and spatial resolution as the simulation model which feeds it. This makes it a valuable tool for analyses ranging from sector-specific challenges (e.g., incentivisation of rooftop PV) to cross-sectoral system wide transformations (e.g., deep decarbonization of energy systems). So far, AIM has been linked with the STREEM (Michas and Flamos, 2023), ATOM (Stavrakas et al., 2019) and BSAM (Kontochristopoulos et al., 2021) models targeting analyses at the rooftop PV sector and the national electricity sector of Greece. The application of STREEM at the municipal level and the application of AIM for cross-sectoral analysis, linked with the JRC-EU-TIMES model, are also planned as described in **section 5.4**.

Computational efficiency

Even though both STREEM and AIM support high temporal resolution, their computational efficiency has proven to be remarkable. Specifically, STREEM's storage dispatch algorithm requires only 14 seconds to simulate the hourly operation of any combination of storage technologies for one year (i.e., 8760 hourly simulation points). Furthermore, the algorithm calculating the required storage capacity, identifies the correlation between storage volume and curtailment decrease, converging to the capacity that maximises the exploitable renewable electricity yield in 6-7 iterations. This means that in about 1.5 minutes, STREEM can provide storage sizing results for the case under study, despite the scale in which it is applied.

The simulation time of AIM on the other hand, depends on the number of policies/strategies that need to be assessed, the number of simulations years and the number of contextual scenarios considered to affect the performance of each policy/strategy. To stress test AIM, it was used to assess 4 policies, in a 10-year time horizon, under the effect of 1000 contextual scenarios in each simulation year. The assessment of the effectiveness of all policies with respect to the set yearly targets, under the effect of all 1000 scenarios per simulation year was performed in 7 seconds. Furthermore, the simulated policy implementation and the consequent update of all alternative policies' performance was achieved in 13 seconds. This highlights that AIM is a valuable participatory tool for providing quick answers to relevant experts and end-users, relevant to *"what will happen if we do one thing rather than another thing"*, as expressed by stakeholders during the consultation process of the H2020 SENTINEL project (Süsser et al., 2022).

Consideration of uncertainty and unforeseen events

Building on the above merits, both models are capable of simulating many scenarios, capturing a wide range of uncertain variables' values, without sacrificing accuracy due to reduced resolution, thus being able to facilitate robust policymaking which moves away from policymaking based on best estimates. Especially for the case of AIM, it enables fast assessment of a large number of energy transition pathways along an analysis horizon, without mandating the same number of simulations to be performed by computational- and time-intensive simulation models. Specifically, it enables the assessment of $p^{m},$ policy/strategy pathways with only $p \cdot m$ simulations performed by a simulation model, where p is the number of policies under investigation and m the number of years in the analysis horizon. Therefore, even if a simulation model requires a significant amount of time to simulate a year of analysis, AIM can be used to augment the analysis space. Indicatively, the BSAM model which was linked with AIM in **Chapter 4**, requires 70-85 minutes to simulate in an hourly resolution an entire year of unit commitment solutions. For a 10-year horizon and 4 policies/strategies to assess (e.g., RES and thermal capacity mixes), a complete pathway analysis (i.e., all possible yearly policy/strategy changes) would require 4^{10} pathway simulations in BSAM, which correspond to an infeasible computational effort. By linking BSAM with AIM, the same number of pathway analyses are feasible, with only 40 simulations required from BSAM, which correspond to about 50 hours of simulations. In this respect, emphasis from simulations models can be given to the simulation of many parametric scenarios corresponding to different contextual evolution scenarios, including extreme or unlikely scenarios. Then, the meta-analysis with AIM can cluster the contextual evolutions which correspond to successful policy outcomes and augment the pathway analysis range. Therefore, with AIM, answering of how the planning objectives can be revisited when operating conditions change, is possible, enabling decision-making with consideration of uncertainty and unforeseen events.

5.3.2. Contribution to the field of policymaking

In addition to its technical contributions in energy modelling, this dissertation also offers valuable insights for policymakers and practitioners. These insights are summarised for the national level of Greece, and upscaled with general implications at the EU level:

Implications for Greece

i. Net-metering schemes, which only compensate prosumers for the energy they consume at their homes and without exemption from grid fees, are insufficient in motivating rooftop PV investments. **A transition to self-consumption schemes with PV and BESS is necessary to empower prosumers** with more control over their generation, relieve them from grid use fees for the self-consumed electricity, and therefore better incentivize PV investments.

ii. Considering the high investment cost of BESS, even with a more attractive self-consumption scheme, **subsidies should be designed in order to kick start investments in the long stagnant rooftop PV sector**. High BESS subsidies should be in place at the beginning, but stepwise reduction in subsidization should be envisaged, in order to avoid public deficits, such as those experienced with the PV feed-in tariffs during the period 2008 to 2013. Combined subsidies partially financing PV and BESS, such as the recently introduced "Rooftop PV" programme (govgr, 2023), could be an option as well, in order to achieve a better balance between prosumers' investment propensity and public expenses. Yet, gradual reduction of subsidies should be envisaged in the long-term, to avoid excessive public costs and unsustainable profiting of prosumers.

iii. At the national power sector level, **a balance among resource potential, economic efficiency and energy-related targets should be sought.** PV-dominated systems offer less costly solutions, but require much hydro generation to achieve energy-related targets, which is not guaranteed in Greece due to water resource uncertainty. WT-dominated systems, on the other hand, achieve energy-related targets sustainably, with minimum contribution from hydro, but are costly and require much storage capacity.

iv. Considering the above, explicit **attention should be paid to the capacity shares of the available RES technologies**. Taking into account the updated ambition for PV and WT (both on- and off-shore) deployment by 2030, VRES capacity mixes with 53-60% WT and 40-47% PV, should be sought. With such capacity mixes, optimal generation complementarity is achieved with PV and WT, requiring minimum storage capacity, and leading to the renewable integration, emissions reduction, and natural gas dependency targets of Greece in a cost-efficient manner and without relying extensively on hydro resources.

v. **The funding and tendering mechanisms should proactively envision the time-wise call for eligible technologies**, and their volume, aiming for efficient RES integration, leveraging technological cost reductions, and optimally exploiting the available funding. For balanced PV and WT mixes with the capacity shares mentioned in the previous bullet point, BESS needs in Greece would be minimum, and needed only after 2029, when RES integration exceeds 58-64%.

Higher preponderance of WT or PV should be followed by higher tendered volume of BESS, which might be needed as early as 2028, and might increase exponentially depending on the chosen PV-WT capacity mix.

vi. **The simplification of licensing procedures is of paramount importance to enable an, as much as possible, shortening of the dependency period on natural gas.** This would enable the necessary frontloaded RES investments in order to counterbalance the lignite phase-out plan by 2028 and limit the use of natural gas as a transition fuel. Towards this direction, the Go-to-areas measure should be transposed into national planning as much as possible.

Implications at the EU level

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i. Alongside net-metering, **self-consumption schemes featuring PV coupled with BESS, should be transposed into member states' national regulations**, enabling prosumers to (i) shift energy generation to times when it is most needed, aligning with the objectives outlined in the REPowerEU plan, (ii) relieve the grid from stressing bilateral energy flows, and (iii) empower them in becoming active energy agents. Financial support would be needed to incentivize consumers to make a shift to self-consumption, nevertheless, the public expenses would be for the benefit of both the prosumer, and the EU efforts for electricity storage systems' deployment.

ii. Despite PV being cheaper and faster to roll-out, WT investments at the EU level should be equally promoted towards a balanced representation of the two technologies. **The complementarity of technical constraints in each country should be taken into account, towards a unified EU electricity system with a balanced RES mix.** WT-dominated systems, despite being expensive, should be sought by countries with limited solar potential, and large availability of appropriate land for WT deployment. PV-dominated systems, despite being less cost-efficient, should be pursued by countries with low wind potential, spatial limitation due to protected area regulations, and large availability of appropriate built environment (i.e., roofs, facades, etc.) for the installation of PV. In any other case, balanced systems should be pursued, which achieve optimal economic efficiency in terms of energy yield per euro spent.

iii. **Former coal- and carbon-intensive areas should be put at the center of the energy transition efforts**, as they feature (i) a ready to use electricity network, (ii) available land for the deployment of RES, and (iii) technical workforce which can be reskilled for occupation in the renewable energy sector. In this respect, member states' tendering procedures should mandate prioritization of calls for projects in such areas, towards accelerated deployment of RES, as well as the just transition of these areas. Furthermore, financial support with increased rates should be given to households of coal- and carbon-intensive areas from the just transition fund, incentivizing citizens to invest in self-consumption schemes, actively contributing to the just transition of their region, as well as their country's national targets.

5.3.3. Contribution to the research community

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

- Five (5) scientific articles in peer-reviewed journals with impact factor (IF), as presented in **Table 5.1**,
- Seven (7) announcements in international peer-reviewed conferences,
- One (1) chapter in a scientific book,
- Seventeen (17) 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 Policy	Elsevier	9.0	2
Energy	Elsevier	9.0	1
Energy Reports	Elsevier	5.2	1
International Journal of Sustainable Energy	Taylor & Francis	3.1	1

*As accessed on the 28th of March 2024

In addition, the author has served as guest editor in the scientific book named "Positive Tipping Points Towards Sustainability" which was published under the Springer Climate series. 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 75 citations and an h-index of 4 according to the "Scopus"[19] database, and an overall of 116 citations and an h-index of 5, based on the "Google Scholar"[20] 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**.

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[19] https://www.scopus.com/authid/detail.uri?authorId=57202856568
[20] https://scholar.google.gr/citations?user=PUkqoU0AAAAJ&hl=en

5.4. Limitations and potential for further research

With the completion of this doctoral dissertation, a series of thoughts and suggestions for further research and improvement of the modelling framework, as well as its application context towards outrightly informed, adaptive and participatory energy modelling, have been formed:

Technical further research

- **AIM**
    1. The presented version of AIM has been developed in order to simulate the implementation of one policy or strategy at a time for a specific period of time. Specifically, AIM allows users to implement a next policy or strategy, only after the expiration of the implementation period of the previous one. However, in real-world situations, it is common for more than one policy or strategies to be implemented simultaneously. In this respect, AIM is planned to be updated to support concurrent policy and strategy implementations, in order to enable the assessment of policy and strategy packages, and identify the most effective components within the packages with respect to each targeted outcome (i.e., emissions reduction, consumer engagement in the energy transition, etc.).
    2. With the planned policy and strategy package implementation expansion of AIM described in the previous point, there is a challenge in estimating the combined output of the various implemented policies and strategies, when the original simulation model has provided only individual policy and strategy simulations. Ideally, the cumulative outcomes should be provided by the original simulation or optimization model. However, considering the big number of combinations that would be needed with increasing policy and strategy components within the package, this would lead to an infeasible number of simulations and a consequent non-tractable computational burden. To tackle this challenge, AIM is planned to be upgraded in order to provide an initial estimation of the combined output of the various policy and strategy combinations by applying one of the following rules: (i) the maximum, (ii) the minimum, or (iii) the average of each outcome as achieved by each policy or strategy individually. While these aggregation methods might not be as accurate as simulating combined policy and strategies in the original model, they are considered to be able to indicate a possible trend of the combined result of the policy and strategy packages under consideration, therefore guiding a reduced and meaningful set of simulations to be performed by the original simulation or optimization model.
    3. When linked with optimization models, there is a discrepancy between the logic of simulation. AIM applies a forward simulation logic, assuming that the outcome of each next

implemented policy or strategy is added to the outcome achieved by the previously implemented one, at the time of policy change. In this respect it performs parallel shifting of each next policy or strategy's outcome as shown in **Fig. 5.2**. Yet, if the optimization model implements a backward simulation logic, decisions made in an earlier timeframe are highly dependent on the choices made in later timeframes. In this case, the forward, stepwise exploratory policy and strategy assessment nature of AIM may provide less accurate results. To improve the accuracy of AIM, a model emulator, which provides estimates of optimization outputs, but much more quickly, is envisaged to be developed and integrated into AIM, in order to allow AIM to make better approximations when linked with models implementing a backward simulation logic. The STEEM emulator described in **section 2.2.2**, will be the basis for the development of the backward simulation emulator.

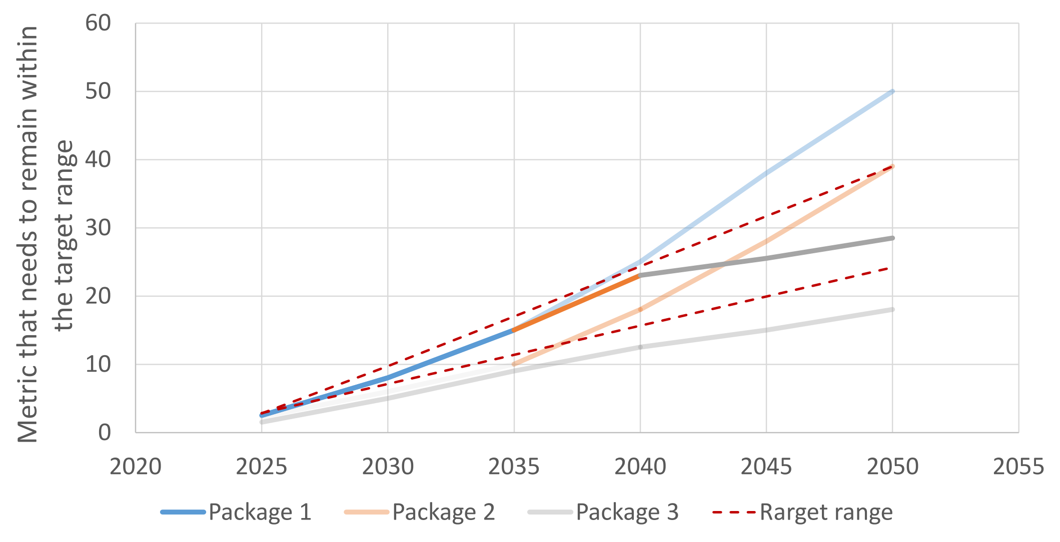

Fig. 5.2. Simulated stepwise policy and strategy implementation in the current version of AIM. The faded lines represent the individual packages simulation outputs. The bold line represents the outcome of the chosen pathway.

4. Finally, AIM currently runs in a web-based manner but only in the local hosting computer (i.e., locally and not online), and the simulation assumption are predetermined (e.g., cost assumptions and subsidy levels of technologies, targeted outputs, etc.). The interface of AIM is planned to be updated, in order to run on a server and be accessible to end users through their web browser. Furthermore, input fields for the assumptions will be made available, in order to enable users to modify their simulations according to their case study specifications.

- **STREEM**
    1. Currently STREEM needs the technical characteristics of the BESS (i.e., depth-of-discharge, duration, etc,.) as input in order to calculate the required BESS capacity for the assumed storage technology. As a further step in its development, STREEM is envisaged to be equipped with an optimization algorithm, which identifies the required storage capacity and the BESS technical specification for the application under study (e.g., use of storage equipment for arbitrage, RES maximization, etc.) or the scale under study (e.g., household, energy community, or national level). In this respect, STREEM would be able to provide recommendations on the most appropriate commercially available technology for the case under study.
    2. Since the horizon of analysis performed in **Chapters 2-4** is until 2030, which is the horizon of the Greek NECP, the performance of the BESS system was assumed to remain constant over the years. An upgrade in STREEM is planned in order to calculate the degradation of the storage capacity with increasing charge and discharge cycles and provide more accurate results in long-term simulations.
    3. Finally, STREEM will be enhanced to account for multiple scenarios of renewable generation profiles, providing pareto fronts of BESS capacity and BESS technical characteristics, which tackle the intermittency uncertainty of VRES.

Application further research

- **AIM**
    1. AIM so far has been linked with models targeting the electricity sector, either at the building level (**Chapter 2**), the national level considering only RES technologies (**Chapter 3**), or the national level considering the electricity market operation with the participation of all available technologies (**Chapter 4**). To showcase the potential of sector coupling, AIM is being linked with the JRC EU TIMES models, in order to explore deep decarbonization pathways for the national energy sector of Switzerland, considering a multitude of sectors, including electricity, transport, industry and buildings.
    2. Furthermore, AIM has been used in this dissertation to explore energy transition pathways from the supply side. Nevertheless, considering the efforts of the EU to improve energy efficiency, AIM is planned to be linked with a demand-side simulation model, in order to explore pathways for combined investments in RES and energy efficiency measures, which maximize the benefits of citizens, while reducing the cost for the transformation of the energy system.

- **STREEM**
    1. Considering the lignite phase-out plan of Greece and the significance of ensuring a just transition in former lignite-dependent regions of Greece, such as Megalopolis and Western Macedonia, STREEM will be applied at the municipal level, in order to explore the storage requirements to supply these regions with up to 100% locally generated RES electricity. The analysis will be made both in island mode and interconnected with the grid, highlighting the importance of battery-grid cooperation in the proper sizing of BESS.
    2. For its application at community level, STREEM will be enhanced to account for fairness and community benefits criteria. Specifically, optimization algorithms will be developed, which will produce strategies for fair energy distribution of locally produced electricity among the community members (i.e., based on community RES project shares, energy poverty risk, etc.). Furthermore, the algorithms will provide recommendations for the charging and discharging plan of the BESS, based on pricing signals from the electricity market, aiming to maximize the savings and potential profits of the energy community.
    3. Finally, STREEM is planned to be linked with a demand side management model, in order to highlight the effect of citizens' engagement in demand response mechanisms, on the BESS volume required in order to balance demand and renewable supply.

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Appendix 1. Brief presentation of models used in the dissertation

Models developed as part of this PhD dissertation

Adaptive polIcymaking Model (AIM): AIM provides real time visualizations of adaptive policy/strategy maps, showing alternative pathways leading to desired policy or strategy outcomes. The interactive policy maps facilitate interactive stakeholder consultation for the design of policies and strategies, which commit to short term objectives and define future contingency actions to prevent failure in case of unexpected contextual parameter changes. AIM evaluates the performance of selected policies/strategies over many combinations of a large number of contextual uncontrollable variables (scenarios), visualizes successful pathways towards a predefined target, and sets up a monitoring system for real world adaptations in case of unexpected contextual future evolutions. The novelty of AIM lies in: (i) using a simple clustering logic, thus it can be easily adapted for soft-linking with a wide variety of models, (ii) generating adaptive policies/strategies for different contexts, by changing the limits of the uncontrollable variables (scenarios), making it a useful tool for application at various scales and contexts, and (iii) facilitating interactive stakeholder consultation for the design of policy/strategy pathways, through real-time and easily interpretable visualizations. Especially with respect to the latter, AIM supports stepwise implementation of policies and strategies, which is a feature not found in scientific literature. This means that a policy or strategy may be chosen for implementation for a specific period of time by a stakeholder, and the results, as well as the plausible policy/strategy pathways forward, are updated almost instantly, making explicit the effect of a specific route followed on future policy and planning actions. With this feature, a tight participatory modelling process is feasible.

Scientific Publication: *Michas, S., Stavrakas, V., Papadelis, S., & Flamos, A. (2020). A transdisciplinary modeling framework for the participatory design of dynamic adaptive policy pathways. Energy Policy, 139, 111350.*

STorage RequirEmEnts and Dispatch Model (STREEM): STREEM simulates at a high temporal resolution the operation of electricity storage systems, aiming at improving the matching of renewable energy generation and electricity demand. It also identifies the storage capacity requirements of a region, towards maximization of renewable energy integration. It can support multiple storage technologies with simple parameterization of its input variables, and it can also simulate the simultaneous operation of short-term (e.g., batteries) and long-term storage (e.g., pumped hydro storage), applying priority rules. The novelty of STREEM is in identifying the correlation between storage volume increase and curtailment decrease. It does so by approximating the actual curve of storage/curtailment correlation, regardless of the storage technology or specifications simulated, while ensuring fast convergence. In fact, the algorithm converges in 6-7 iterations, avoiding storage capacity overshooting, by gradually decreasing the storage increase slope towards the targeted curtailment levels, following the storage/curtailment curve forced by the technical specifications of the modelled storage technology. The applicability of STREEM ranges from local energy communities to national or international scale.

Scientific Publication: *Michas, S., & Flamos, A. (2023). Are there preferable capacity combinations of renewables and storage? Exploratory quantifications along various technology deployment pathways. Energy Policy, 174, 113455.*

Other models used in the PhD dissertation

Business Strategy Assessment Model (BSAM): BSAM is an agent-based electricity wholesale market model which simulates the operations within a power pool central dispatch day-ahead electricity market. The model simulates electricity generators as entities who progressively learn to bid their capacities in a day-ahead competitive wholesale market, with ultimate goal the maximization of their profits. In parallel, a unit commitment and economic dispatch algorithm calculates the cost-optimal power mix to satisfy demand, the quantities injected by each generation unit, the market clearing price, as well as, derived outputs such as carbon emissions and profits of each generator. The model can support cost-benefit analysis of future policy and/or technology deployment scenarios.

Scientific Publication: *Kontochristopoulos, Y., Michas, S., Kleanthis, N., & Flamos, A. (2021). Investigating the market effects of increased RES penetration with BSAM: A wholesale electricity market simulator. Energy Reports, 7, 4905-4929.*

Agent-based Technology adOption Model (ATOM): ATOM simulates the dynamics of technology adoption among consumers. The model is supported by a complete framework for parameter estimation based on historical data, and for the quantification of the uncertainty that governs its ability to replicate reality. ATOM can be used to explore adoption and diffusion scenarios of sociotechnical innovations, based on historical data available and observations, in different EU member states. The three main ways that sociotechnical innovations, as e.g., energy communities, ecovillages, etc., tend to influence larger society are through (1) replication, (2) growth in scale, and (3) translation. ATOM explores all three ways, by addressing replication as the growth of the number of the innovations under study in the context of interest, growth in scale as the growth of their influence through partnerships, programmes and incentives they provide to citizens, and translation as the adoption of respective policies and practices by mainstream society and institutions.

Scientific Publication: *Stavrakas, V., Papadelis, S., & Flamos, A. (2019). An agent-based model to simulate technology adoption quantifying behavioural uncertainty of consumers. Applied Energy, 255, 113795.*

Appendix 2. Contribution of the PhD candidate to academic material

Scientific articles published in peer-reviewed journals

1. **Michas, S.**, & Flamos, A. (2024), Least-cost or sustainable? Exploring power sector transition pathways. *Energy*, Special Issue on "Energy system modelling in support of the European energy transition: Pathways towards 2030 and the vision of climate neutrality by 2050", 131086. doi: 10.1016/j.energy.2024.131086
2. **Michas, S.**, & Flamos, A. (2023). Are there preferable capacity combinations of renewables and storage? Exploratory quantifications along various technology deployment pathways. *Energy Policy*, 174, 113455. doi: 10.1016/j.enpol.2023.113455
3. Kontochristopoulos, Y., **Michas, S.**, Kleanthis, N., & Flamos, A. (2021). Investigating the market effects of increased RES penetration with BSAM: A wholesale electricity market simulator. *Energy Reports*, 7, 4905-4929. doi: 10.1016/j.egyr.2021.07.052
4. **Michas, S.**, Stavrakas, V., Papadelis, S., & Flamos, A. (2020). A transdisciplinary modeling framework for the participatory design of dynamic adaptive policy pathways. *Energy Policy*, 139, 111350. doi: 10.1016/j.enpol.2020.111350
5. **Michas, S.**, Stavrakas, V., Spyridaki, N. A., & Flamos, A. (2019). Identifying Research Priorities for the further development and deployment of Solar Photovoltaics. *International Journal of Sustainable Energy*, 38(3), 276-296. doi: 10.1080/14786451.2018.1495207

Chapters published in scientific books

1. Frankowski, J., Sokołowski, J., **Michas, S.**, Mazurkiewicz, J., Kleanthis, N. & Antosiewicz, M. (2024). Assessing macroeconomic effects of a carbon tax as a tipping intervention in economies undergoing coal phase-out: the cases of Poland and Greece. Chapter in the book "Positive Tipping Points Towards Sustainability: Understanding the Conditions and Strategies for Fast Decarbonization in Regions". Springer Climate. doi: 10.1007/978-3-031-50762-5

Announcements in conferences

1. **Michas, S.** & Flamos, A. (2023). Dodging the energy crisis? Renewable deployment pathways to 2030. *ECEMP 2023: Net Zero, intermediate targets, and sectoral decarbonization facing geopolitical and macroeconomic challenges*, 5-6 October, Online
2. **Michas, S.** & Flamos, A. (2023). Locked-in or open-sighted? Exploring energy transition pathways resilient to external disruptions. *18th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES)*, 24-29 September, Dubrovnik, Croatia

3. **Michas, S.** & Flamos, A. (2023). Exploratory assessments of renewable energy sources and storage mixes. 5th International Exhibition "Verde.tec" on Environmental Technologies, 17-19 March 2023, Athens, Greece
4. Kleanthis, N., **Michas, S.**, Flamos, A. (2020). Investigating electricity generation by analysing influential factors in the Greek electricity system in 2030, *15th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES),* 1-5 September, Online
5. **Michas, S.**, Kleanthis, N., Flamos, A. (2020). How much storage capacity is needed for a sustainable and cost-efficient nearly-zero emissions electricity system? The case of Greece. *4th SEE Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES).* 28 June – 2 July, Online
6. Stavrakas, V., **Michas, S.**, Papadelis, S., & Flamos, A. (2018). Achieving a low-carbon power system through empowering consumers to produce and store clean energy at the local level: The case of Greece. *7th International Symposium & 29th National Conference on Operational Research (HELORS) Conference*, 14-16 June, Chania, Greece
7. Papadopoulou, A., Vasileiou, G., **Michas, S.**, Flamos A. (2017). CSP business models and value chain mapping: Insights from the CSP industry. *12th International Scientific Conference on Energy and Climate Change*, 10 October, Athens, Greece

Technical reports & other studies

1. Cots, F., Fosse, J., Tàbara, J.D. & **Michas, S.** (2023). Policy Brief on Tipping investments towards clean technologies. Enabling Positive Tipping Points towards clean-energy transitions in Coal and Carbon Intensive Regions (TIPPING+) project.
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3. Cots, F., Fosse, J., Tàbara, J.D. & **Michas, S.** (2023). Policy Brief on Cultural, identity, behavioural and demographic issues in public engagement and energy community transformations. Enabling Positive Tipping Points towards clean-energy transitions in Coal and Carbon Intensive Regions (TIPPING+) project.
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5. Cots, F., Fosse, J., Tàbara, J.D. & **Michas, S.** (2023). Policy Brief on Justice as trigger and outcome of positive low-carbon tipping points. Enabling Positive Tipping Points towards clean-energy transitions in Coal and Carbon Intensive Regions (TIPPING+) project.
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