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A multicriteria modelling framework for evaluating clean energy transitions: the case of Greece as electricity exporter

Diamantis Koutsandreas [a,b,*], Behzad Zamanipour [a], Ilkka Keppo [a]

[a] Department of Energy and Mechanical Engineering, Aalto University, Otakaari 4, 02150, Espoo, Finland
[b] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany

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ABSTRACT

The development of clean power generation interacts with various policy objectives pertaining to the energy system, the general economy, people's health, critical resources, and biodiversity, which can be synergistic or conflicting. In this respect, assessing these synergies and trade-offs together within a multicriteria framework has become critical, yet remains inadequately addressed in the literature. This paper contributes to the literature by examining a broad spectrum of trade-offs associated with clean energy development in a Mediterranean country, namely Greece, along with the associated economic impacts of it becoming a clean electricity supplier to its neighbouring countries. In this context, the study further contributes to the literature by developing and linking a technology-rich optimization model representing Greece's energy and resource systems with a Recursive-Dynamic Computable General Equilibrium model for the Greek economy. These models are coupled with a multicriteria framework, employing the hybrid AHP-TOPSIS method along with proxy indicators reflecting impacts on costs, critical resources, energy security, people's health, biodiversity, and the economy. The results revealed that policies involving electricity exports stand out as "no regret" options for most decision-maker types, potentially expanding the Greek economy by an average of 0.12 %–0.26 % annually over the 2025–2050 period, depending on electricity price evolution, compared to a baseline scenario in which the country remains a net electricity importer throughout the entire period.

Nomenclature (decision variables in bold)

Linear Optimization Model		$\mathbf{E_{T,y}}$	electricity production (GWh)
Indices and Sets		$\mathbf{C^{new}_{T,y}}$	capacity investment in the system (GW)
y	set of years	$\boldsymbol{\alpha_{T,l,y}}$	activity rate of technology (PJ)
T	*set of* technologies	SWI_y	Shannon–Wiener Index (SWI) for the power system in year *y* *(unit free)*
l	time slices into which the year is divided (day and night for each of twelve months)	$p_{T,y}$	ratio of technologies in the power mix
Parameters		*General Equilibrium Model*	

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Abbreviations: BECCS, bioenergy with carbon capture and storage; RD, Recursive-Dynamic; CGE, Computable General Equilibrium; TIMES, The Integrated Markal Efom System; TOPSIS, Technique for Order of Preference by Similarity to Ideal Solution; OSeMOSYS, Open Source energy MOdelling SYStem; CSP, Concentrated Solar Power; PV, photovoltaic; REF, Reference Energy System; GDP, Gross Domestic Product; MANAGE, Mitigation, Adaptation and New Technologies Applied General Equilibrium; GTAP, Global Trade Analysis Project; SAM, Social Accounting Matrix; CES, constant-elasticity-of-substitution; BAU, baseline scenario; SSP2, second Shared Socio-economic Pathway; NC1.5, New Carriers for 1.5 °C; EURef, EU Reference scenario; VIKOR, VIsekriterijumska optimizcija i KOmpromisno Resenje (in Serbian); SWI, Shannon–Wiener Index; 1,4-DCB-Eq, 1,4 kilo tons-Dichlorobenzene equivalent; Tons N-Eq, tones of nitrogen equivalents; EURef price, EU Reference scenario price; ETS, Emissions Trading System; AHP, Analytic Hierarchy Process; GAMS, General Algebraic Modeling System.

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* Corresponding author. Department of Energy and Mechanical Engineering, Aalto University, Otakaari 4, 02150, Espoo, Finland.
E-mail address: diamantis.koutsandreas@aalto.fi (D. Koutsandreas).

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(*continued*)

y_o	base year of the modelling horizon	*Indices and Sets*	
Y	final year of the modelling horizon	y	set of years
r	discount rate	d	final demand accounts
E_y^{lim}	annual CO_2 emission limit in year y *(Mton)*	F	set of production factors
$\theta_{l,y}$	fraction of the year represented by time slice l in year y	Parameters	
$\varepsilon_{T,y}$	CO_2 emissions ratio of technologies in year y *(Mton/PJ)*	δ_f	share parameter of production factors in the production function
LA_T^{cap}	land area impact factor of technology for operating one unit of installed technology capacity (km^2/GW)	ρ	substitution parameter between production factors
LA_T^{fuel}	land area impact factor of input fuel per unit of produced electricity (km^2/GWh)	σ	elasticity of substitution between production factors
CM_T^{cap}	critical material impact factor for producing one unit of technology capacity (tn/GW)	A	productivity parameter
HT_T^{cap}	human toxicity impact factor for producing one unit of technology capacity (Kilo tons 1,4-DCB-Eq/GW)	Variables	
ME_T^{cap}	marine eutrophication impact factor for producing one unit of technology capacity (Tons N-Eq/GW)	$\boldsymbol{q_f}$	input of production factor f in the production function (Million \$)
Variables		$\boldsymbol{KSE}$	Capital-skilled labour-energy composite input in production (Million \$)
$I_{T,y}$	Annual investment costs (Million \$)	$\boldsymbol{KS}$	Capital-skilled labour composite input in production (Million \$)
$VC_{T,y}$	Annual variable operating costs (Million \$)	$\boldsymbol{LAB1}$	Unskilled labour bundle in production (Million \$)
$FC_{T,y}$	Annual fixed operating costs (Million \$)	$\boldsymbol{LAB2}$	Skilled labour bundle in production (Million \$)
$LA_{T,y}$	Annual total land area impact for power generation (km^2)	$\boldsymbol{LAND}$	Land input in production (Million \$)
$CM_{T,y}$	annual critical materials requirements for power generation (tn)	$\boldsymbol{x_{d,y}}$	total real expenditures on goods and services by the final demand account d in year y (Million \$)
$HT_{T,y}$	annual human toxicity impact of power generation (Kilo tons 1,4-DCB-Eq)	$\boldsymbol{RB_y}$	real change in inventories within the economy in year y (Million \$)
$ME_{T,y}$	annual marine eutrophication impact of power generation (Tons N-Eq)	$\boldsymbol{RX_y}$	real exports in year y (Million \$)
$\boldsymbol{\alpha_{T,l,y}}$	activity rate of technologies during time slice l in year y *(PJ)*	$\boldsymbol{RM_y}$	real imports in year y (Million \$)
$\boldsymbol{C_{T,y}^{tot}}$	installed technology capacity in the system (GW)	$\boldsymbol{VA_y}$	the value-added component of production in year y (Million \$)
		$\boldsymbol{RGDP_y}$	the real GDP in year y (Million \$)

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1. Introduction

Decarbonizing energy systems and the economy requires the extensive development of clean energy technologies—i.e., those operating without emitting pollutants into the environment. However, these technologies require high upfront capital investments, which may increase energy costs, and are closely associated with multiple implications across resource systems. First, the land required for installing renewable generators can lead to increased land use competition, particularly due to the land intensity of wind turbines (as shown by Palmer-Wilson et al. [1] for Canada). Furthermore, depending on their location, renewable technologies may also harm local biodiversity, as discussed by Gasparatos et al. [2]. The transition to clean energy also presents several challenges, such as technological constraints on the maximum deployment or annual growth of certain clean power technologies (e.g., geothermal; as noted by Hu et al. [3]) and dependence on critical materials (as discussed in Zepf et al. [4]), which can create planning bottlenecks, and a lack of societal acceptance for others (e.g., nuclear power), which may result in increased social resistance. What's more, the weather-dependent nature of renewable technologies can lead to curtailments in power generation, thereby stressing the importance of integrating flexibility options into the system, such as storage technologies and reliance on a diverse technology mix (a detailed review of flexibility options is provided by Engeland et al. [5]).

These challenges call for a multidimensional evaluation of clean energy transitions that factor in all these trade-off dynamics. This means going beyond an efficiency-focused approach that solely looks at energy costs and prices, weighing aspects such as resource depletion, biodiversity loss, health impacts (e.g., the direct or indirect effects of wind turbines and solar power plants), energy security, and broader economic ramifications (i.e., spill-over effects on the overall economy, such as on gross domestic product and household income, from changes in the energy system). Such trade-offs associated with clean electricity development have been extensively examined in the existing literature, sometimes within the context of multicriteria frameworks (see Section 2 for an analytical description of these studies). However, there have been critical aspects of clean energy transitions overlooked by these studies, such as the interactions between the energy sector and the broader economy and the biodiversity implications, which can affect decision-making by introducing strong trade-offs. Specifically, considering all these aspects simultaneously within a multicriteria framework enables the examination of the whole results space subject to the entailed conditions and assumptions (please refer to Section 2 for a nuanced description of the research gap). This decision-making type for energy planning could particularly fit the problems of today's world (e.g., climate change), by considering aspects beyond the utilitarian perspective (i.e., optimal resource allocation), like intergenerational and interspecies justice.

Furthermore, electricity trade emerges as a crucial factor in providing system flexibility alongside existing options (e.g., electricity storage). As demonstrated by Halbrügge et al. [6] for the case of Germany, cross-border electricity trade can facilitate the transition to high-renewable systems. Countries can export surplus electricity to other nations during favourable weather conditions and import electricity when domestic power generation falls short of meeting demand. In such a scenario, households that produce energy can deliver their excess electricity to the grid, which can then be exported to other countries, harnessing economic gains, as discussed by Zakeri et al. [7]. However, exporting electricity while simultaneously decarbonizing and electrifying the economy is inextricably tied to the extensive development of clean power generation. While this development may be beneficial at the local level, it can result in supply disruptions and negative global consequences, particularly for countries that are major producers of clean power technologies. It is, therefore, crucial to holistically assess the trade-offs related to clean electricity production within a multicriteria framework while factoring in the potential for exporting clean electricity—an aspect that has been largely overlooked in the existing literature.

Based on the identified research gap (please refer to Section 2 for a critical discussion on this), this paper contributes to the literature by introducing a novel multicriteria modelling approach for assessing clean energy transitions. Although using well-established methods, our framework's innovation lies in the simultaneous incorporation of a broad list of potentially critical aspects to clean energy transitions, such as critical resource use, biodiversity impacts, and macroeconomic ramifications. Despite their potential importance to decision-makers, these aspects haven't been considered simultaneously along with conventional criteria for energy planning (e.g., cost, emissions) in the literature. These dimensions are evaluated together within a multicriteria framework alongside the system cost, energy security, and human health impact indicators, based on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

The study further contributes to the literature by developing an integrated modelling framework for Greece, which consists of: (i) a technology-rich linear optimization model that represents Greece's power system along with its key interconnections to resource systems, climate, human health, and biodiversity; (ii) a macroeconomic Recursive-Dynamic (RD) Computable General Equilibrium (CGE) model that simulates the functioning of the Greek economy and the behaviour of its agents, while accounting for substitution possibilities of energy. While the focus of the first model is to identify the cost-optimal technological pathway that meets energy demand and climate targets, the second assesses the resulting economic transformations of these changes (e.g., changes in the mix of production factors). This is the first time such a modelling suite has been developed for Greece, as previous studies have mostly focused on specific sectors, such as the power sector (see for example Koutsandreas et al. [8]), overlooking the interactions across different systems (e.g., between the power sector and resource systems or the economy).

The study also contributes to the research legacy by expanding the knowledge space of the potential implications of clean energy transition pathways and the economics of export possibilities for a Mediterranean country. It does so by applying the developed multicriteria modelling framework to Greece, a country with substantial potential for becoming clean electricity exporter (see for example Fyrippis et al. [9]). This is supported by its geographical position, acting as a bridge between Europe, North Africa and the Middle East, and its aspiration to become a clean electricity provider and corridor to Europe. This aspiration is reflected through relevant initiatives that have been underway, such as the Euro Asia Interconnector Project—aiming to interconnect the power systems of Greece, Cyprus, and Israel with the European transmission network [10].

As exporting electricity depends on price dynamics, we first seek to identify the price threshold that makes exporting electricity profitable, surpassing electricity generation costs. In turn, we apply a sensitivity analysis on optimal levels of clean electricity generation and exports across electricity prices. For the spectrum of prices that make electricity exports economically meaningful, we apply the proposed evaluation framework to investigate the following question: *Do the economic and energy security benefits of exporting clean electricity compensate for the potential implications on critical resources, human health, and biodiversity?* We also apply a sensitivity analysis with respect to the aspects of the analysis that decision-makers value the most, considering various decision-maker archetypes. This approach allows us to explore result conditionality with respect to policy priorities, rather than identify a single 'optimal policy' across all decision-maker types.

The remainder of this paper is organized as follows. Section 2 reviews the relevant body of literature to uncover the research gap our paper aims to fill, while Section 3 describes the proposed methodological framework for assessing clean energy transitions and its application to the case of Greece. Section 4 presents the key results of the analysis and Section 5 concludes the paper.

2. Literature overview

The trade-offs associated with the development of clean electricity have been extensively examined in the current body of literature. Table 1 presents a taxonomy of indicative studies examining the trade-off dynamics in renewable energy development. Several studies, such as Kati et al. [11] and Powell and Lenton [12], examined the interactions between high-renewable transition scenarios and interlinked perspectives, such as land-use and biodiversity, using scenario analysis. By doing so, these studies either identified high potential for renewable power generation (e.g., zones capable of supporting wind power generation 1.5 times Greece's national goal [11]) or significant impacts on biodiversity [12]. Taking a broader view, Huijbregts et al. [13] developed a life-cycle impact assessment framework that accounted for further unwanted implications of these scenarios, such as impacts on human health, ecosystems, and resource availability. Building on this, Wang et al. [14] applied this framework to assess critical material cycles in the metal-energy nexus of China's 2050 renewable transition.

However, neither scenario analysis nor the life-cycle assessment captures the complex dynamics of the power system while simultaneously accounting for the implications of technology deployment. This can be addressed through energy system planning models that weigh the detailed technological interactions at a system level. While many studies have assessed the implications of clean energy transitions using energy system modelling frameworks, they have usually focused narrowly on power sector technology dynamics and associated costs (e.g., Ref. [15]), overlooking interlinked systems such as resource systems. A study that went beyond this approach is Tröndle et al. [16], who used the Calliope modelling framework to assess the trade-offs within the energy-land use-society nexus of a fully renewable electricity system in Europe across various system scales.

In the same spirit, Grimsrud et al. [17] performed a spatial allocation of wind power plants aimed at minimizing biodiversity impacts, integrating environmental factors such as wilderness and biodiversity into the energy system model IFE-TIMES[1]-Norway. Furthermore, while often overlooked, there are significant interactions between the energy transition and the broader economy. Addressing this gap, Gjorgiev et al. [18] evaluated the macroeconomic implications of clean electricity development using the high-resolution modelling platform Nexus-e. Similarly, Sasse et al. [19] evaluated the inequality implications of a low-carbon electricity system in Europe. The results of the above studies revealed that considering factors beyond economic efficiency can make cost-based 'optimal' technology pathways 'undesirable' for decision makers. However, these studies examined the trade-offs between renewable power generation and other interconnected perspectives in isolation, without considering them simultaneously within a multicriteria framework. A body of literature took this step further by applying a multicriteria approach to evaluate competing energy strategies, aiming to uncover robust mitigation pathways that perform well across a range of criteria. In this endeavour, energy system models have been typically coupled with multicriteria decision analysis frameworks to evaluate competing strategies' performance across multiple

[1] The Integrated Markal Efom System.

Table 1
Taxonomy of indicative literature studies examining the trade-off dynamics in renewable energy development.

Study	Objective	Nexus Focus	Method/Model	Region
Kati et al. [11]	Identifying appropriate zones for installing wind turbines	Biodiversity, land use	Spatially explicit prioritization zoning system, scenario analysis	Greece
Powell and Lenton [12]	Examining trade-offs between mitigation and biodiversity	Environment, biodiversity	Scenario analysis	Global
Stoy et al. [23]	Evaluating the impacts of bioenergy with carbon capture and storage (BECCS)	Food, water, energy, biodiversity, society	Qualitative framework, scenario analysis	Upper Missouri River Basin, USA
Huijbregts et al. [13]	Introducing a framework for life cycle impact assessment	Human health, ecosystems, and resources	Life cycle impact assessment framework	Generic
Wang et al. [14]	Assessing critical material constraints for renewable development	Critical materials, energy, environment	Material-cycle framework	China
Grimsrud et al. [17]	Planning spatial allocation of wind power plants	Biodiversity, energy	System model planning (IFE-TIMES-Norway model)	Norway
Tröndle et al. [16]	Quantifying trade-offs between geographic scale, cost, infrastructure, land use, and social implications of fully renewable electricity	Energy, land use, society	System model planning (Calliope)	Europe
Lerede et al. [20]	Evaluating electrification speed in road transport sector	Environment, economy, energy	Stochastic multicriteria acceptability analysis coupled with system model planning (EUROfusion TIMES energy system model)	Europe
Parkinson et al. [22]	Evaluating transformation strategies for the energy system	Economy, environment, water, energy	interactive multicriteria model analysis, using the Saudi Arabia Electricity-Water Planning model (SEWP)	Saudi Arabia
Volkart et al. [21]	Assessing transition pathways for the energy system	Resources, ecosystems, climate, economy, society, energy	Multicriteria decision analysis coupled with system model planning (Swiss MARKAL model)	Switzerland
Gjorgiev et al. [18]	Evaluating interactions between the electricity system and the broader economy	Electricity system, macroeconomy	Integrated Energy-Economic Modeling, using Nexus-e: platform combining one top-down macroeconomic module with four high-resolution bottom-up power system modules	Switzerland
Sasse et al. [19]	Evaluation of decarbonization strategies for the power sector	Land use, climate, economy, society, energy	System modelling planning (EXPANSE, an optimization power system model)	Europe

dimensions.

Indicatively, Lerede et al. [20] applied a stochastic multicriteria acceptability analysis to evaluate various road transport decarbonization pathways of increasing electrification rates for Europe, integrating the EUROfusion TIMES Model with an additive value function and economic, environmental, and energy criteria, while considering various decision-maker types. Their results indicated that high electrification strategies for the road transport sector generally outperform their counterparts. Similarly, Volkart et al. [21] coupled the Swiss MARKAL model and a weighted sum method to evaluate transition pathways for Switzerland's energy system against environmental, economic, social, and energy security criteria. Their findings indicated that stringent climate policies can yield co-benefits such as reduced fossil fuel use, resource dependency, severe accidents, and societal conflict. In a similar vein, Parkinson et al. [22] developed a multicriteria modelling framework to assess transformation pathways in the water-energy nexus of Saudi Arabia, revealing trade-offs between water withdrawal, costs, and emissions. Despite providing valuable insights, these studies hinged on a rather limited set of dimensions per case, excluding aspects that may introduce strong trade-offs, such as broader economic consequences or biodiversity impacts.

To sum up, the existing body of literature: (i) hasn't taken a systems perspective, (ii) has examined trade-offs in isolation rather than within a multicriteria framework simultaneously, or, (iii) when applying such a framework, has used a limited number of criteria instead of a broad range of implications from clean energy transitions. Consequently, conclusions may reflect only a narrow view of result conditionality, thereby providing skewed perspectives to decision-makers. This can explain the discrepancies observed across the outcomes of these studies: while some identified significant trade-offs between the level of stringency and evaluated dimensions, others identified significant synergies. Moreover, the potential for exporting renewable electricity is usually overlooked in high renewable scenarios although it may deliver significant economic benefits and provide a valuable option for system flexibility.

This gap underscores the need for a paradigm shift towards more holistic energy planning—one that incorporates a broader, possibly conflicting, set of indicators to better reflect the underlying trade-offs among competing system configurations. This analysis aims to take this step further by considering a wide range of interlinked dimensions to renewable power generation within a multicriteria framework, while factoring in the possibility for electricity exports.

3. Methodological framework

3.1. Overview

The methodological framework adopted in this study involves two models with distinct focuses and rationales, coupled with a decision analysis framework. These components and their key interactions are illustrated in Fig. 1. First, the bottom-up cost-optimization model identifies the cost-optimal system configuration for the power sector across examined scenarios, while also calculating associated system costs and implications of power system development on resource systems, the environment, human health, and biodiversity. The results of this model are then passed on to a macroeconomic RD CGE model encompassing the modus operandi of the general economy and the behaviour of its agents (see Subsection 3.2.2 for more information), with it evaluating the impacts on the wider economy arising from changes in the power system. The results from these models feed into a multicriteria decision analysis framework, composed of multiple criteria and the hybrid AHP–TOPSIS method. Criteria are quantified based on model outputs, after which TOPSIS evaluates the overall performance of strategies using weights derived from the AHP method.

3.2. Modelling framework

3.2.1. Bottom-up technological modelling

Power system development interacts with, and affects, resource systems, the environment, society, and the wider economy. As such, emphasis has been placed on factoring these interactions when evaluating power system development. Here, we extend a supply cost optimization model for the power sector of Greece, built based on the Open Source energy MOdelling SYStem (OSeMOSYS) model generator (OSe-

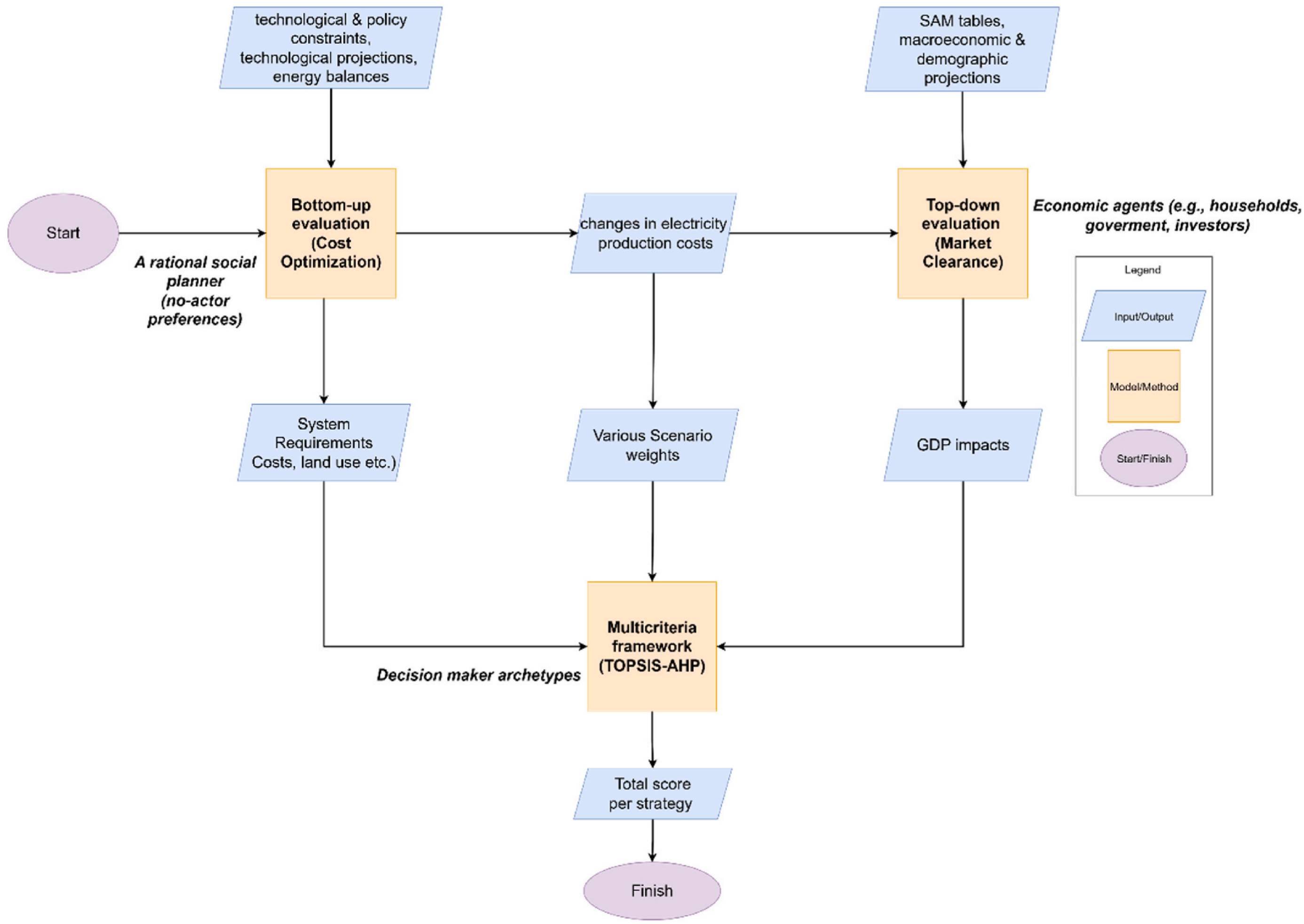

Fig. 1. Flowchart of the methodological approach adopted in this study (SAM: Social Accounting Matrix).

MOSYS-Greece; [24]). This model was analytically described in Koutsandreas et al. [8], while Koutsandreas & Keppo [25] described its extension to Greece's transport sector, and Koutsandreas [26] described the incorporation of land requirements from power generation in it. The model applies a deterministic, perfect-foresight linear optimization, whereby decisions are made by one implied social planner with a cost minimization rationale (i.e., no actor heterogeneity or preferences); while future targets and technological trends are already known from the beginning of the modelling horizon. The model identifies the least-cost energy system configuration on an annual basis in terms of technology capacity development and utilization, subject to established restrictions and targets. For each strategy analysed, a single set of solutions corresponds to a single set of input data. This can be mathematically described by Equation (1).

$$Min \sum_{y=y_o}^{Y} \frac{\sum_T \left(I_{T,y} + FC_{T,y} + VC_{T,y}\right)}{(1+r)^{y-y_o}} \tag{1}$$

where y is a year within the modelling horizon, spanning from the base year y_o (2019) to the final year Y (2050), I denotes the investment costs for technology T in year y, $FC_{T,y}$ *and* $VC_{T,y}$ represent the fixed and variable operational cost, respectively, for technology T in year y, and r is the discount rate. Moreover, the model calculates the CO_2 emissions from power generation, as shown in Equation (2).

$$\left(\sum_T \sum_l \varepsilon_{T,y} \cdot \alpha_{T,l,y} \cdot \theta_{l,y}\right) \leq E_y^{lim} \tag{2}$$

where T indexes the technologies in the model, l indexes the time slices into which the year is divided (24 time slices: two time frames—day and night—for each of twelve months), $\varepsilon_{T,y}$ represents the CO_2 emissions ratio of technology T for year y, $\alpha_{T,l,y}$ represents the activity rate of technology T during time slice l for year y, $\theta_{l,y}$ represents the fraction of the year represented by time slice l in year y, and e_y^{lim} is the limit on allowable CO_2 emissions in year y. Regarding variable renewable generation, we define a capacity factor profile across the considered time slices using data from online simulators [27], while we extract the electricity demand profile from the ENTSO-E database.

To define generation profiles for solar and wind technologies, we used data from six regions across the Greek territory with distinct climatological conditions: Central Greece, Peloponnese, Crete, the Ionian Islands, Eastern Macedonia & Thrace, and the Southern Aegean Sea. For offshore wind, we considered three maritime areas: Aegean Sea, the Ionian Sea, and the Sea of Crete. Within each region, we extracted three representative points, which spread across the area. In turn, we aggregated these regional profiles (using a simple average) into one representative profile per technology. To ensure system reliability, we set a reserve margin of 1 % in the model, meaning that the system must maintain available capacity at all times sufficient to produce at least 1 % more electricity than the annual peak demand. Indeed, this reserve margin is lower than what is typically assumed in power system modelling. This choice reflects the analysis's emphasis on electricity trade, not only from an economic point of view, but also as a flexibility option—that is, when renewable power generation doesn't suffice to meet demand (even with the 1 % reserve margin), electricity can be imported from other countries to fill the gap.

To account for power system requirements and implications across associated dimensions, we expand the model to include technology-specific coefficients. These factors allow for quantifying the implications of each technology on selected proxy indicators, which serve as a representation of the examined dimensions within the model. We determine the value of these coefficients using the data reported in relevant studies: Palmer-Wilson et al. [1] for land requirements from power generation and Arvesen et al. [28] for the remaining indicators. These data, along with the equations added in the model, are reported in Appendix A. Furthermore, the extended version of OSeMOSYS-Greece is available on GitHub: https://github.com/daymontas1/GRIMS.git.

For energy system requirements, we consider critical resources: land and critical materials. Land requirements are calculated with the *footprint and spacing* approach, as it considers both the area occupied by energy technologies, including the required spacing between and around them for the sake of efficiency [1]. The latter is particularly important for the expansion of clean electricity capacity. We consider as

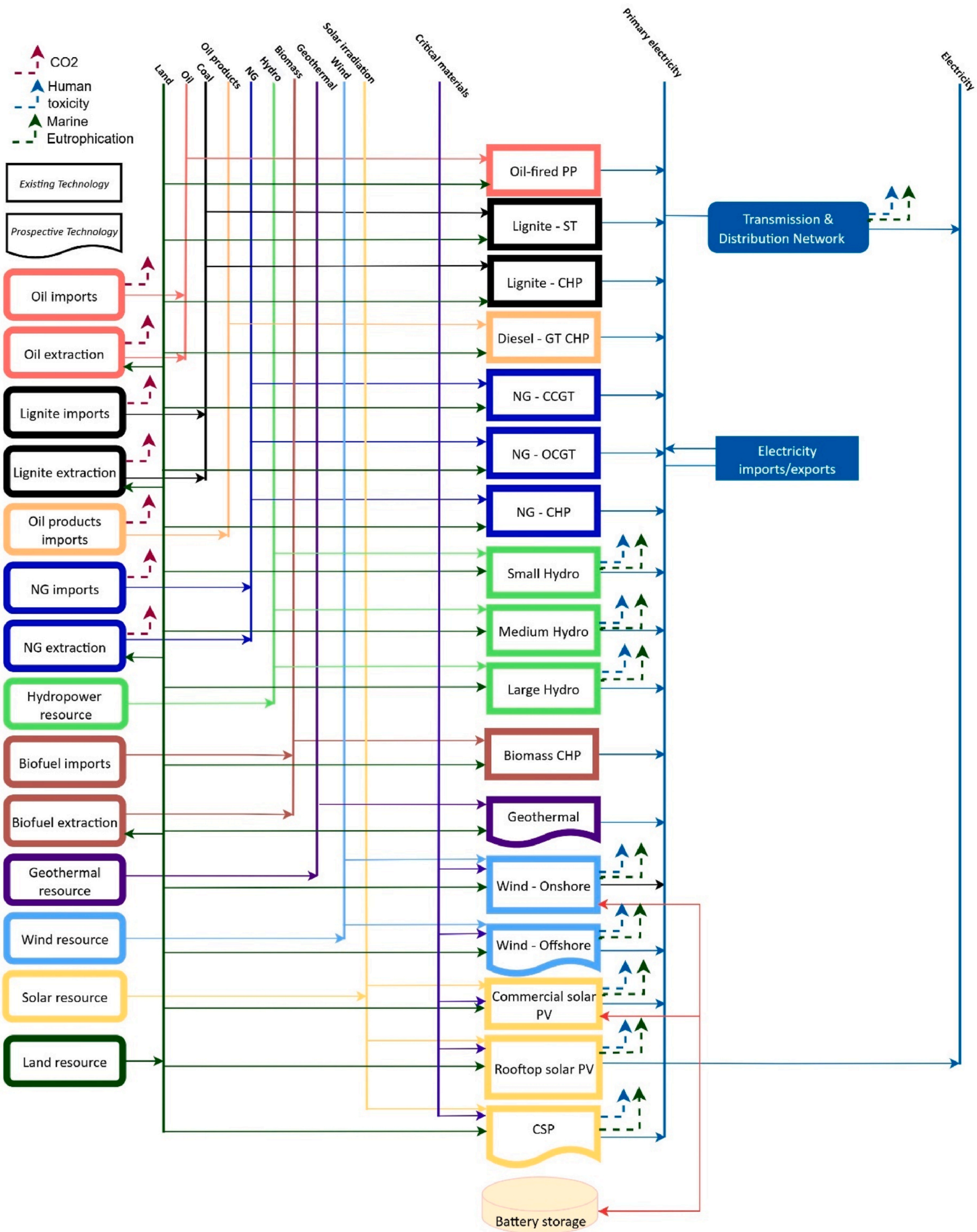

Fig. 2. Reference Energy System (REF) of the power sector of Greece describing the range and flow of procedures from collecting primary energy sources (left side) to converting them into useful energy and transferring it into final demand sectors (right side).

critical materials: the dysprosium (Dy) and neodymium (Nd) for wind turbines; the gallium (Ga), indium (In), and tellurium (Te) for solar photovoltaics; and the cobalt (Co), Dy, lanthanum (La), lithium (Li), Nd. On the other hand, energy system implications account for: human health, proxied by human toxicity; biodiversity, proxied by marine eutrophication; and energy security, proxied by the Shannon–Wiener Index (SWI).

For critical materials demand, human toxicity, and marine eutrophication, technology-specific coefficients are defined per unit of capacity built for each power generation technology. Consequently, annual implications are calculated with respect to the new capacity additions in each year. Impacts from the operation phase of technologies are not considered, as they are negligible compared to those associated with their construction phase. As far as technology replacement cycles are concerned, they are explicitly considered in our analysis. Each technology is assigned a technical lifetime, after which it is decommissioned. At that point, the model reinvests in either the same or an alternative power technology based on a cost-optimization rationale and specified constraints, thereby triggering new implications across evaluated dimensions.

Both human toxicity and marine eutrophication mainly occur during the construction phase of clean technologies [28], whereas the set of power technologies that affect biodiversity and human health includes: grid, hydro, Concentrated Solar Power (CSP), solar photovoltaic (PV), storage, and wind turbines. SWI is used to quantify the diversity of a community and, in this context, indicates the diversity of system technology configuration. High SWI values reflect a diversified system configuration and subsequently enhanced system security. It should be mentioned that our analysis focuses on elements most relevant to Greece—for instance, we don't consider the water dimension in the evaluation of examined scenarios, as this is not a critical issue for Greece, where abundant water resources are available.

Fig. 2 illustrates the Reference Energy System (REF) sketched in the model. This figure depicts the entire range and flow of procedures from collecting primary energy sources (left side) to converting them into useful electricity and transferring it into final demand sectors (right side). Lines represent the flows of energy carriers, critical materials, and blocks represent technologies that receive the former as input or produce them. Dotted arrows reflect the potential implications of technologies on climate, human health, and ecosystems. The technologies portfolio in the model includes both existing (squares) and future technologies (twisted squares), which may be inserted in the future based on the intentions of the Greek government.

With the above-described calibration, we allow the model to roughly estimate not only technology portfolios and associated costs (capital and operational), but also the broader implications of power system development on critical resources, biodiversity, and human health.

3.2.2. Model linkage

We establish a link between the optimization model and a macroeconomic model to evaluate the general economy's response to amendments in the power system. This linkage mechanism involves a sequence: the optimization model calculates differences in energy costs from a baseline in a counterfactual scenario, which are then translated into economic shocks to the general economy for the macroeconomic model (i.e., "one-way" linkage). We don't exchange data in the opposite direction—i.e., what would be considered "two-way" linkage—due to the structure of this exercise. In such an exchange, economics models would typically inform engineering models regarding the demand response of households to changes in energy costs. Electricity export scenarios, however, in our framework result in lower energy costs as they assume electricity prices higher than power generation costs, in turn implying an increased final energy demand that must be met by the system. This higher demand though would restrict the capability of the system to export electricity, which is at the core of our analysis (see Section 3.3.), and is thus avoided.

Initially, both models are calibrated to common macroeconomic assumptions to describe the same socioeconomic trajectory (see Section 3.2.) and emission profiles, thereby ensuring a harmonized starting point. These macroeconomic assumptions are primarily related to gross domestic product (GDP) and population growth and are directly set in the macroeconomic model to build the baseline scenario. In the optimization model, these assumptions are reflected in the final energy demand set in the model. Both models have the same regional coverage and modelling horizon, while the power sector represents a distinct sector in the macroeconomic model. The linkage between the two models is established through directly exchanging linking variables, which pertain to energy costs (as calculated based on Equation (1)), encompassing all energy supply and demand-related costs, as well as transmission and distribution costs. Deviations in energy costs from the baseline are set as economic shocks in the macroeconomic model by amending household expenditures, assuming that these cost changes are passed on to the final consumers.

It should be noted that there are discrepancies in agent representation and underlying rationales between the two models: the bottom-up model features a rational, cost-focused social planner with perfect foresight (see subsection 3.2.1 for details), while the top-down model features interacting economic agents (see subsection 3.2.3 for details). Despite these differences, the results from each model are used to evaluate the performance of examined strategies from different perspectives. Consequently, this heterogeneity between models doesn't compromise the interpretability of the results.

3.2.3. Top-down economic modelling

To evaluate the economy-wide implications of power system development, we develop a dynamic, single-country CGE model for Greece. Specifically, we adjust the Mitigation, Adaptation and New Technologies Applied General Equilibrium (MANAGE) model [29] to the particularities of the Greek economy, hereafter referred to as MANAGE-Greece. We extract the data on the Greek economy from the Global Trade Analysis Project (GTAP) database version 11 [30], using the Social Accounting Matrix (SAM) with 2017 as a reference year. We aggregate the economic sectors into 10 categories, including electricity as a distinct sector. This setup facilitates communication between the CGE model and the engineering optimization model. It should be noted that, unlike the engineering model, the CGE model doesn't differentiate between individual power generation technologies, treating the electricity sector as a single entity.

We ensure the representativeness of these data by conducting "backcasting" exercises, where model results are compared to historical data for the Greek economy. The elasticity parameters of the model—describing the response of economic agents to shocks (e.g., income change)—are adjusted in the process to identify those that best fit the particularities of the Greek economy, based on resulting model accuracy. These exercises follow the same framework as the planned simulations; however, instead of projecting into the future, the model is extrapolated into the past to validate its accuracy against observed historical data. Specifically, the model starts from the same base year, with power generation costs applied exogenously based on their historical evolution. The key variable of interest for evaluating the model's accuracy is GDP, which is then compared to historical data. The annual real GDP is calculated as shown in Equation (3).

$$\mathrm{RGDP}_y = \sum_d x_{d,y} + \mathrm{RB}_y + \mathrm{RX}_y - \mathrm{RM}_y \tag{3}$$

where $x_{d,y}$ represents the total real expenditures on goods and services by the final demand account d in the year y, RB_y accounts for the real change in stocks or inventories (i.e., non-sold produced goods) within the economy in year y, RX_y account for real total exports, and RM_y represent real total imports in year y.

The MANAGE macroeconomic modelling framework has been mainly applied to developing countries (e.g., Ref. [31]), and its main added value lies in presenting a higher specification for the energy sector. Therefore, it allows for more nuanced modelling of the possibilities for substitution between capital, labour, and energy. This is implemented through dedicated nested constant-elasticity-of-substitution (CES) functions on the production side, as shown in Equation (4).

$$\mathrm{VA}_y = A\left(\sum_{f \in F} \delta_f \cdot q_f^{\rho}\right)^{\frac{1}{\rho}} \tag{4}$$

where VA_y is the value-added component of production in year y; A is the productivity parameter; F is the set of production factors; q_f^{ρ} accounts for the input of production factor f in the production function; and δ_f represents the share of each production factor in the production function, thereby determining their relative importance in the production process. At the first level of the nested function, $F = [KSE, LAB1, LAND]$, where KSE is the capital-skilled labour-energy composite, $LAB1$ represents the unskilled labour bundle, and $LAND$ accounts for the land input. The KSE composite is determined by a substitution between the capital-skilled labour composite (KS) and the energy bundle. KS is determined at a lower level by a substitution between capital and skilled labour ($LAB2$), while capital itself is differentiated into 'fixed' and 'mobile', according to whether it is sector-specific or partially/fully mobile across sectors, respectively. The substitution parameter, ρ, is calculated based on the elasticity of substitution, σ, which determines how easily one input can be substituted with another in the production process (Equation (5)).

$$\rho = \frac{\sigma - 1}{\sigma} \tag{5}$$

Modelling possibilities for energy substitution in the production process is particularly suited for evaluating climate change mitigation strategies, which fundamentally aim to transform the current energy consumption and production patterns. The primary model rationale is market-clearing—that is, determining the prices at which demand equals supply, leaving no incentive for any agent to deviate. In this framework, households provide labour and capital to enterprises and, in return, receive income from them, as well as money transfers. Enterprises use this input, along with intermediate products, to produce goods and provide services, selling them to households, the government, or international markets. The government receives tax payments and provides transfers and subsidies to households and producers. Households and enterprises seek to maximize their utility and profits, respectively. Model solutions are produced on an annual basis in a static equilibrium manner, with dynamic equations linking and updating exogenous factors (e.g., capital accumulation).

To formulate the baseline scenario for the Greek economy—reflecting how it would develop based on the key macroeconomic and demographic projections—we use the same assumptions considered in the bottom-up model (see Section 3.2.). In cases of data unavailability, we leverage data from the second Shared Socio-economic Pathway (SSP2) [32], which outlines a "middle of the road" socio-economic pathway that resembles past patterns, thereby making it suitable as the baseline scenario for this analysis. The key growth projections—including GDP, population, workforce, and capital supply—are provided to the model as exogenous shocks. Capital supply is calculated as a function of gross fixed capital investments and depreciation, based on the formula proposed in Fouré et al. [33]. Gross fixed capital investments are extracted from Ref. [34], whereas in the post-2020 period, they are forecasted via a linear regression model that correlates them with GDP and population. Land and natural resources are assumed to be in a fixed supply within the modelling horizon.

We then simulate the economy-wide implications of the shocks triggered by the examined scenarios. These simulations are built on top of the baseline scenario by exploiting the results of the bottom-up optimization model of the analysis (*see 3.2.2*). Power generation cost changes are assumed to fully pass on to the final energy prices. All simulations are performed through the implementation of MANAGE in the General Algebraic Modeling System (GAMS) using CONOPT 3 as a solver.

3.3. Scenario framework

The analysis examines two policy scenarios. First, the scenario involving the decarbonization of the Greek economy based on the penetration of new clean fuels—the so-called New Carriers for 1.5 °C (NC1.5) [35]—is considered the baseline scenario of the analysis. This is done because it is consistent with the latest intentions of the Greek government prioritizing a faster green transition. In this scenario, the activity level for the technologies associated with electricity imports and exports is defined exogenously to the optimization model (see Table 2). This is achieved by setting the minimum and maximum activity levels for import and export technologies in the optimization model equal to the assumed trade assumptions.

In the counterfactual scenario, the model determines endogenously the activity levels of electricity import and export technologies (hereafter referred to as "Export-Optimized Pathway"). This decision is driven by a cost minimization rationale and the capacity of power grid infrastructure for interconnecting Greece with other countries, based on both existing capabilities and planned future expansions. Electricity export revenues are considered to decrease energy system costs. As such, exporting electricity is economically justified when electricity prices exceed production costs. The key assumptions of these scenarios are presented in Table 2. Power and energy sectors are set to decarbonize by 2035 and 2050, respectively. Maximum land availability is calculated according to Equation (A.1) and Ref. [35].

We first seek to identify the marginal electricity price making it profitable for Greece to export clean electricity in the post-2035 period. Between the range of that price and the price projected by the EU reference scenario [36], we stress-test the cost-optimal level of electricity generation and net imports against different electricity prices. NC1.5 envisions an aggressive electrification of the transport sector, a more moderate electrification of the residential and industry sectors, and a decline in the electricity demand of the services sector after 2030, primarily due to energy efficiency measures (Fig. 3) [35]. These assumptions about final demand align with the rationale of exporting electricity to neighbouring countries, implying that sufficient domestic electricity levels are already being met.

3.4. Multicriteria evaluation of clean energy development

3.4.1. Method

Among multicriteria methods, those based on measuring the geometric distance of alternatives from a reference ideal point are notably

Table 2
Key assumptions of the examined policy scenarios in this study (Data are sourced or calculated by authors based on [35]).

Indicator		Scenario	
		NC1.5 (Baseline)	Export-Optimized Pathway
Decarbonization date	Power sector	2035	
	Energy sector	2050	
Electrification rate (% of final demand)	2030	32 %	
	2050	48 %	
Net electricity imports (PJ)	2030	7.4	Calculated endogenously by the optimization model
	2050	3.9	
Land availability for renewable infrastructure (km^2)		12, 300	

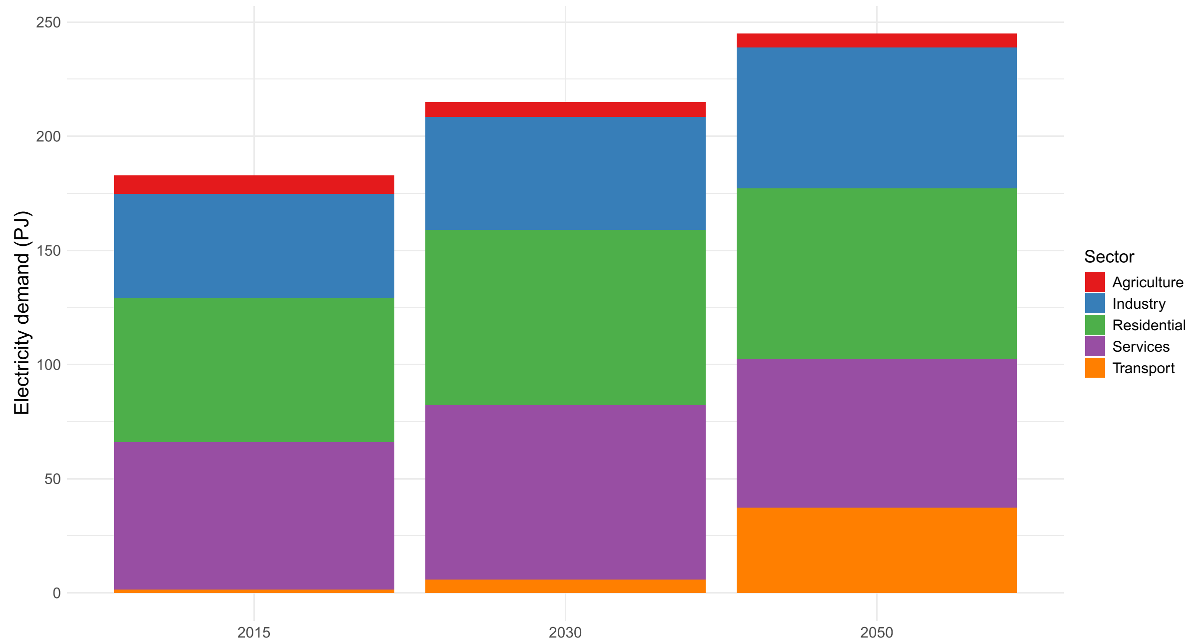

Fig. 3. Final electricity demand considered, per sector and in total, in the examined policy scenarios over the 2023–2050 period (Adapted by the authors based on [35]).

robust [37]. These methods stand out for their prevalent use in the existing body of literature, especially in the realm of energy and climate decision making [38]. In this study, we use the TOPSIS method to assess the multifaceted trade-offs involved in clean energy development [39]. This decision is driven by the fact that TOPSIS evaluates alternatives based on their geometrical distance from both a positive and negative ideal solution, formed by the best and worst performances recorded at each criterion among the examined alternatives. By embodying the aspects of both profit and loss through these ideal solutions as proxies, it features a more balanced decision-making approach [37].

Other benefits of TOPSIS include its flexibility to handle multicriteria decision problems with any number or scale of criteria and alternatives, and its use of vectorized normalization. Although influenced by the units of measurement, this normalization type is more robust against outliers than Min-Max scaling [40]. TOPSIS is usually combined with other multicriteria methods. For example, in the context of energy planning, Koutsandreas et al. [8] combined TOPSIS with VIKOR,[2] while d'Amor-e-Domenech et al. [41] employed TOPSIS along with four additional methods, including AHP, the Comparison by Advantages, Simple Additive Weighting, and Complex Proportional Assessment. TOPSIS has also been extended into fuzzy forms to address ambiguity and imprecision in decision-making [42]. The key formulas involved in the TOPSIS method are described in Appendix B.

3.4.2. *Evaluation criteria*

Table 3 presents the evaluation criteria used in the analysis, pertaining to different perspectives of clean energy capacity expansion that may be important for decision-makers under certain circumstances. These criteria, termed family criteria, are evaluated using relevant proxy indicators. Many of these proxy indicators can be in conflict, as improving one may compromise another. The family criteria include cost, use of critical resources, energy security, human health, biodiversity, and socio-economic development. Strategies' performance across these indicators is quantified through the utilized modelling framework, and thus different modelling frameworks could support alternative or additional indicators.

The analysis further classifies proxy indicators into "local" and "global" (column "Regional scope"; Table 3), based on where impacts materialize [43]. "Local" indicators relate to the country being assessed (e.g., energy cost), while "global" ones reflect impacts on countries producing or supplying power technologies or resources (e.g., critical materials). Criteria weights are assigned at the proxy level, as conceptually similar proxy indicators may differ in underlying rationales or regional scopes, thereby appealing to different decision-makers. For instance, a decision-maker focused solely on Greece may assign zero weight to "critical resources", whereas one considering interregional justice might prioritize it as highly as "land use".

We perform a sensitivity analysis for each criterion and TOPSIS results against electricity price variability. However, to allow for inspecting results also across the dimensions of technologies and time, we apply the sensitivity analysis for two indicative electricity prices: the EU Reference scenario price ("EURef price") and half of this price. In addition, we explore how results vary across the weight space by considering different indicative archetypes of decision-makers. To quantify the criteria weights for each archetype, we use the analytic hierarchy process (AHP) —a multicriteria method that has been extensively applied in the literature for this scope in energy planning exercises [44]. AHP is chosen for its effectiveness in supporting pair-wise comparisons within hierarchical decision-making contexts.

We consider an "equal weights" scenario to represent "balanced" decision-makers across proxy indicators. We also consider one scenario for each proxy indicator as the primary driver for decision-makers, while also factoring in the regional scope, global or local, of the criteria. This is modelled by treating the most important criterion per case as "strongly more important" than others of a different regional scope and "moderately more important" than those within the same scope. This approach allows one to keep consistency with how the real world's decision-makers may behave, resulting in seven weight scenarios. The assumed importance relations and corresponding weights are presented in Tables 4 and 5, respectively. Exploring the weight space helps identify strategies performing well across a range of decision-maker types, usually referred to as "acceptable" [20].

In all cases, we compute the consistency ratio (CR) to ensure the consistency between the pairwise comparisons. As expected, given that the evaluations are based on predefined, consistent rules without human

[2] VIsekriterijumska optimizcija i KOmpromisno Resenje (in Serbian).

Table 3
Overview of the family criteria and proxy indicators used in the analysis (Data are sourced from Refs. [1,28,45]).

Family Criteria	Regional scope	Unit	Proxy indicators	Description
Cost	Local	Euro/Megawatt hour	C_1: Levelized cost of electricity (▾)	Cost of electricity per unit of final demand
Critical Resources	Local	km^2	C_2: Land use (▾)	Land occupied by renewable infrastructure including required distance, and land used for biomass cultivation
	Global	Tones	C_3: Critical material use (▾)	Critical material needed for producing the power technologies inserted in the system [×]
Energy security	Local	Unit free	C_4: Diversity of installed power (▴)	Calculated based on Shannon–Wiener Index (SWI; see section 3.1.1)
Human health	Global	Kilo tons 1,4-DCB-Eq*	C_5: Human toxicity (▾)	Impact of constructing the power technologies inserted in the system on human toxicity [×]
Biodiversity	Global	Tons N-Eq**	C_6: Marine eutrophication (▾)	Impact of constructing the power technologies inserted in the system on marine eutrophication [⊗]
Socio-economic	Local	Unit free (% change vs baseline)	C_7: GDP (▴)	Impact of energy system development on the GDP of the economy

(*): human toxicity compared to 1,4 kilo tons-Dichlorobenzene equivalent, (**):contribution of nitrogen and phosphorus compounds to marine eutrophication in terms of tones of nitrogen equivalents, [×]: model results about operation and capital investments costs of system technologies, [◊]: model results about produced electricity of system technologies, (▾): Cost criterion, (▴): Benefit criterion, [⊗]: it refers to grid, hydro, CSP, solar PV, storage, and wind turbine.

intervention, CR values remain well below the commonly accepted threshold of 0.1 (0.0072 in all scenarios, except for the equal weights scenarios, where it is 0).

4. Results

This section presents the main results for the examined scenarios using the modelling framework described above, both at the level of individual evaluation criteria and overall performance across all of them. The payoff table used for the multicriteria evaluation, as well as the positive and negative ideal solutions recorded between the examined strategies across evaluation criteria, are provided in the GitHub repository accompanying this paper (https://github.com/daymontas1/GRIMS.git). All monetary results are expressed in 2019 values. Fig. 4 presents the annual power generation and net electricity imports (negative values represent net exports) per power technology under the "Export-Optimized Pathway" and, in total, under the baseline scenario over the 2023–2050 period. This is done for the "EURef price", while the dotted lines show how the cost-optimal total annual electricity production and net electricity imports fluctuate under alternative electricity price assumptions. As shown, electricity production consistently increases through 2050, driven by the electrification of the Greek economy, regardless of export levels. The addition of electricity exports leads to a more rapid increase in domestic power generation, surpassing the linear growth associated with electrification alone (Fig. 4).

Electricity exports become profitable at prices higher than €36 per Megawatt hour (MWh) of final demand after 2035. As electricity prices increase, the cost-optimal level of electricity exports rises, prompting higher domestic electricity production (Fig. 4). At half the EURefprice, the optimal export level is around 26 TWh (35 % of domestic consumption), which rises to 32 TWh (roughly 43 %) at the EURefprice. At higher than the EURef prices, however, electricity exports hardly deviate as domestic renewable production reaches land availability constraints (see Table 2).

Fig. 5 illustrates the annual power generation cost by component (i.e., annualized capital cost, operational cost, and ETS cost) under the "Export-Optimized Pathway", along with the total cost under the baseline scenario. It also provides a sensitivity analysis for the "Export-Optimized Pathway" and reports the average annual costs across examined scenarios over the 2023–2050 period. Although results are highly sensitive to electricity prices, export revenues can result in negative operational costs, substantially alleviating overall power generation costs. Specifically, exporting clean electricity could mitigate power generation costs by at least €17.52 per MWh annually during the 2023–2050 period, with potential cost reductions reaching up to €36.6 per MWh.

Cost reductions in power generation can expand the disposable income of households, which can be saved, invested, or spent in the final demand sectors of the Greek economy. This could, in turn, bring about an expansionary effect on the economy, as illustrated in Fig. 6. This figure depicts the potential impact of exporting clean electricity on the Greek economy's GDP under the "EURef price" and half of that price. Specifically, this development could enlarge the Greek economy by at least 0.11 % annually over the 2023–2050 period. As with power generation costs, GDP impacts highly depend on electricity prices, with the potential to reach as high as 0.24 %. These results highlight the strong

Table 4
Importance relationships between proxy indicators assumed for each decision-maker (DM) archetype (> moderately more important, ≫ strongly more important).

DMs archetypes	Criteria relationships
Balanced	$C_1 = C_2 = C_4 = C_7 = C_3 = C_5 = C_6 = C_7$
Cost-focused	$C_1 > (C_2, C_4, C_7)$, $C_1 \gg (C_3, C_5, C_6)$, $(C_2, C_4, C_7) > (C_3, C_5, C_6)$
Land use-focused	$C_2 > (C_1, C_4, C_7)$, $C_2 \gg (C_3, C_5, C_6)$, $(C_1, C_4, C_7) > (C_3, C_5, C_6)$
Critical Material-focused	$C_3 > (C_5, C_6)$, $C_3 \gg (C_1, C_2, C_4, C_7)$, $(C_5, C_6) > (C_1, C_2, C_4, C_7)$
Energy security-focused	$C_4 > (C_1, C_2, C_7)$, $C_4 \gg (C_3, C_5, C_6)$, $(C_1, C_2, C_7) > (C_3, C_5, C_6)$
Human health-focused	$C_5 > (C_3, C_6)$, $C_5 \gg (C_1, C_2, C_4, C_7)$, $(C_3, C_6) > (C_1, C_2, C_4, C_7)$
Biodiversity-focused	$C_6 > (C_3, C_5)$, $C_6 \gg (C_1, C_2, C_4, C_7)$, $(C_3, C_5) > (C_1, C_2, C_4, C_7)$
GDP-focused	$C_7 > (C_1, C_2, C_4)$, $C_7 \gg (C_3, C_5, C_6)$, $(C_1, C_2, C_4) > (C_3, C_5, C_6)$

Table 5
Criteria weights assumed under each DM, as derived by applying the AHP method based on the importance relations presented in Table 4 for proxy indicators.

DMs archetypes	Criteria weights						
	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Balanced	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Cost-focused	0.36	0.16	0.06	0.16	0.06	0.06	0.16
Land use-focused	0.16	0.36	0.06	0.16	0.06	0.06	0.16
Critical Material-focused	0.06	0.06	0.38	0.06	0.18	0.18	0.06
Energy security-focused	0.16	0.16	0.06	0.36	0.06	0.06	0.16
Human health-focused	0.06	0.06	0.18	0.06	0.38	0.18	0.06
Biodiversity-focused	0.06	0.06	0.18	0.06	0.18	0.38	0.06
GDP-focused	0.16	0.16	0.06	0.16	0.06	0.06	0.36

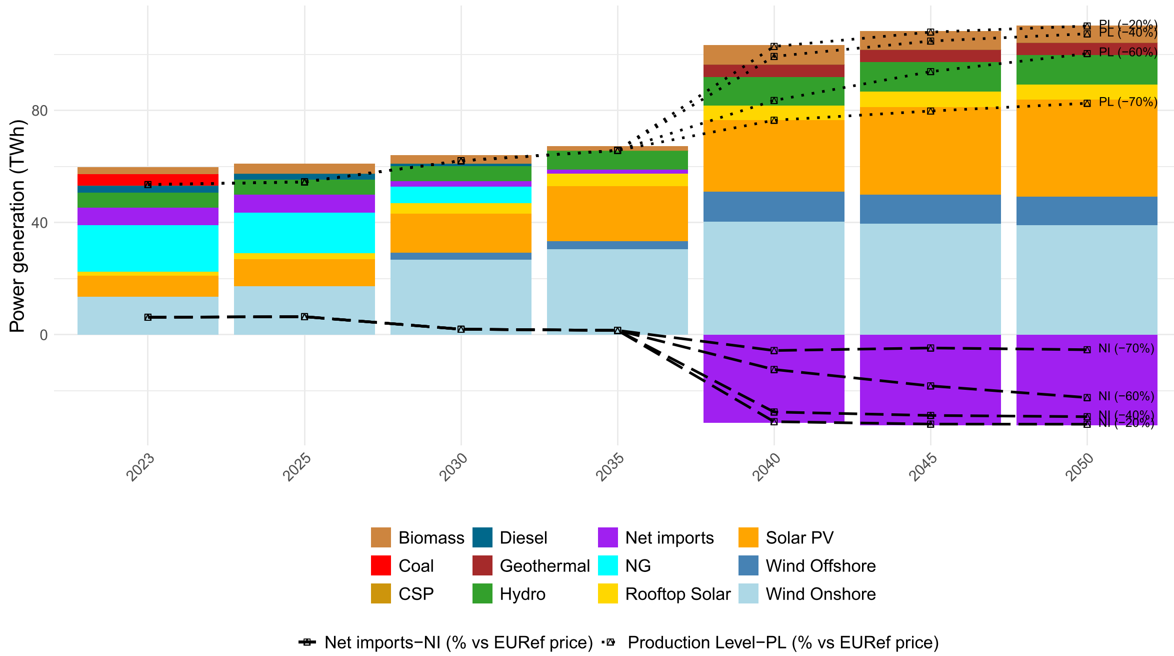

Fig. 4. Annual power generation and net electricity imports in Terawatt hour (TWh) by power technology for the "Export-Optimized Pathway" and, in total, for the baseline scenario (BaU) over 2023–2050, based on the EU Reference scenario price ("EURef price"). The dotted lines illustrate deviations in the cost-optimal total power generation and net imports in response to electricity price changes relative to the "EURef price".

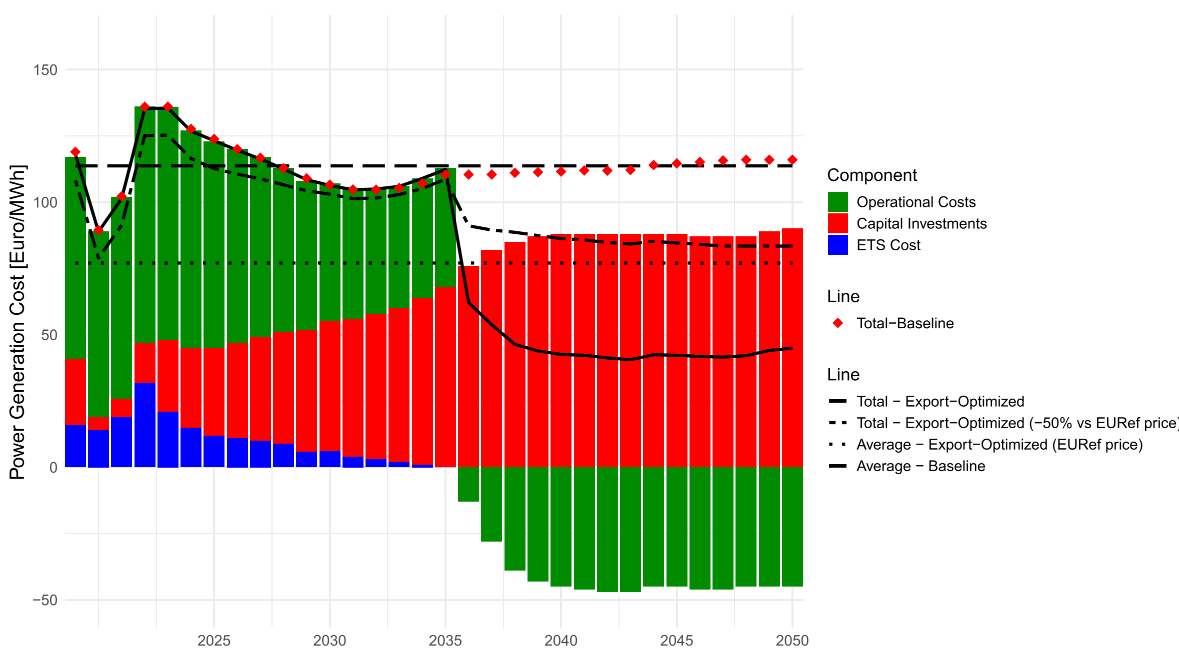

Fig. 5. Annual power generation cost (Euro) per Megawatt hour (MWh) of final demand, broken down by cost component for the "Export-Optimized Pathway" and, in total, for the baseline scenario over 2023–2050, based on the "EURef price". The dotted lines signify total power generation costs under the "Export-Optimized Pathway" at half the "EURef price" and the average annual costs across examined scenarios.

economic potential of clean electricity exports.

As shown, the positive macroeconomic effect intensifies after 2035, when export revenues grow more rapidly than capital investment requirements. Interestingly, though, in the pre-2035 period, prior to the onset of exports, the expansion of clean power generation induces only a marginal negative effect on GDP. This is because the increased capital investment requirements are largely offset by reductions in operational costs, driven by decreased fossil fuel consumption, mainly natural gas, which also results in lower ETS costs. Therefore, a trivial medium-term negative economic impact is offset by substantial economic gains in the long term.

In addition to the economic benefits of exporting clean electricity, the potential unintended repercussions of such an endeavour (e.g., on critical resources) should also be considered. Fig. 7 indicates the annual land area occupied by renewable power technologies under the "Export-Optimized Pathway" (per technology or use) and the baseline scenario (in total) over the 2023–2050 period. It also shows the variability in land use under lower clean power generation expansion levels, and the

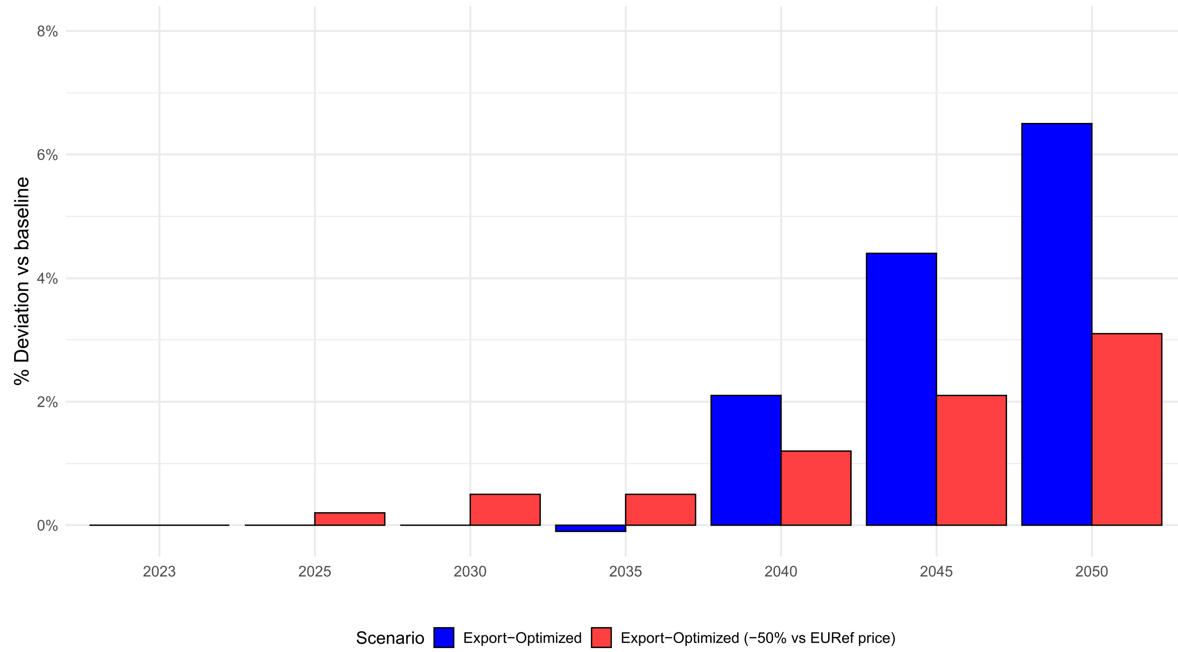

Fig. 6. Impact (% deviation) of the "Export-Optimized Pathway" on the GDP of the Greek economy over the 2023–2050 period compared to the baseline scenario, for the "EURef price" and half of this price.

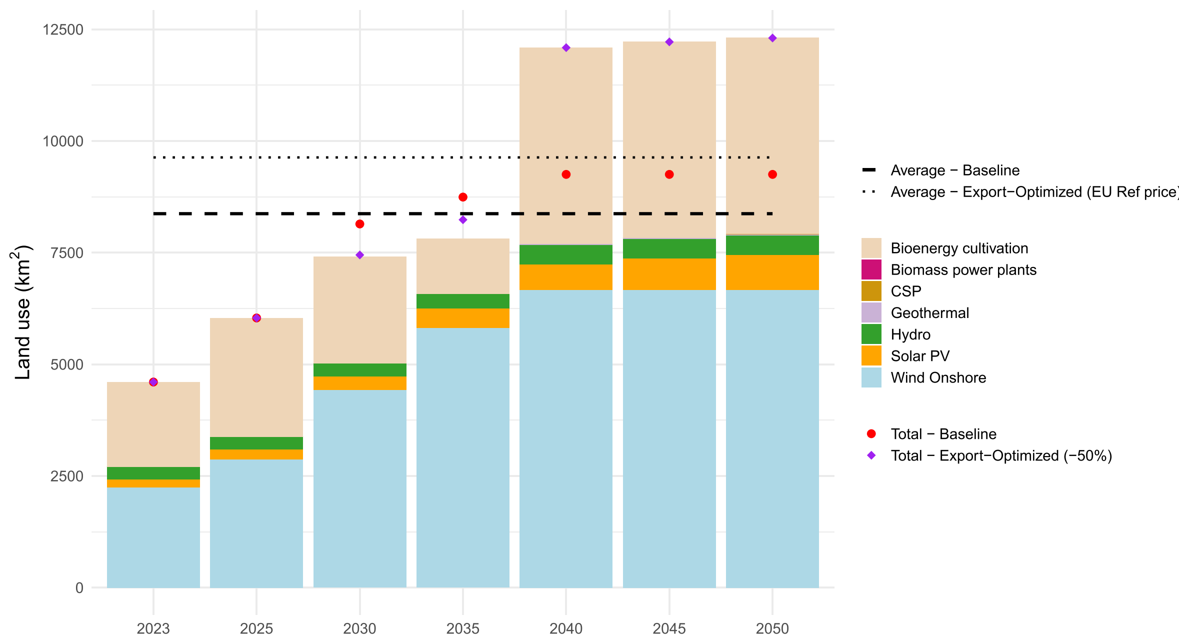

Fig. 7. Annual land use (km^2) by system renewable power generator for the "Export-Optimized Pathway" and, in total, for the baseline scenario over 2023–2050, based on the "EURef price". The dotted lines illustrate the average annual land use across the examined scenarios.

average annual land use across examined scenarios. As observed, transforming Greece into a clean electricity exporter requires substantially more land for renewable power generation, about 1259 km^2 annually. This is primarily attributed to the capacity expansion of wind power technologies and bioenergy cultivation. Fig. 7 also includes the estimated land area already occupied by the existing clean power technologies at the beginning of the modelling horizon.

Notably, increased levels of clean power expansion in the post-2035 period are associated with decreased land requirements before 2035. This is ascribed to the perfect foresight rationale of the model, wherein future electricity export revenues influence investment decisions. Therefore, in the pre-2035 period, the model prioritizes investments in technologies with higher capacity factors (i.e., offshore wind and small hydropower), which also present low land intensiveness. These early investments facilitate large-scale renewable electricity generation later on. Conversely, decreased levels of power generation after 2035 lead to early investments in land-intensive technologies (e.g., wind onshore and solar PV), thereby pushing land requirements later.

Fig. 8 provides an approximation of the critical materials needed to grow clean power generation during 2023–2050, highlighting potential supply risks. Notably, a supply bottleneck would affect several countries beyond Greece, due to the concentration of clean technology value chains in specific countries [46]. As depicted, supplying clean electricity to other countries is inextricably connected to a high critical material

Fig. 8. Annual critical material demand (tn) for constructing the newly inserted renewable power generators in the system for the "Export-Optimized Pathway" (per technology) and baseline (in total) over 2023–2050, based on the "EURef price". The dotted lines represent the annual average critical material demand across the examined scenarios.

demand. Although of a rather low scale—averaging at 0.52 tons annually during 2023-2035—critical material requirements are more front-loaded compared to the no-exports scenario, mainly referring to the pre-2040 period. This aspect increases the risk of supply bottlenecks.

Fig. 9 illustrates the potential implications of building new renewable capacity on marine eutrophication, broken down by technology for the "Export-Optimized Pathway", and in total for the baseline scenario over 2023–2050, based on the "EURef price". This provides an approximation of the potential repercussions on biodiversity. This figure includes a sensitivity analysis for the "Export-Optimized Pathway" and the average annual impacts across examined scenarios. As shown, supplying clean electricity abroad may result in marine eutrophication impacts amounting to 64.14 tons N-Eq, on average, annually. This primarily occurs in the 2034–2041 period due to the penetration of hydropower technologies in the system, which exhibit the highest eutrophication impacts (see Appendix A).

The expansion of hydropower capacity during this period also results in increased human toxicity risks. Fig. 10 illustrates the potential impact

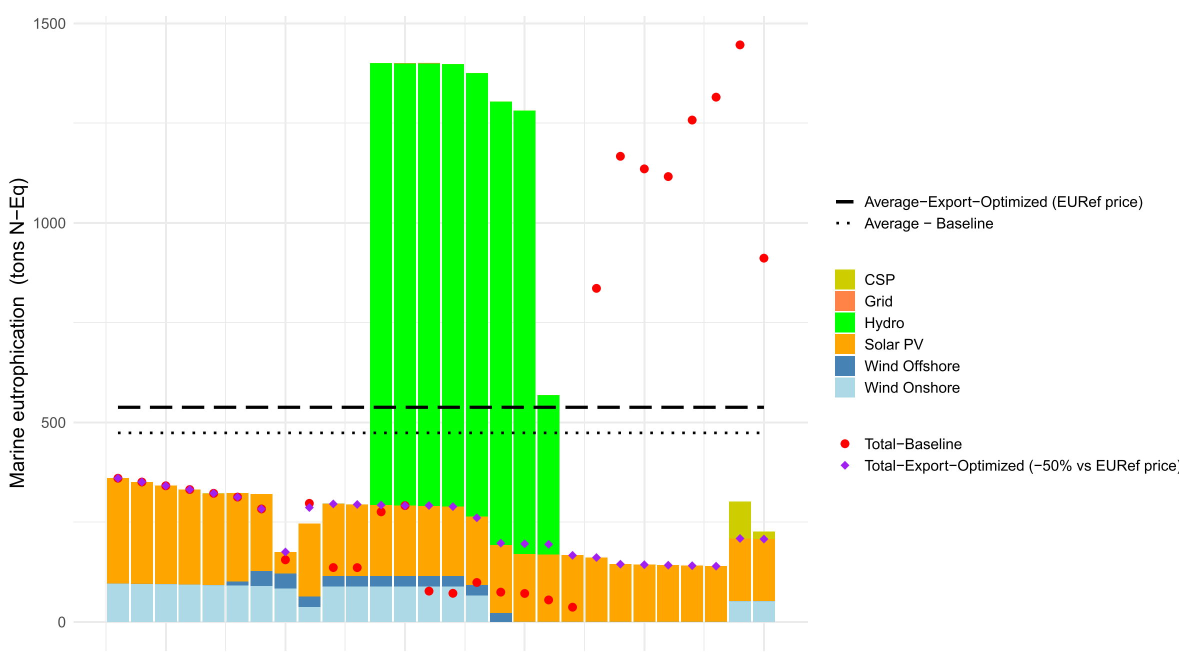

Fig. 9. Annual impact on marine eutrophication in tones of nitrogen equivalents (tons N-Eq) by renewable power generator for the "Export-Optimized Pathway" and, in total, for the baseline scenario over 2023–2050 ("EURef price"). Dotted lines reflect the average annual impacts of the examined scenarios over the 2023–2050 period.

on human toxicity by newly inserted power technology for the “Export-Optimized Pathway”, and the total annual impact under the baseline scenario, for the “EURef price”. On average, transforming Greece into a clean electricity supplier may induce an impact on human toxicity in the order of 171.60 kilo tons 1,4-DCB-Eq on an annual basis during 2023–2050.

Beyond economic benefits, the “Export-Optimized Pathway” features a more diverse power mix, as demonstrated in Fig. 11. This figure depicts the annual SWI for both examined scenarios over the 2030–2050 period. Higher SWI values signify greater diversity and therefore resilience against supply disruptions and tail-risk events [47], something particularly important in today’s world, characterized by successive crises and tectonic changes [48]. This higher diversity is driven by the increased penetration of alternative clean technologies (i.e., wind offshore and geothermal energy) compared to baseline, required to scale up clean electricity exports. Notably, power mix diversity decreases in the pre-2035 period in all cases, driven by the model’s economic rationale, which overlooks concerns such as energy security.

Fig. 12 illustrates the results of the TOPSIS multicriteria method across different decision-maker types. These results are expressed as proximity to the ideal solution, with high D values indicating high desirability for decision-makers. As shown, scenarios involving electricity exports feature strong economic and energy security benefits, but are accompanied by increased risks related to human toxicity and critical resources. The “Export-Optimized Pathway” outperforms the no-exports scenario in most cases when considering all evaluation criteria together. The difference is more pronounced when economic criteria are prioritized, largely because electricity export revenues decrease energy costs and subsequently grow household income.

Conversely, when human health or biodiversity are the primary concerns, the baseline scenario performs comparably with the electricity exports scenario—if not better. Notably, low-scale electricity export scenarios may reduce biodiversity risks compared to the no-exports scenario. This is ascribed to the decreased reliance on hydropower technology in the post-2042 period—the technology with the highest marine eutrophication impact—solely driven by an economic rationale. Nonetheless, biodiversity risks escalate in high electricity export scenarios.

Consequently, moderate levels of clean electricity exports can deliver better outcomes for biodiversity-conscious decision-makers compared to both high and no export scenarios. Additionally, the superiority of the export scenario for decision makers prioritizing critical resources is explained by its only moderate increase in resource demand. This is due to the reliance on alternative clean technologies, such as wind offshore and geothermal, which feature lower critical resource requirements (see Appendix A).

It is noteworthy that there can be interactions between local and global perspectives. For instance, global developments can produce local spill-over effects even in countries not directly involved in clean technology supply chains, such as Greece. Therefore, while the proposed evaluation framework mainly refers to decision-makers driven by interregional and intergenerational justice motives, it may benefit all decision-maker types.

5. Conclusions

Scaling up clean power generation can provide significant environmental, economic, and geopolitical benefits. However, it may also lead to supply bottlenecks and adverse repercussions, such as depleting critical resources, harming biodiversity, or affecting human health. Here, we assessed these trade-offs for a country with substantial potential for becoming a clean electricity exporter, namely Greece. To do so, we built and utilized a technology-rich optimization model illustrating Greece’s power energy and resource systems, along with a RD CGE model representing the Greek economy. We integrated these models with a multicriteria framework consisting of the TOPSIS method and six criteria: cost, critical resources use, energy security, human health, biodiversity, and socio-economic development.

Our findings indicated that it would become economically viable for Greece to export clean electricity in the post-2035 period at electricity prices higher than €36 per MWh, while the higher the electricity price, the larger the cost-optimal level of electricity exports. However, the Greek clean power generation was found to reach saturation around the export levels associated with the “EURef price” owing to land

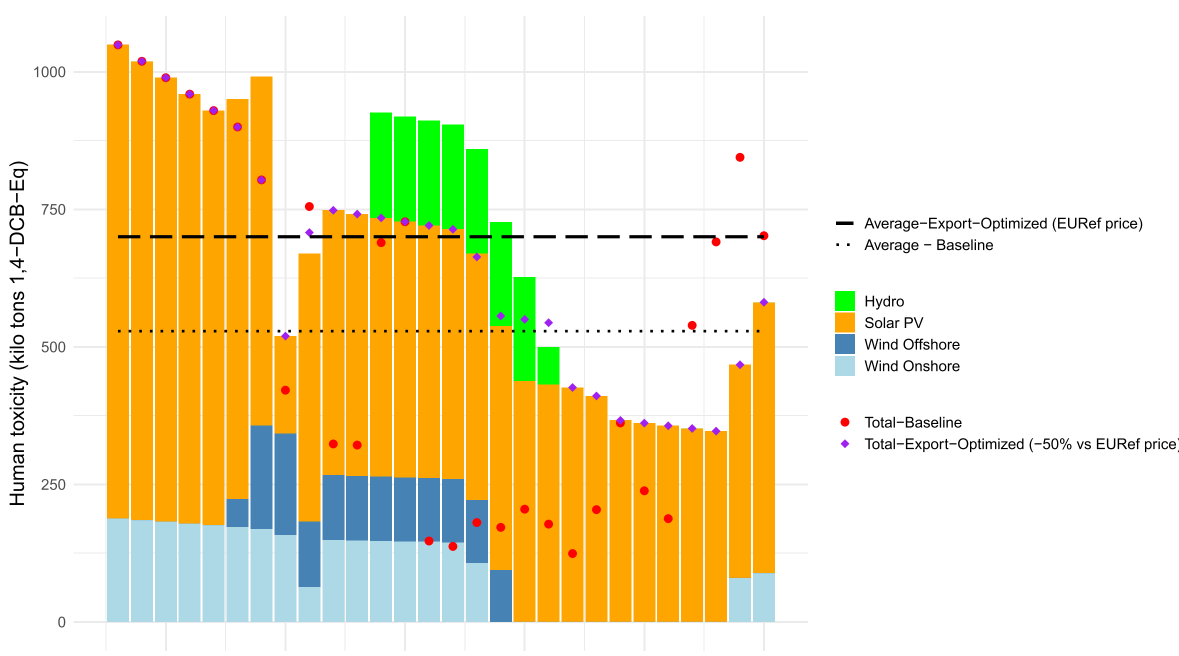

Fig. 10. Annual impact on human toxicity in 1,4 kilo tons-Dichlorobenzene equivalent (kilo tons 1,4-DCB-Eq) by power technology for the “Export-Optimized Pathway” and, in total, for the baseline scenario over 2023–2050, based on the for the case of the “EURef price”. Dotted lines account for the average annual impacts of the examined scenarios over the 2023–2050 period.

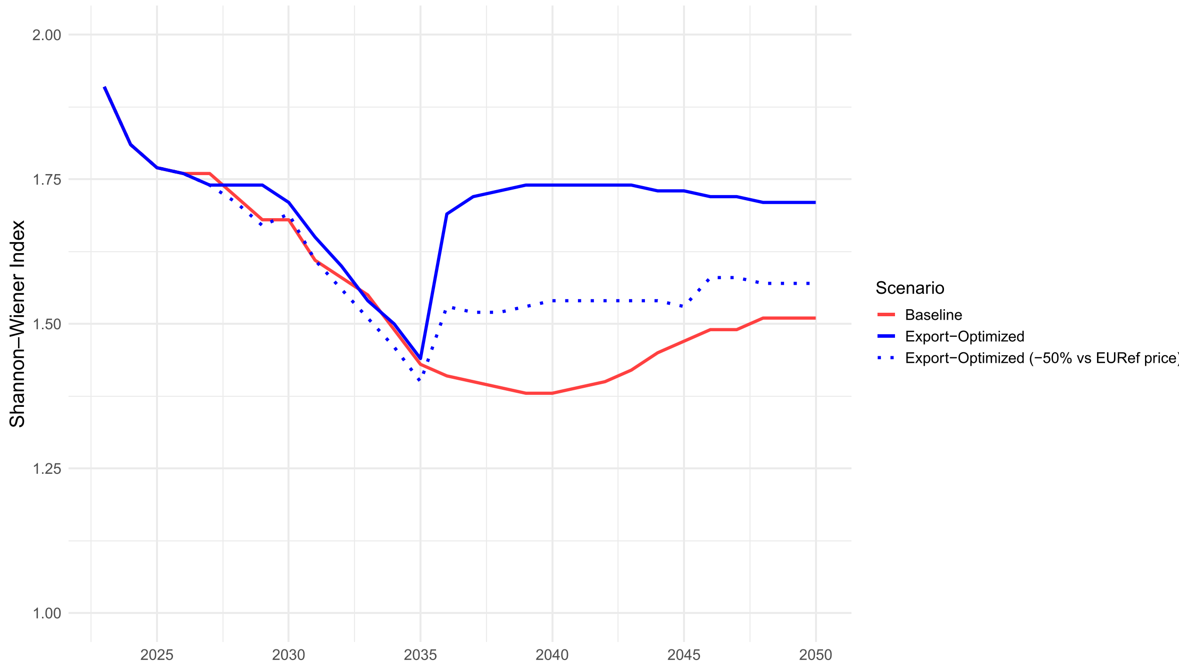

Fig. 11. Annual Shannon-Wiener Index (SWI) for the “Export-Optimized Pathway” and baseline over the 2023–2050 period. High SWI values reflect a diverse power mix and high resilience against supply disruptions.

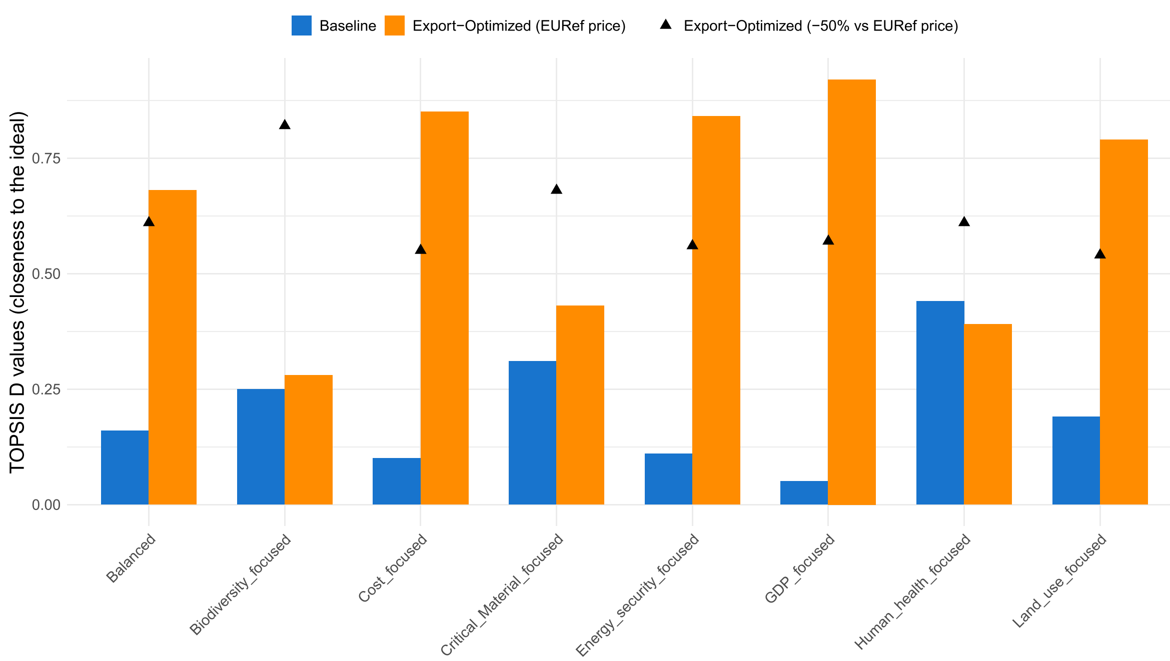

Fig. 12. TOPSIS D closeness to the ideal values for the “Export-Optimized Pathway” and baseline over the 2023–2050 period across various decision-maker types. High TOPSIS D values signify robust strategies for decision-makers.

availability. The analysis also showed that exporting clean electricity could mitigate annual power generation costs in Greece by at least €17.5/MWh, thereby increasing the disposable income of Greek citizens. This, in turn, could contribute to annual GDP growth of at least 0.12 % during the 2023–2050 period. However, the economic footprint of exporting clean electricity was found to be highly sensitive to electricity market prices.

Regarding the implications on critical resources, the analysis revealed that transforming Greece into a clean electricity supplier would come with an increase in land demand for renewable power generation of approximately 1259 km^2 annually over 2023–2050. It was also found that this endeavor could increase critical material demand by around 0.52 tons annually, primarily concerning the 2034–2041 period. Although these factors may lead to potential supply bottlenecks, the results indicated that this scenario would lead to a more diverse power mix, thereby enhancing system resilience against supply disruptions. This outcome is attributed to the higher penetration of alternative renewable technologies (e.g., geothermal, wind offshore) in the mix to scale up clean electricity generation. Additionally, the electricity export scenario was found to induce environmental impacts, such as marine eutrophication (64.14 kilo tons N-Eq annually) and human toxicity (171.6 tons 1,4-DCB-Eq annually).

The results from the multicriteria evaluation indicated that policies involving clean electricity exports are generally more favourable for most types of decision-makers than no-exports policies. In particular, the results revealed that the higher the level of clean electricity exports, the higher the utility for decision-makers, especially for those with economy-driven objectives. This trend was found to be reversed only for human health- or biodiversity-focused decision-makers: human health-driven decision-makers may choose to implement a "no-exports" policy, while biodiversity-driven ones may opt for lower-scale electricity exports.

This analysis came with certain caveats that could inspire future research in the field. First, we didn't apply a multiobjective optimization, as this would require hard-linking the employed models into a single "super model" to derive the Pareto front, and would also result in a highly computationally demanding problem given the high number of evaluated dimensions. Furthermore, our analysis didn't not systematically account for uncertainties in variable renewable generation within the modelling framework (e.g., Ref. [49]), as the long-term scope of the study makes it both computationally challenging and of limited relevance—the effects of these fluctuations tend to neutralize in the long run.

Additionally, although our modelling included transmission and distribution technologies for Greece and its interconnections, it lacked spatial heterogeneity. Moreover, we considered the countries that may trade electricity with Greece in terms of power grid infrastructure, without factoring in developments within their national systems. A future study could address this aspect by employing a modelling framework at a European level — modelling only Greece's neighbouring countries wouldn't suffice, as it would omit the interactions of these countries with their other neighbours. Additionally, critical materials were assessed in aggregate, overlooking the distinct factors that make each material critical, such as supply concentration or demand-supply imbalances. We also applied impact coefficients uniformly across each technology type (e.g., wind technologies), although there can be significant technical variations within the same technology type (e.g., different critical material demand)—something that could be addressed in future work.

CRediT authorship contribution statement

Diamantis Koutsandreas: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Behzad Zamanipour:** Writing – review & editing, Validation, Investigation, Data curation. **Ilkka Keppo:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2025.124622.

Data availability

The model equations and input data are provided as supplementary material and are also available on GitHub: https://github.com/daymontas1/GRIMS.git.

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