

**ΟΙΚΟΝΟΜΙΚΟ
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ATHENS UNIVERSITY
OF ECONOMICS
AND BUSINESS



DECARBONIZATION UNDER SEASONAL PRESSURE: INTEGRATED ENERGY-WATER-ECONOMY MODELLING OF TOURISM-DRIVEN PEAKS IN GREECE AND CYPRUS

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Decarbonization under seasonal pressure: Integrated Energy–Water–Economy modelling of tourism-driven peaks in Greece and Cyprus



SDSN Global Climate Hub

Report:

Decarbonization under seasonal pressure: Integrated Energy–Water–Economy modelling of tourism-driven peaks in Greece and Cyprus

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[The Global Climate Hub](#)

The [UN Sustainable Development Solutions Network's \(SDSN\)](#) response to the multifaceted contemporary challenges is the [Global Climate Hub \(GCH\)](#), which came as an initiative for change, leveraging science-based solutions for a holistic and equitable sustainability transition (Alamanos, 2024b; Koundouri et al., 2024). These solutions are developed at regional, national, and sub-national level based both on the scientific expertise of its members, and the engagement with local policymakers (representatives of central and/or local government) – there are dedicated teams of GCH scientists specialized across various fields, working in research projects, as well as a network of SDSN National Hubs, facilitating communication, outreach, and solutions' implementation.

The GCH is hosted by [Athens University of Economics and Business \(AUEB\)](#) and the [“Athena” Research and Innovation Center in Information, Communication, and Knowledge Technologies \(ATHENA RC\)](#), both integral components of the [Alliance of Excellence for Research and Innovation on Aephoria \(AE4RIA\)](#) – in Greek ‘aephoria’ is a synonymous concept to sustainable development). Within the GCH, AE4RIA plays a vital role in securing funding from competitive projects, ensuring the necessary resources to fulfill its multidimensional mission. The Research Centre for Atmospheric Physics and Climatology of the Academy of Athens also supports the GCH.

Our philosophy

The philosophy of the GCH is to break science-policy-implementation silos by building Systems Transformation Pathways, that are explicitly Science-Based, Stakeholder Co-Designed, Blended Finance-Supported. Humanity already possesses the science, the technology, the policies, and even the financial resources—both public and private—to achieve complex sustainability goals, such as the SDGs. Yet, implementation remains poor.

While such frameworks, such as the SDGs provide direction, there is no robust structure explicitly tasked with driving their implementation at scale. We need an operational [GLOBAL COMMONS](#) approach, capable of aligning global efforts, creating accountability, ensuring effective coordination, and delivering results on the ground. This is what the GC promotes.

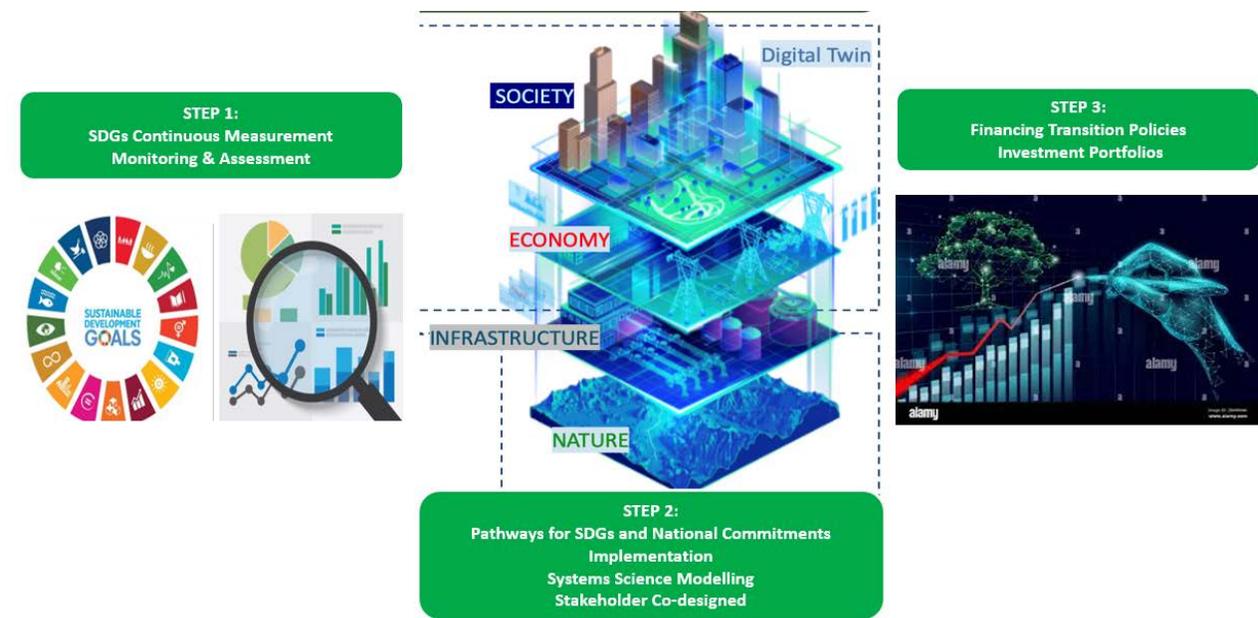


Figure a. The 3-step approach of the GCH: A Global Commons vision for SDGs Implementation. First, we implement advanced monitoring approaches for SDGs Continuous Measurement, Monitoring & Assessment. The 2nd stage refers to the systems modelling, creation of multi-sectoral digital twins and the development of sustainable pathways. The final stage ensures the detection and mobilization of financial instruments to materialize the designed transitions.

First stage: SDG measurement – Continuous Monitoring and assessment

The objective of this stage is to build a rigorous evidence base that is spatially explicit, temporally consistent, and policy-relevant. This is achieved by harmonizing observational and administrative data, remote sensing layers, socio-economic statistics and infrastructure inventories; perform baseline diagnostics (resource stocks, vulnerabilities, hotspot mapping); develop digital twins and quality-assured data pipelines to feed models. The output is a policy-use-ready interactive baseline dashboard, hotspot maps and risk matrices that identify priority interventions and inform resource allocation, shortlisting of policy levers for immediate action.

Second stage: Systems modelling application approach

Science-based transformational pathways for SDGs implementation: We convene stakeholders in living labs to define objectives, constraints and plausible narratives; run coupled modelling chains (spatial land-use, water risk, marine use, energy system simulation & optimization, CGE macroeconomic assessments) with scenario ensembles; evaluate synergies, trade-offs and distributional outcomes across SDG indicators. Thus, we co-produce pathways that are technically feasible, economically realistic and socially acceptable. The output is a portfolio of candidate transformation pathways (short/medium/long horizons), quantified co-benefits and trade-off matrices, ranked policy packages and investment roadmaps for decision makers.

The GCH combines the critical innovations illustrated in Figure b to achieve this 3-step approach, which work as a framework for the analysis of any problem. These innovations are interlinked and complementary, feeding each other with necessary information, to deliver optimal sets of technological, policy, fiscal and financial measures to address complex sustainability challenges, build and maintain cross-disciplinary collaborations and stakeholder engagement.

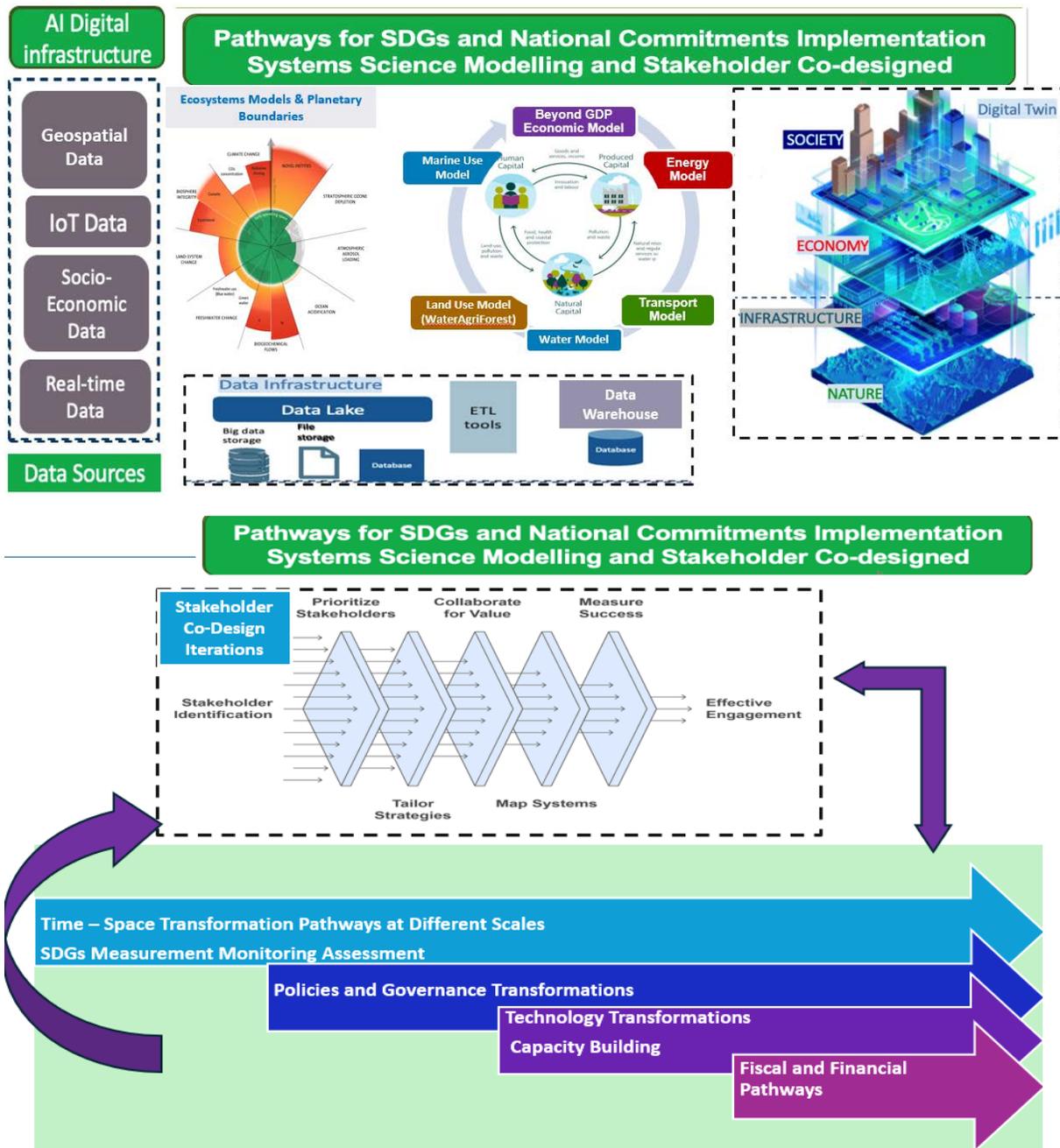


Figure b. The systemic innovation of the GCH, integrating multi-data through AI-supported infrastructure, multi-model assessments and pathways simulations, with digital twins, stakeholder engagement and co-designed sustainability pathways. Integrated models are used/developed, which are coupled and updated

to simulate real-world scenarios. Based on their insights and the stakeholders' input, the socio-economic narrative is developed, simulating the social and economic systems. Their results are the basis to co-design solution pathways with the stakeholders, within a two-way interaction with the models, ensuring realistic representation of the problems and solutions. Data and models are publicly accessible to enhance reproducibility. These pathways can be implemented through policy and governance & technology transformations, assisted by fiscal and financial instruments we mobilize (3rd stage).

Examples of pathways can include technical solutions (e.g. for decarbonization), the consideration of existing technologies, circular economy, nature-based solutions, digitalization, innovation commercialization, sustainable finance and adaptation investment schemes (e.g., green bonds, Environment Social Governance – ESG metrics, and market incentives), and policy reforms (legislative and regulatory interventions to support the implementation and long-term viability of the pathways). To the best of our knowledge, this is a globally unique effort for science-driven, holistic, human-centric approaches aiming to sustainability, climate neutrality and resilience pathways at national level. Its nature, with the existence of national hubs in different countries ensures stability, continuation, and commitment for the long-term implementation of the solutions. This is also beneficial in terms of up-scaling potential, knowledge transfer, and international experience and capacity building across its dedicated teams.

Third stage: Financing Pathways and Investment Portfolio

This refers to the financing of the co-designed pathways and the fair and equitable allocation of the results. Effective transformation requires aligned fiscal instruments, blended finance and policy coherence, linking funding sources to priority measures and using compact KPIs to track progress. The Pathways2Resilience (P2R) Catalogue for Adaptation Finance supports this shift by offering a comprehensive overview of 55 funding sources, 61 financial instruments and 169 case studies, helping regions overcome financing barriers, develop Adaptation Investment Plans and scale both adaptation and mitigation efforts. Yet, progress is constrained by shrinking fiscal space and an unfair, short-term-oriented global financial system that is crisis-prone and exacerbates vulnerabilities in developing countries. This multi-crisis context highlights the urgent need to reform the global financial architecture and massively scale up affordable long-term finance by aligning all flows with the SDGs.

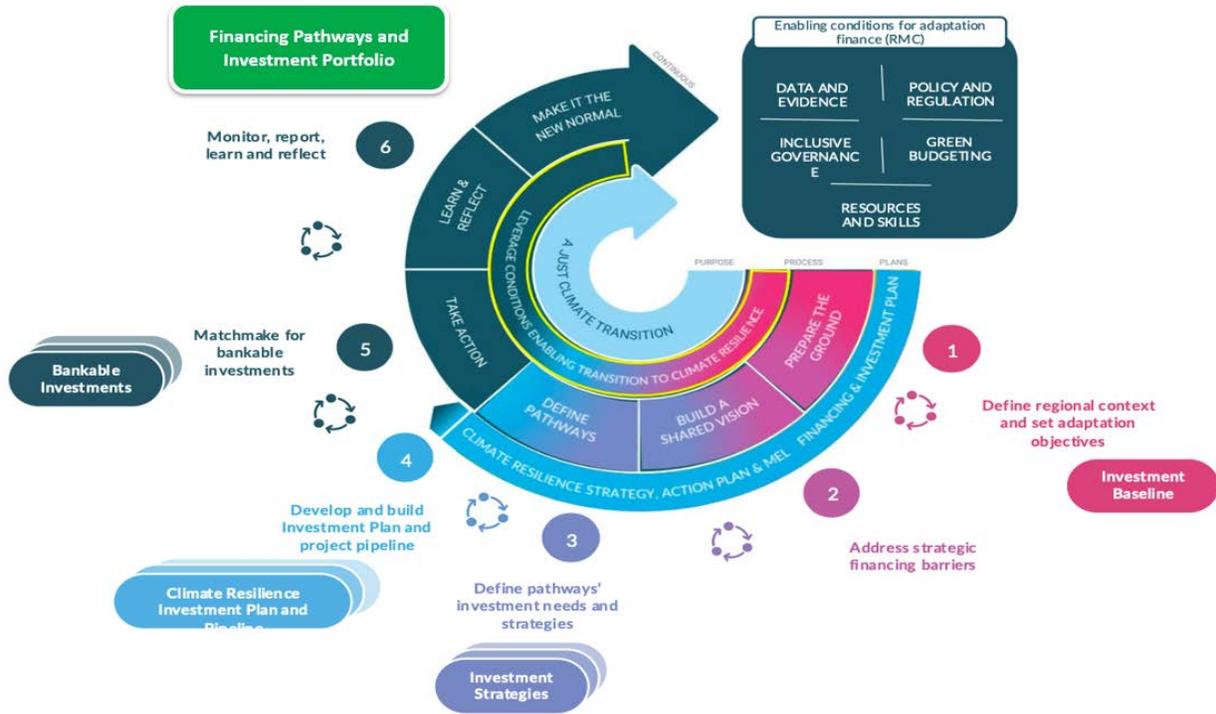


Figure c. The 3rd stage of the GCH approach includes the financing of pathways through investment portfolios.

Nine units as necessary scientific areas for sustainability

The GCH consists of nine separate units/working teams that have expertise to handle relevant research and practical applications (Figure d). These units are scientific areas, conceived as necessary 'steps' towards sustainability, as each one contributes a unique perspective and insight towards the development of customized strategies for climate neutrality, resilience, and sustainability. All units operate under the philosophy explained above, together or in combination with other units.

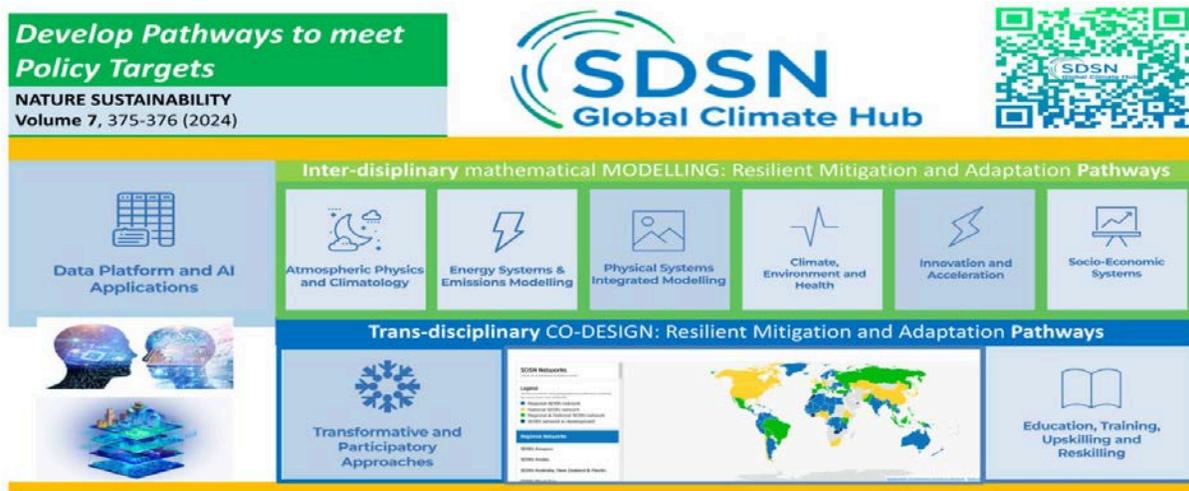


Figure d. The 9 units of the Global Climate Hub.

EXECUTIVE ABSTRACT

Tourism is the economic backbone of many Mediterranean communities, but its benefits come with a hidden problem: the seasonal surge of visitors concentrates energy and water demand into a few months each year. This report asks a practical question: ***can national decarbonization plans that succeed on annual targets also ensure reliable service and water security during short, intense tourism peaks?*** To answer this, ***we built an integrated modelling framework linking a global economy model (GTAP-E) with a detailed energy model (LEAP) and a water-withdrawal module (WaterReqGCH), and we ran coherent Business-as-Usual and National-Commitment scenarios to 2050 for Greece and Cyprus.***

Three headline messages emerge:

- First, National-Commitment measures deliver major gains on annual metrics: economy-wide technology and efficiency changes cut annual energy-sector emissions dramatically in both countries and reduce long-run final energy needs compared with unchecked growth.
- Second, and crucially, ***annual success does not automatically remove seasonal risk***: when we translate economy-wide activity into monthly energy and water profiles using observed post-pandemic tourism seasonality, tourism-linked sectors (air and water transport, accommodation and tourism services) ***still generate strong summer peaks (often close to or above current peak levels) even under ambitious decarbonization assumptions***. So, these countries can be “on track” for net-zero on paper while still being vulnerable to summer outages and water shortages in practice.
- Third, the shape of seasonality matters for policy: Greece shows sharper, higher mid-summer peaks concentrated in a few months, while Cyprus shows a longer high-season plateau. This difference implies ***different operational and investment priorities between the two countries (short, intense surge management in Greece; extended seasonal resilience in Cyprus)***.

These results come from an intentionally conservative, policy-oriented design: GTAP-E produces macro-consistent sectoral activity paths, LEAP converts those into sectoral energy and emissions outcomes under NECP measures, and WaterReqGCH disaggregates annual withdrawals into months using tourism and agricultural seasonality proxies. The chain preserves economy-level consistency while making intra-annual peaks visible—an assessment style that is still rare in national (annual) planning exercises.

For policymakers the implications are straightforward and actionable, summarized in our final section:

- Add peak-aware diagnostics to energy and water plans: require scenario tests that report peak-month electricity demand in tourism-linked services, peak system adequacy metrics (summer capacity margin, stress hours), and peak-month water-stress indicators.
- Target peak drivers, not just annual averages: accelerate efficiency and demand-management in accommodation and tourism services, promote temporal pricing and incentives to shift demand to shoulder months, and prioritize shore-power, electrified services at airports and ports.
- Coordinate energy and water operations where peaks co-locate (islands, coastal ports): schedule maintenance outside peak windows, align desalination and pumping plans with expected seasonal electricity supply, and embed contingency rules in water management plans.
- Tailor strategies to the national seasonality signature rather than applying a one-size-fits-all approach across the region.

This report does not claim to forecast the future; it offers a robust diagnostic: under realistic activity trajectories, tourism seasonality remains a potential operational constraint even when countries are reducing annual emissions. That diagnostic should reshape how we judge decarbonization progress: success must be measured by both annual climate metrics and seasonal operational resilience. The modelling framework and policy steps documented here provide a practical blueprint for other tourism-intensive, water-sensitive regions that face the same trade-offs between greener energy systems and the resilience needed to serve peak-season communities and visitors.

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1. Introduction

Tourism in the Mediterranean has grown rapidly over recent decades, becoming a major economic pillar for countries. However, this growth is highly seasonal, with visitor flows concentrated in a few warm months and in geographically confined coastal and island nodes (Niavis, 2020; Krabokoukis & Polyzos, 2024). That pronounced seasonality produces short-lived but intense peak loads that stress energy systems (cooling demand, transport fuels, grid flexibility), freshwater supplies (especially on islands and coastal aquifers), waste-management and sanitation services, and local infrastructure for housing and mobility (Milano *et al.*, 2019; Mihalic, 2020). These concentrated pressures are not clearly depicted in annual totals, and characterize the practical problem of overtourism: when short periods of extreme demand exceed institutional and infrastructural capacity, they make residents' everyday life more difficult, degrade visitor experience, and threaten the long-run sustainability of destinations (Cheung & Li, 2018; Garau-Vadell *et al.*, 2018). The result is a tightly coupled economy–energy–water–infrastructure nexus in which seasonal tourism peaks amplify operational risks and compound climate vulnerabilities (hotter, drier summers, altered season timing), making the management of peak loads and resource security an urgent policy priority for Mediterranean destinations.

Globally, governments and regions have explicitly or implicitly committed to net-zero targets by 2050. National decarbonization plans and National Determined Contributions (NDCs) overwhelmingly emphasize energy-system transformations: rapid deployment of renewables, electrification, and efficiency improvements in supply and demand (Koundouri *et al.*, 2025a; Koundouri *et al.*, 2025b; Fragkos *et al.*, 2024). Those energy-first strategies are necessary but often narrow (Alamanos *et al.*, 2024; Koundouri & Alamanos, 2023): by focusing principally on supply-side technology and aggregate annual emissions they can overlook important cross-sectoral drivers of demand (sectoral composition, fuel type switching, transport and tourism growth) and non-energy resource constraints such as freshwater availability. This gap matters most in places where large, short-lived peaks in activity produces highly asymmetric loads on electricity, fuels and water that are not visible in annual totals (Alamanos, 2024a; Gleick & Palaniappan, 2010; McCabe *et al.*, 2008). Such effects are more evident in the tourism-driven summer surges in the Mediterranean countries (Roson & Sartori, 2014; Angeli *et al.*, 2020). Crucially, tourism tends to receive limited explicit treatment in national decarbonization planning, so potential trade-offs and cross-sectoral feedbacks (e.g., raising electricity needs, peak aviation and maritime fuel demand, pressure on local water supplies) remain under-quantified (Ricard *et al.*, 2023).

To address this gap, we apply a holistic, coupled economy–energy–water assessment to account for cross-sectoral effects and trade-offs (in line with the broader philosophy of (Alamanos, 2024c), to major Mediterranean tourism hotspots, where we can isolate and quantify the tourism effects and seasonality. The objective is to explore whether and how seasonal peaks undermine or complicate net-zero pathways, to quantify those interactions for the first time in these settings, and to provide transferable guidance for other seasonally stressed destinations worldwide. In order to answer this research and practical question thoroughly, we linked a global Computable General Equilibrium (CGE) model (GTAP-E) which provides sectoral activity drivers, feeding a sectoral energy–emissions model (LEAP) and a purpose-built water module (WaterReqGCH), allowing consistent translation of economy-wide structural change into monthly energy and water demand, under baseline and National Commitments (NC) scenarios.

Literature Review

Many national decarbonization assessments are built around bottom-up energy accounting/optimization tools (e.g., LEAP- or ESOM-type, or based on tools like TIMES and PyPSA), producing technology and emissions pathways without economy-wide equilibrium feedbacks on prices, sectoral output, trade, and welfare (Emodi et al., 2017). Where macroeconomic consistency is needed, the literature shows that explicit CGE–energy system linkages exist but remain specialized and methodologically demanding, which helps explain why they are still not standard in national energy/water planning practice (Krook-Riekkola et al., 2017; Fattahi et al., 2023a). The very few applications linking CGE with energy models are so far focusing on certain sectors (Meng et al., 2018; Delzeit et al., 2020). This supports a research gap around economy–sector coupling: most national energy/decarbonization studies still rely on exogenous or simplified sectoral drivers rather than tightly coupled CGE producing internally consistent sectoral activity and trade patterns for the same assessment, considering all sectors of the economy.

In water planning and water-management assessments, a parallel pattern appears: widely used decision-support frameworks emphasize hydrology, demands, allocations, and scenario evaluation, often without an explicit economy module that endogenizes sectoral production, consumption, and trade responses to water scarcity or water policy (Bekchanov et al., 2017; Koundouri et al., 2025). This reinforces the “not designed together” critique for national planning: even when water tools can represent multiple demands and infrastructure choices, they typically do so through engineering/hydrology-centric structures rather than being integrated with a general equilibrium representation of the whole economy (Alamanos et al., 2020; Alamanos et al., 2019; Alamanos, 2021; Alamanos et al., 2019; Alamanos et al., 2021). The opposite also appears in the literature, with several applications that are built solely based on economic models without considering the hydrologic or engineering aspects of sectoral water withdrawal patterns (Luckmann et al., 2014; Englezos et al., 2023).

On the other hand, tourism is often handled in a separate analytical tradition, which helps explain why it is frequently not explicitly isolated in national energy–water decarbonization planning models. Tourism-related emissions and supply-chain effects are commonly quantified using tourism satellite accounts and input–output approaches, which can attribute embodied emissions across sectors but are not usually linked to energy system and hydrological modules in the same framework (Li et al., 2019). For environmental impacts, specific resources’ footprints are the main approach (Cazcarro et al., 2014; Michailidou et al., 2015). Likewise, tourism can be modelled with tourism-focused CGE simulations (e.g., carbon tax impacts within tourism), but these studies typically evaluate tourism as the object of analysis rather than producing an integrated set of national energy–water decarbonization pathways where tourism seasonality and infrastructure constraints are jointly reconciled (Zhang & Zhang, 2018). Therefore, the explicit separation of tourism-induced activity from other demand drivers across supply chains and trade flows remains limited in the modelling architectures that dominate national energy/water decarbonization assessments.

A key technical reason why seasonal peak isolation is scarce is the well-documented trade-off between temporal resolution and tractability in long-horizon energy-system modelling: many studies aggregate time series (representative days, time slices, clustering) to keep optimization and scenario runs computationally feasible, which can blur intra-annual peaks and peak-driven constraints (Nahmmacher et al., 2016; Hoffmann et al., 2020). As a result, even when annual totals are robust, peak system stress (capacity adequacy, water-for-cooling bottlenecks, or coincident seasonal demand surges) is harder to

attribute to a specific driver such as tourism—especially when tourism demand is embedded within broader “services/municipal” aggregates (Escriva-Bou et al., 2018; Grubert & Marshall, 2022). There are studies that quantify tourism effects at monthly resolution in specific places (e.g., coastal municipalities), which highlights that the methods exist but remain unevenly adopted and rarely carried through into national, cross-sector decarbonization planning workflows (Toth et al., 2018; Alamanos, 2021; Rupp et al., 2024).

These limitations propagate into policy evaluation: NECP-style measures and national commitments are often assessed as long-run emissions and technology outcomes, while the literature shows that building operational, linked frameworks that reconcile macroeconomics (CGE), detailed energy infrastructure, and resource constraints is challenging and still not routine (Koundouri et al., 2026a). At the same time, the widespread use of temporal aggregation in long-term energy planning means that peak and seasonal stress-testing, and its interaction with water constraints, can be systematically underemphasized relative to annualized indicators, limiting guidance on how near-term policy packages shift peak risks rather than just cumulative totals (Pfenninger, 2017). So, there is a need for integrated, linked national frameworks that: (i) preserve enough intra-annual detail to isolate peak drivers (including service-sector seasonality where relevant), (ii) separate tourism-induced demand from other drivers across supply chains, and (iii) evaluate decarbonization measures not only on long-run totals but also on peak system stress under water constraints (Fattahi et al., 2023b; Hoffman, 2018; Koundouri et al., 2025c; Krook-Riekkola et al., 2017).

Despite a growing body of national energy-transition modelling for each country, e.g., long-horizon decarbonization pathway work for Greece (Tigas et al., 2015; Alamanos, Devves, et al., 2025) and for Cyprus (Demetriou et al., 2021), and water-stress/availability modelling that is typically geographically partial (Koutroulis et al., 2013; Cleridou et al., 2014a; Alamanos et al., 2018), there remains a Mediterranean evidence gap: an absence of comprehensive, model-based assessments for Greece and Cyprus (two major tourism destinations) that jointly evaluate energy pathways, emissions, and water stress under policy scenarios.

Objective and Contribution

The objective of this study is to address these gaps outlined in the previous sub-section. It aims to quantify how tourism-driven seasonality translates into peak energy demand, emissions and water stress under a business-as-usual baseline and under full implementation of National Commitments (NC) measures to 2050. By linking a global CGE providing consistent sectoral drivers into a detailed energy model (LEAP) and a water module, we present an integrated framework for annual and intra-annual patterns and trade-offs, while explicitly isolating tourism to quantify its national-scale effects.

The contribution is twofold: methodologically, we present a multi-model, economy-to-sector assessment that combines global general equilibrium outcomes with energy and water analysis to capture tourism seasonality. Second, practically, we provide model-informed, actionable insights for policymakers, grid and water operators, tourism planners and investors. Thus, we provide specific recommendations on infrastructure timing, demand-management, and coordinated sectoral planning expressed in explicit annual and seasonal metrics to support NC implementation and resilient service provision during tourism peaks.

2. Case studies

Tourism demand in Europe is highly seasonal, and that the strongest seasonality is concentrated in the Mediterranean/South-East, where summer peaks coincide with heat, drought risk, and high electricity demand for cooling (World Bank Publications, 2014; Alamanos, Xenarios, et al., 2025). Greece and Cyprus are mature Mediterranean touristic destinations where tourism functions not only as a major export service, but also as a central driver of short-run demand fluctuations and infrastructure loads. Their tourism models are characterized by strong peak-season concentration in coastal and island destinations, implying that pressures on energy, water, transport, and municipal services are often determined by temporal spikes rather than annual averages, an especially relevant setting for analyzing overtourism and seasonality-linked resource stress (Batista e Silva et al., 2018). According to Eurostat's data (Eurostat, 2024) July–August concentrate a very large share of annual tourism nights, with Greece and Cyprus being among the countries with the strongest seasonality.

In Greece, inbound travel is both large in scale and increasingly concentrated in the high season (Fig.1). Bank of Greece reports 40.7 million inbound travellers in 2024 and €21.6 billion in travel receipts, alongside 240.8 million overnight stays by non-residents (Kathimerini, 2025). The contribution of travel and tourism to GDP and employment is approximately one fifth, highlighting Greece's high macroeconomic exposure to tourism cycles (Hatzimarinakis & Hackl, 2023). Seasonality is pronounced in accommodation activity. The Hellenic Statistical Authority estimates that 63.8% of nights spent in hotels, similar establishments, campsites, and short-stay accommodation occur between July and October, underscoring the concentration of tourism intensity within a few months (Devves et al., 2025a; Koundouri et al., 2026b)(Devves et al., 2025; Koundouri et al., 2025). In policy terms, Greece's final updated National Energy and Climate Plan (NECP) sets the national decarbonization direction (renewables expansion, electrification, infrastructure), providing the formal scenario-policy backbone for analysing system transition pathways. Water planning is governed through the Water Framework Directive (WFD) River Basin Management Plans (RBMPs), with Greece operating multi-RBD planning cycles and documented implementation pressures around plan updates, which is directly relevant when positioning “energy–water–policy” integration as a research need. On the modelling literature side, national-scale decarbonization pathway studies for Greece exist (e.g., long-horizon renewable penetration / decarbonization targets), but they typically remain energy-system focused and do not operationalize explicit tourism-driven seasonal demand as a distinct driver within an integrated energy–water–economy framework (Devves et al., 2025b; Koundouri et al., 2025d). Complementary water-stress work is often regional/sectoral (e.g., agricultural basins or small islands), supporting the claim that Greece lacks comprehensive national, cross-sector modelling that can trace seasonal service-demand peaks into coupled water–energy stress outcomes under policy scenarios (Alamanos & Koundouri, 2024b).

Cyprus exhibits similarly high dependence on tourism, with considerable sensitivity to peak-season demand and strong reliance on air connectivity (Fig.1). Cyprus Statistical Service reports 6.11 million travellers arriving in 2023, including 3.85 million tourist arrivals, and estimates tourism revenue at €3 billion (CyprusMail, 2026). Arrivals were overwhelmingly by air (about 95%), and the mean duration of stay was 8.6 nights. In macroeconomic terms, the total contribution of travel and tourism was about 12% of GDP in 2022, with direct effects at 5.5% of GDP, indicating substantial economy-wide exposure even before accounting for the recent revenue rebound (Cystat, 2026; gov.cy, 2025). Cyprus is an insular energy system with limited indigenous resources and a well-documented water scarcity and drought sensitivity,

which makes it a strong case for analysing water constraints as a binding condition for service provision during summer peaks (Cleridou et al., 2014a). Again, the NECP is the natural reference for policy-scenario and decarbonization design in a national transition assessment, while water governance similarly follows RBMP cycles, with Cyprus' 3rd RBMP (2021–2027) establishing the planning basis (Water Framework Directive, 2023).

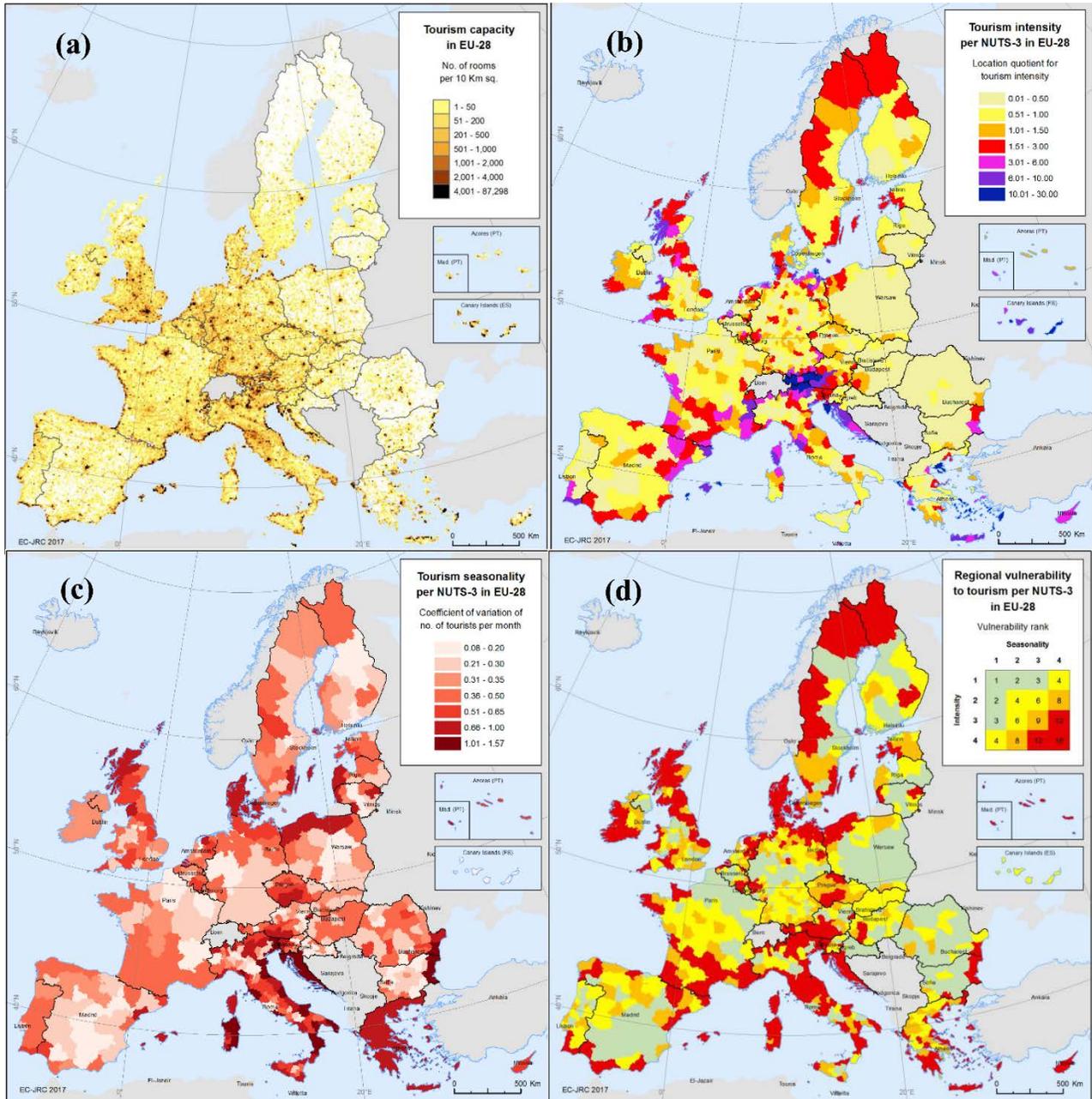


Figure 1: Touristic pressures in Europe, indicating that: (a) Greece and Cyprus have relatively less capacity than other countries. However, they are facing among the highest intensities (b), and seasonality peaks (c). These findings rank Greece and Cyprus among the top vulnerable hot-spots to tourism. Adapted from: (Batista e Silva et al., 2018).

Specifically, focusing on the natural resources, the most compelling evidence comes from the European EEA, reporting the water scarcity and seasonal press per country (Fig.2). Cyprus comes first with significant difference, followed by Malta and Greece.

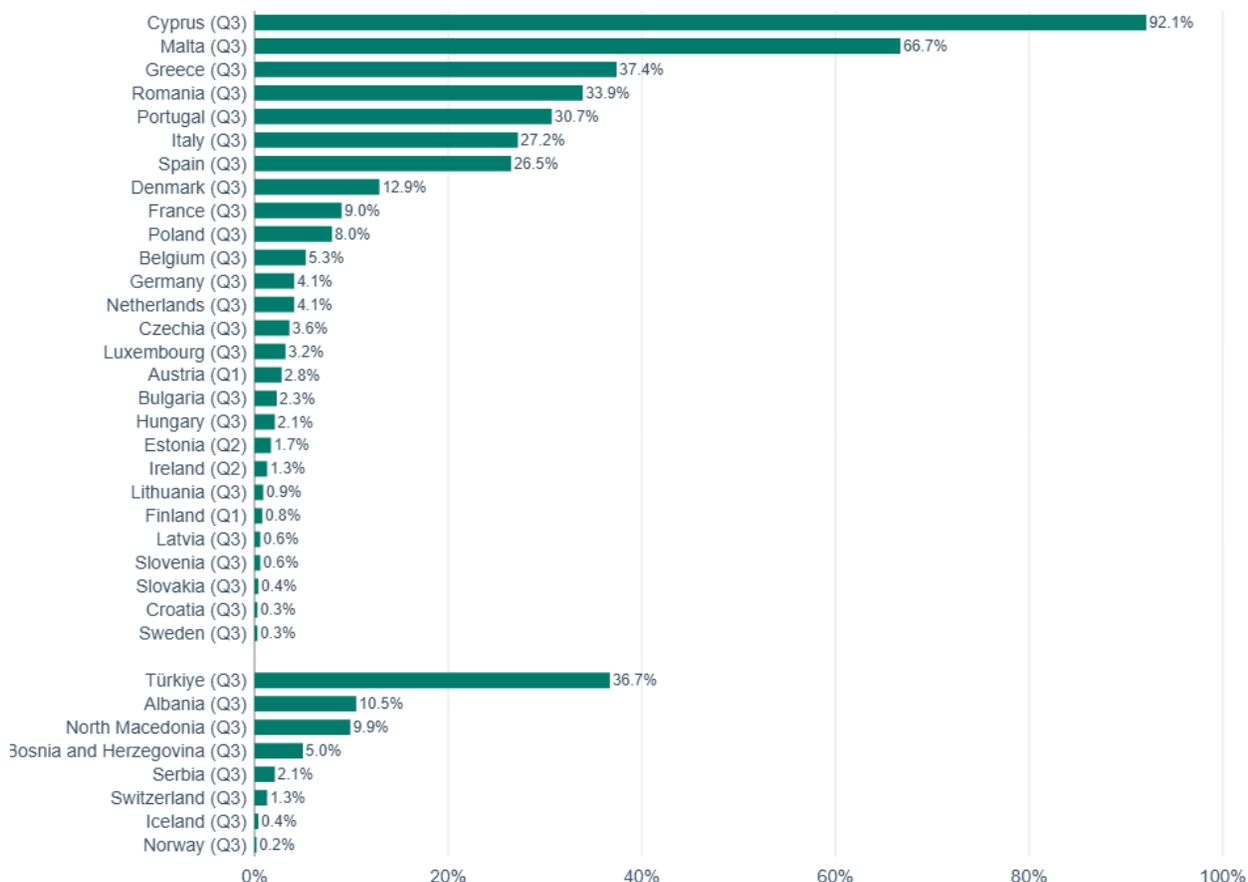


Figure 2: Worst seasonal water scarcity conditions for European countries in 2023, measured by the water exploitation index plus (WEI+). Source: EEA (European Environment Agency, 2024).

Together, these profiles motivate focusing on Greece and Cyprus as high-tourism-intensity systems where seasonal demand peaks can plausibly translate into binding constraints and stress episodes in energy and water services. Greece and Cyprus represent a broader class of tourism-peaked, water-constrained, heat-exposed systems where climate-driven summer stress aligns with service-demand seasonality and rapid decarbonization requirements. Therefore, the resulting insights of this analysis should be especially relevant to other Mediterranean and island/coastal contexts (several shown in Fig.1) such as Spain (Balearics/Canaries), Portugal (Algarve/Madeira), Italy (islands/southern regions), Croatia/Adriatic, and to similar tourism–water–energy stress settings globally (e.g., Aegean-like island systems, Caribbean SIDS, Red Sea destinations, parts of coastal North Africa and the Middle East), where governance analogues exist even if policy instruments differ.

3. Methodology

In order to give a complete picture of sectoral-driven seasonality (including tourism) evolve and translate into energy-system stress and water pressures, we coupled an economy-wide CGE model with detailed sectoral models for the energy and water systems. The Global Trade Analysis Project (GTAP-E) CGE model was used first to generate a consistent long-run macroeconomic and sectoral demand baseline under the Shared Socioeconomic Pathways (SSP) projections to 2050. This demand drives the energy consumption fuel supplies, with the respective emissions, and water withdrawals.

Using a global CGE is essential in this context since tourism-related sectors, and their supply chains, are shaped by international trade, factor markets, and relative prices. Hence, the sectoral trajectories for Greece and Cyprus are determined as outcomes of a global general equilibrium rather than merely country-specific extrapolations, contrary to most existing approaches. Next, these sectoral outputs are used as activity drivers in an energy-emissions model and, in parallel, a water module (Fig. 3).

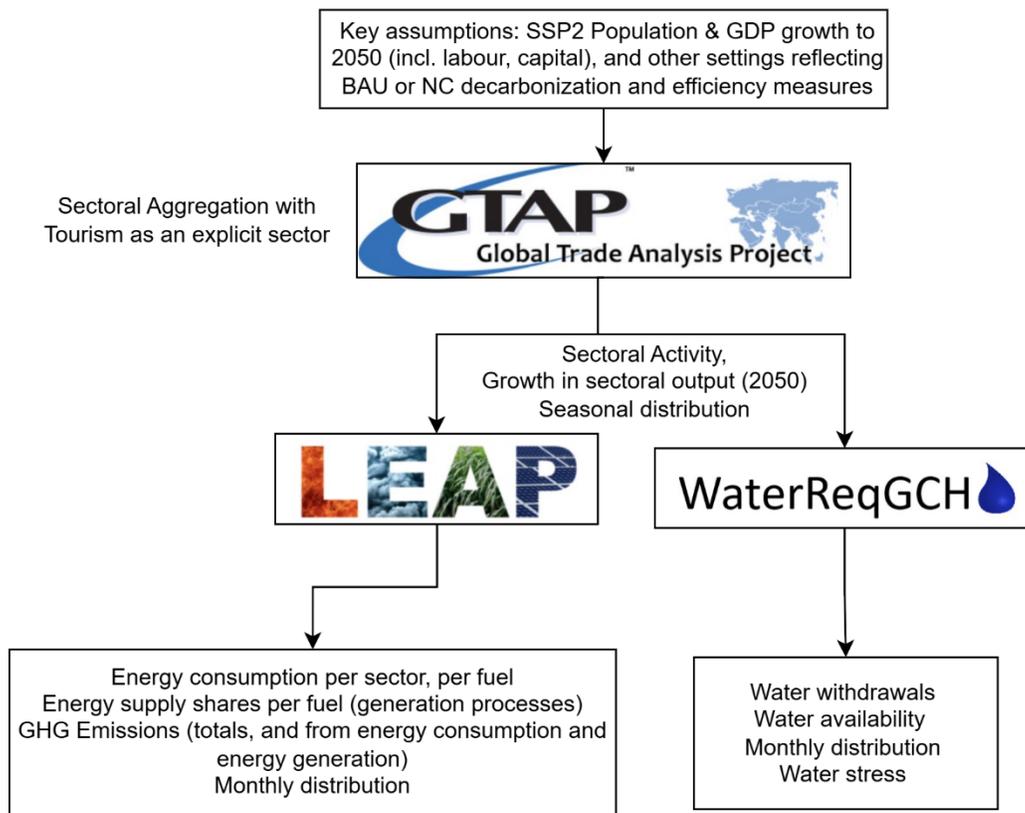


Figure 3. The modelling framework, with the tools, their inputs and outputs, and their connections.

The Global Trade Analysis Project (GTAP) model



We use GTAP-E, an energy-environment extension of the standard GTAP CGE framework, to project sectoral economic activity under a globally consistent equilibrium (Aguiar et al., 2022a)]. GTAP is a multi-region, multi-sector CGE model

widely used for trade and policy analysis, typically assuming competitive markets, constant returns to scale, and Armington differentiation between domestic and imported goods (Hertel, 1997). GTAP-E augments this structure by explicitly representing energy commodities and linking fossil-fuel combustion to CO₂ emissions, enabling energy-economy interactions within the general equilibrium solution (Burniaux & Truong, 2002).

The CGE calibration is anchored to 2017 as the base year, consistent with GTAP database vintages that include 2017 as a reference year (Aguiar et al., 2022b). Exogenous projections for population and macroeconomic drivers (GDP, labor, and capital growth) follow the SSP2 (“middle-of-the-road”) pathway (Riahi et al., 2017). These trajectories are imposed in GTAP-E as the long-run drivers of factor endowments and economic scale, and the model is solved to produce a 2050 equilibrium that includes, among others, sectoral output levels for Greece and Cyprus.

For consistency with the sectoral structure required in the subsequent sectoral energy and water models as well as this study’s focus on tourism-related activities, the GTAP sectors are aggregated to a study-specific classification (Table 1). The key output transferred from GTAP-E to the energy and water models is sectoral output (by aggregated sector), subsequently interpreted as the activity level that drives final energy and water demand in each corresponding energy and water branch. This mapping allows the energy and water systems trajectories to reflect economy-wide structural change and international equilibrium effects.

Table 1. GTAP-E sectoral aggregation used in this study

Sectors	Sub-sectors
Residential	Municipal, non-touristic residences.
Industry	Mining extraction, bovine meat products, other meat products, vegetable oils & fats, dairy products, processed rice, sugar, other food products, beverages & tobacco products, textiles, wearing apparel, leather products, wood products, paper products & publishing, chemical products, basic pharmaceutical products, rubber & plastic products, other mineral products, ferrous metals, metal products, other metals, computer & electronic equipment, machinery & other equipment, motor vehicles & parts, other transport equipment, other manufacturing
Coal	Mining & agglomeration of hard coal, lignite & peat
Oil products	Manufacture of coke & refined petroleum products
Natural gas	Extraction of natural gas, service activities incidental to oil & gas extraction excluding surveying (part)
Electricity	Electricity, steam & air conditioning supply
Agriculture	Paddy rice, wheat, cereal grains, vegetables & fruits & nuts, oil seeds, sugar cane & sugar beet, plant-based fibers, other crops, bovine cattle & sheep &

	goats, other animal products, raw milk, wool & silk-worm cocoons, forestry, fishing
Land transport	Land transport & transport via pipelines
Air transport	Air transport
Water transport	Water transport
Core tourism services	Accommodation & food & service activities, recreation & other services
Tourism-supporting services	Wholesale & retail trade, warehousing & support activities, information & communication, other business services
Other services	Insurance, other financial services, real estate, education, human health and social work, other governmental services, dwellings
Water services	Water supply & sewage & waste management & remediation activities

Cross-sectoral Energy-Emissions Analysis



Energy use and emissions are simulated using the Low Emissions Analysis Platform (LEAP), a scenario-based, long-term integrated energy-environment modelling tool developed by the Stockholm Environment Institute and widely applied for national and sub-

national energy and climate planning (Koundouri et al., 2025c). It has been developed as a scenario-based modelling tool that explores how emissions may change in the future. LEAP has been employed in numerous applications globally, from local municipalities to national governments (Fall & Mbodji, 2022a). For instance, countries have utilized LEAP to develop their Nationally Determined Contributions (NDCs) under the Paris Agreement, showcasing its relevance in climate policy formulation. The model’s flexibility enables it to accommodate various methodologies, including bottom-up end-use accounting and top-down macroeconomic modelling, making it suitable for integrated resource planning and GHG mitigation assessments (Fall & Mbodji, 2022b). This functionality allows for the simulation of specific policies as modelling scenarios, enabling detailed evaluation of their impacts and trade-offs. The model’s ability to simulate different scenarios has been particularly useful in exploring future conditions and/or ways for decarbonization (Liu et al., 2021; Xu et al., 2024).

LEAP represents final energy demand by sector and fuel, energy supply through primary/secondary resources and transformation processes (e.g., power generation, refining, transmission and distribution), and the associated GHG and air pollutant emissions.

Final energy demand in each sector is modelled using LEAP’s standard accounting identity (Eq. 1):

$$D_{sector,scenario} = AL_{sector,scenario} \cdot EI_{sector,scenario} \tag{1}$$

where *D* is the energy demand, *AL* the activity level, and *EI* an annual energy intensity (energy use per unit of activity).

In the base year, final energy consumption per sector and fuel is taken from Eurostat energy balances (Eurostat, 2024). Sectoral activity levels for industry, agriculture, transportation, and services branches are taken from GTAP-E outputs (base year), allowing base-year energy intensities to be computed as in Eq. (1). For the residential sector, we employ the number of buildings as the activity level, approximated as shown in Eq. (2). In projection years, activity levels evolve following the GTAP-E-derived sectoral trajectory to 2050, while energy intensities vary by scenario.

$$\text{Buildings} = \text{Population/Persons_per_Hshld} \quad (2)$$

The energy supply module represents both energy resources, capturing the availability and key attributes of primary and secondary fuels, and the set of transformation activities that convert, transmit, and deliver energy via technologies such as power plants, refineries, and electricity grids. This module ensures energy-balance consistency between demand requirements and supply-side production and losses.

For all sectors' energy consumption, and per each fuel's combustion, LEAP estimates the respective GHG emissions, using built-in emission coefficients per category, according to the global warming potentials approach of the IPCC's Sixth Assessment Report (Pachauri et al., 2015). Table 2 summarizes: (i) the final demand sectors, their activity level definitions and sources; (ii) the key supply-side elements; and (iii) the pollutants tracked.

Table 2. The main types of inputs in the LEAP model, for each sector.

Energy Demand		
Sectors	Activity Level (AL)	Data Sources
Residential	Number of buildings (calculated based on SSP2 population projections and average number of persons per household, see Eq. (2))	IIASA; EUROSTAT
Industry	Sectoral output	EUROSTAT; Own calculations (GTAP)
Agriculture	Sectoral output	EUROSTAT; Own calculations (GTAP)
Land transport	Sectoral output	EUROSTAT; Own calculations (GTAP)
Air transport	Sectoral output	EUROSTAT; Own calculations (GTAP)
Water transport	Sectoral output	EUROSTAT; Own calculations (GTAP)
Core tourism services	Sectoral output	EUROSTAT; Own calculations (GTAP)
Tourism-supporting services	Sectoral output	EUROSTAT; Own calculations (GTAP)
Other services	Sectoral output	EUROSTAT; Own calculations (GTAP)
Water services	Sectoral output	EUROSTAT; Own calculations (GTAP)

Energy Supply (fuels' production processes to cover the demand)		
Primary resources	Solar, crude oil, coal lignite, hydropower, wind, coal, municipal solid waste, biofuels	EUROSTAT; IEA; ELSTAT
Secondary resources	Diesel, petroleum coke, refinery feedstocks, residual fuel oil, kerosene, CNG, LPG, gasoline, Hydrogen, biogas, oil, heat, electricity, synthetic fuels	
Transformation processes	Transmission and distribution, synthetic fuel production, generation of hydrogen, electricity, heat, oil refining – with the associated losses	
GHG Emissions		
Types of pollutants	CO ₂ , CH ₄ , N ₂ O, PM2.5, Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF ₆), Black Carbon (BC), Organic Carbon (OC)	IPCC

Water Requirements and Supply



As part of this coupled economy–energy-emissions–water assessment, we quantify sectoral freshwater withdrawals (Mm³), and water stress, by (i) calibrating base-year water-use intensities to national withdrawal totals, (ii) projecting future withdrawals using scenario-consistent activity drivers (from the economic model GTAP), (iii) disaggregating annual withdrawals to monthly profiles using sector-specific seasonality shares, and (iv) computing annual and seasonalized water-stress indicators based on blue-water availability.

For the estimation of the water withdrawals, the WaterReqGCH model was used, which synthesizes existing databases and analyses them to provide insights on water use and stress (Alamanos & Koundouri, 2024a).

Following a standard accounting structure analogous to energy-demand modelling in LEAP, sectoral water withdrawals (W) are computed from an intensity (I) × activity (A) formulation using the economy module activity drivers from GTAP, per sector s and year y (Eq. 3).

$$W_{s,y} = A_{s,y} \cdot I_{s,y} \tag{3}$$

where $I_{s,y}$ is the calibrated base-year withdrawal intensity (Mm³ per activity unit).

The sectors s that were used in this model were the main uses consuming water, namely irrigation, industry, municipal, livestock, tourism. Their activity levels were obtained from GTAP-E’s results, as sectoral outputs, and according to their annual growth factors to 2050 (Table 3).

Base-year total freshwater abstraction/withdrawals and sectoral allocation ranges are derived from national water accounts and complementary statistics from Eurostat water datasets (AQUASTAT & FAO, 2026; Eurostat, 2025), expressed in million cubic metres (Mm³).

Blue-water availability and the “baseline water stress” definition follow the (Aqueduct, 2026) convention, where baseline water stress (S_t) is the ratio of annual withdrawals (W_t) to mean available renewable blue water (B_t) (Eq. 4). The data were retrieved from Aqueduct’s Water Risk Atlas, including its future projections (Aqueduct, 2026). This is the most commonly used approach to estimate hydrological water stress at scale.

$$S_t = \frac{W_t}{B_t} \quad (4)$$

Tourism seasonality representation and data

To capture within-year (monthly) tourism seasonality and its implications for peak energy and water pressures, we develop monthly seasonality factors for the tourism-related sectors identified in Table 1, namely land transport, air transport, water transport, core tourism services, and tourism-supporting services. Because the core GTAP-LEAP linkage is annual, seasonality is introduced as a temporal disaggregation layer that preserves annual totals while revealing intra-annual peaks.

For each country and each tourism indicator $x_{y,m}$ (where y : year, m : month) described below, we compile monthly observations for 2022-2024 and compute a post-COVID “typical year” profile using: (i) the monthly mean \bar{x}_m (Eq. 5) and (ii) the corresponding monthly shares s_m (Eq. 6).

$$\bar{x}_m = \frac{1}{3} \sum_{y=2022}^{2024} x_{y,m} \quad (5)$$

$$s_m = \frac{\bar{x}_m}{\sum_{m=1}^{12} \bar{x}_m} \quad (6)$$

These shares are then used to disaggregate annual sectoral activity from GTAP/LEAP into monthly activity and to compute monthly energy demand accordingly.

We focus on 2022-2024 to represent the post-pandemic tourism system and to avoid the structural break induced by COVID-19 (e.g., travel restrictions and abrupt demand collapse), which is widely documented to disrupt tourism time series and complicate inference based on pre-2020 seasonality patterns (Škare et al., 2021; Gössling & Schweiggart, 2022).

For air transport, monthly seasonality factors are derived from Eurostat data on passengers carried (Eurostat, 2026c). We rely on the Eurostat methodology that excludes double counting in national and intra-EU aggregates by using departure declarations. The resulting monthly passenger shares are applied to the air transportation activity series in LEAP (Table 2) to obtain monthly air-transport activity profiles consistent with annual GTAP-driven growth.

For water transport, monthly seasonality factors are derived from official port traveler statistics. For Greece, we use the Maritime Traffic Data dataset (govgr, 2026), which provides passenger traffic information with route and port identifiers and covers a period beginning in 2017 (Koundouri et al., 2025e). Daily observations are aggregated to monthly totals and then converted to 2022-2024 monthly

shares. For Cyprus, monthly arrivals and departures of travelers by port are obtained from the Statistical Service of Cyprus (CYSTAT-DB, 2026). We aggregate to national monthly totals and compute the 2022-2024 typical-year shares. These shares are applied to the water transportation activity series in LEAP.

For land transport, we construct the monthly seasonality profile using Eurostat’s monthly energy balances for oil products, relying on observed gross inland deliveries – observed of road fuels as a high-frequency proxy for apparent consumption, and thus for mobility intensity. Specifically, we extract monthly inland-market deliveries of motor gasoline and road diesel from Eurostat’s supply and transformation of oil and petroleum products dataset and compute a 2022-2024 average monthly distribution to represent a post-COVID typical year (Eurostat, 2026a). Eurostat/IEA reporting guidance defines observed gross inland deliveries as observed deliveries of oil products from primary sources to the inland market, which may differ from calculated inland deliveries derived from supply-side identities. This makes this proxy particularly useful for capturing a clean monthly signal of domestic fuel use when direct monthly mobility indicators are unavailable. We emphasize motor gasoline because it is closely linked to passenger-car activity, while road diesel is explicitly on-road and helps avoid confounding with non-transport uses. As with all market-deliveries proxies, our proxy does not represent pure end-use consumption and can be influenced by inventory or commercial movements, but it is a pragmatic and commonly used approach for recovering seasonality profiles.

For core tourism services and tourism-supporting services (Table 1), explicit monthly output/activity data are not available at the required sectoral granularity. We therefore use the monthly distribution of nights spent in tourist accommodation establishments as a proxy for the seasonal profile of tourist presence and tourism-related service demand. This proxy is widely used in the tourism literature because overnight stays are a standard demand-side indicator and are commonly employed as a proxy for tourism flows and tourism demand intensity (Claveria & Torra, 2014). Monthly nights-spent distributions are obtained from Eurostat’s tourism accommodation statistics (Eurostat, 2026b), from which we compute 2022-2024 typical-year monthly shares. These shares are applied to the core tourism and tourism-supporting services activity series in LEAP.

Regarding the WaterReGCH model, the same approach is followed, where base-year tourism activity is measured as annual nights spent in tourist accommodation establishments (guest-nights, annual and monthly) from official tourism statistics (Eurostat, 2026b). Tourism water-use intensity is parameterised in litres per guest-night (L/GN) using peer-reviewed and benchmark evidence, with a scenario range capturing wide uncertainty and heterogeneity across accommodation types and service levels, ranging from 150-600 lt/guest-night, according to values reported from the relevant literature (Tang, 2025). To avoid double counting with reported municipal withdrawals, the non-tourism municipal component is defined according to the relevant GTAP and LEAP’s sectors, and then projected independently using its own activity driver and/or intensity pathway. Annual water withdrawals are distributed to months using sector-specific monthly shares $p_{s,m}$ according to values reported from the relevant literature (GreenForum, 2022; Kolokytha, 1998; Kolokytha et al., 2002; Koundouri et al., 2025a; 2025d; MadeBlue, 2026), so that monthly national withdrawals can then be estimated by Equation 7. This enables identification of peak-demand months and tourism-season pressure consistent with Mediterranean seasonality.

$$W_{s,m} = W_{s,y} \cdot p_{s,m}, \quad \sum_{m=1}^{12} (p_{s,m}) = 1 \quad (7)$$

Scenario Analysis

All models described run under a common simulation period, from 2020 to 2050, at a monthly (and annual) time-step, and under common scenarios. These scenarios refer to the Business-as-usual (BAU) and National Commitments (NC) conditions. In the BAU scenario, no additional energy-system interventions are assumed beyond the evolution of socioeconomic drivers. These refer to the SSP2 Exogenous projections for population and macroeconomic drivers (GDP, labor, and capital growth) follow the SSP2 “middle-of-the-road” scenario, which are translated into exogenous projections for population and macroeconomic drivers (GDP, labor, and capital growth) for GTAP-E, which in turn drives the demands for energy (LEAP) and water (WaterReqGCH) models.

The NC scenario assumes the full implementation of each country’s National Energy and Climate Plan (NECP), reflecting the legally binding objectives for each country. A detailed assessment of the Greek and Cypriot NECPs was performed to facilitate their simulation, including information on energy use efficiencies and cleaner energy mixes, expected fuel shares (phasing out fossil fuels and replacing them with cleaner ones). These were explicitly simulated in GTAP-E and LEAP (e.g., for the NC scenario, activity levels remain consistent with the GTAP-E baseline, while sectoral energy intensities and supply-side technology parameters are modified to reflect the decarbonization measures outlined in the NECPs, such as efficiency improvements, electrification, fuel switching, and changes in the power generation mix, yielding alternative trajectories for energy use and emissions. For the water sector, the Water Framework Directive 2000/60/EC (European Parliament, 2000) establishes a comprehensive framework for water policy, aiming to protect and enhance the quality of water resources across Member-States. While the WFD sets overarching objectives for achieving 'good status' of all water bodies, it does not prescribe specific water consumption reduction targets for individual sectors (European Parliament, 2000). In all Member-States, the implementation of the WFD is carried out through River Basin Management Plans (RBMPs), assessing the status of water bodies and outline Programmes of Measures (PoMs) to address identified issues. While the RBMPs focus on protecting and managing water resources, they do not set explicit sector-specific water consumption reduction targets or measures. Instead, they emphasize the need to improve water efficiency and sustainable use across various sectors (Karavitis & Oikonomou, 2024), rather than setting targets for specific improvements in withdrawals and water availability. These are mostly captured by upper- and lower- end estimates of the future pathways of water withdrawals, availability and stress, as provided by the Aqueduct Water Atlas (Aqueduct, 2026), which we used to test low-end pressures (analogous to the NC, reflecting potentially reduced intensities via efficiency, leakage/NRW reductions, improved irrigation practices and/or increased non-conventional supply that reduces reliance on renewable blue-water withdrawals), and high-end pressures (as a worst-case of upper-end intensities for all sectors, indicating weaker efficiency progress, and higher sectoral withdrawal shares within plausible bounds).

4. Results

Economic model results

The GTAP baseline provides the macro-consistent evolution of sectoral activity to 2050 under SSP2 drivers (Table 3). In both countries, the sectors most directly connected to tourism expand markedly over the horizon, implying that, without targeted policy, tourism-related activity becomes an increasingly important determinant of water and final energy demand.

Table 3. Activity level per sector. The GTAP baseline provides the macro-consistent evolution of sectoral activity to 2050 under SSP2 drivers. The reported activity output levels in 2017 and 2050 are benchmark quantity indices expressed in base-year (constant-price) value units (\$), since benchmark prices are normalized to 1. Therefore, the reported growth rates should be interpreted as real (fixed-price) output/volume changes rather than nominal (current-price) changes. In both countries, the sectors most directly connected to tourism expand markedly over the horizon, implying that, without targeted policy, tourism-related activity becomes an increasingly important determinant of water and final energy demand.

Greece			
Sectors	2017	2050	Growth (%)
Industry	54628.71	61059.55	11.8%
Agriculture	21612.68	24579.25	13.7%
Land transport	8800.90	13409.66	52.4%
Air transport	2713.52	4413.42	62.6%
Water transport	16009.96	30894.39	93.0%
Core tourism	38149.56	69185.93	81.4%
Tourism-supporting services	83983.41	120643.00	43.7%
Other services	89696.39	139869.98	55.9%
Water services	2199.38	3260.13	48.2%
Residential	4454116.88	4073795.00	-8.5%
Cyprus			
Sectors	2017	2050	Growth (%)
Industry	6106.02	11200.82	83.4%
Agriculture	908.59	1432.10	57.6%
Land transport	537.94	996.86	85.3%
Air transport	332.92	1041.74	212.9%
Water transport	5265.50	10225.60	94.2%
Core tourism	6757.33	13877.24	105.4%
Tourism-supporting services	13462.38	23268.85	72.8%
Other services	14175.74	32357.70	128.3%
Water services	381.83	662.69	73.6%
Residential	470010.31	553139.30	17.7%

In Greece, the largest percentage increases to 2050 occur in water transport (+93.0%), core tourism industries (+81.4%), and air transport (+62.6%), with land transport also expanding considerably (+52.4%). Tourism-supporting services rise by 43.7%, while other services grow by 55.9%. By contrast, residential

activity slightly contracts (-8.5%), consistent with the relatively weak population dynamics embedded in the SSP2 macro path. These patterns highlight that, even in a context of subdued household-related activity, the tourism-transport-services nexus can dominate incremental energy and water demand pressures, particularly in peak-season months where these activities are concentrated.

In Cyprus, the projected expansion is even more tourism- and mobility-intensive. Air transport exhibits the strongest increase (+212.9%), followed by core tourism industries (+105.4%) and water transport (+94.2%). At the same time, other services rise substantially (+128.3%), and industry also grows (+83.4%), while residential activity increases modestly (+17.7%). Overall, the baseline suggests a strong upward shift in the scale of tourism-related services and international connectivity, which is particularly relevant for Cyprus given its starting point of higher dependence on aviation-related flows and imported fuels.

Energy-Emissions results

Figures 4 and 5 translate the GTAP activity trajectories into annual final energy demand and demand-side GHG emissions by sector under the two scenarios in each country. Under BAU, total final energy demand rises over time in both countries, reflecting the growth in transport and tourism-related service activities identified by GTAP. Greece’s BAU final energy demand in 2050 is about 41% higher than in 2022, driven mainly by sharp increases in water transport (+102.9%) and core tourism services (+89.4%). In Cyprus, we observe an increase in total final energy consumption of approximately 93% by 2050, consistent with the much stronger growth in Cyprus’ tourism-related sectors. Demand-side emissions follow the same qualitative pattern. In Greece, emissions increase by about 58% under BAU, while in Cyprus by about 119%. This indicates that, without additional measures, sectoral growth translates into substantial additional emissions, especially in the more oil-dependent system.

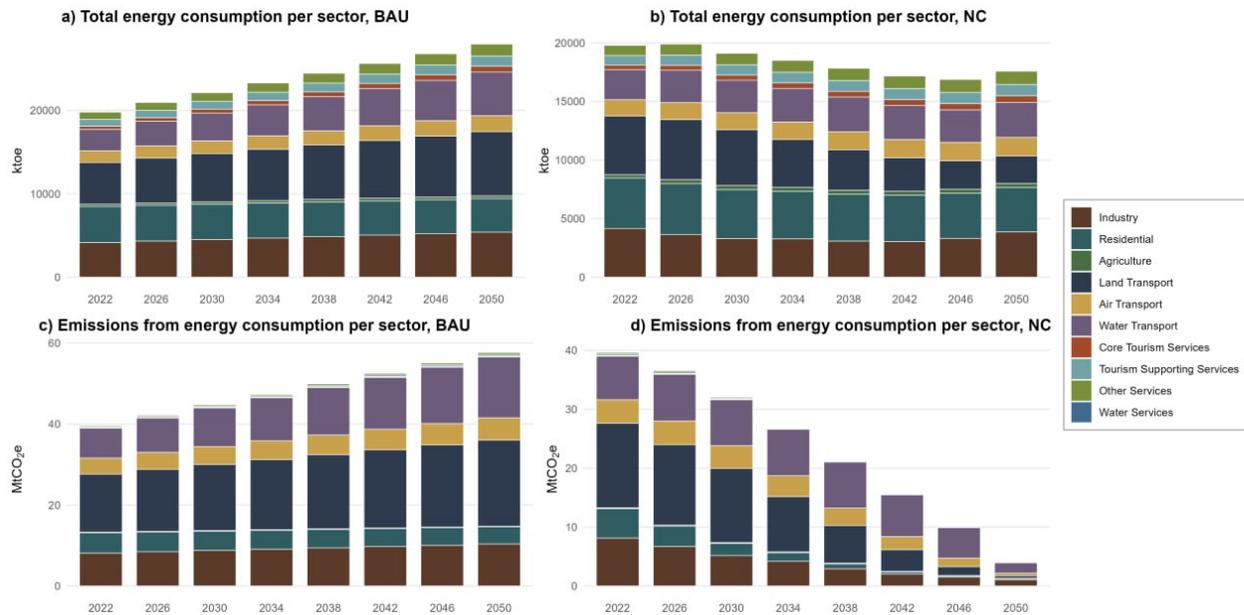


Figure 4. Total energy consumption per sector in Greece, under the BAU (a) and the NC scenario (b), with the respective GHG emissions (100-Year GWP), under the BAU (c) and the NC scenarios (d).

By construction, the NC scenario modifies the technology and efficiency pathways in line with the national plans, and the results show a clear decoupling of activity growth from energy use and emissions. In both countries, total final energy demand declines between 2022 and 2050 under NC (approximately -11% in Greece and -8.5% in Cyprus), suggesting that the combined effects of end-use efficiency improvements and electrification dominate the upward pressure coming from higher activity levels in transportation and services. The response of emissions is much stronger. Demand-side GHG emissions decline by about 90% in Greece and 77% in Cyprus by 2050 relative to 2022. However, these are annual outcomes. They indicate the scale of decarbonization achievable in aggregate, but do not by themselves eliminate the possibility of high peak-season loads and localized stress in the energy-water nexus. This is addressed in the seasonal component of our analysis.

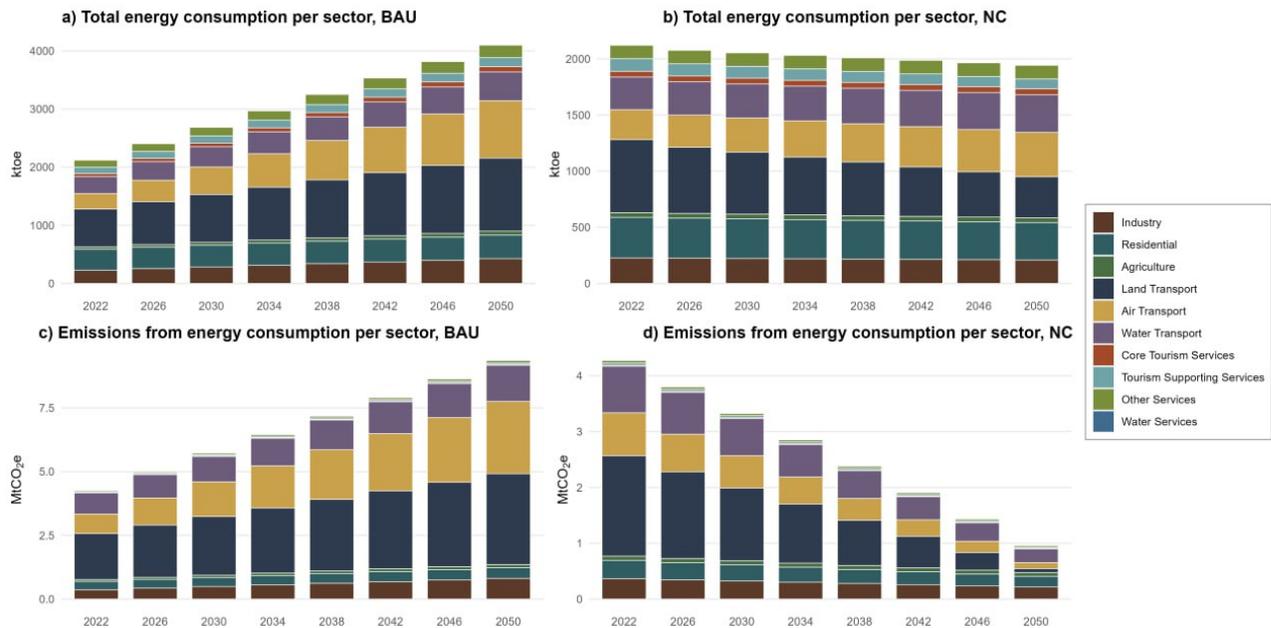


Figure 5. Total energy consumption per sector in Cyprus, under the BAU (a) and the NC scenario (b), with the respective GHG emissions (100-Year GWP), under the BAU (c) and the NC scenarios (d).

Figures 6 and 7 summarize the evolution of energy conversion and associated supply-side emissions. In Greece, the total level of energy conversion output remains broadly stable through 2050 in both scenarios, but the emissions intensity diverges sharply. Supply-side emissions rise under BAU (about +52% by 2050 vs 2022) and fall under NC (about -79%). This pattern is consistent with a BAU pathway that preserves a fossil-heavy conversion structure, versus an NC pathway that substantially reduces the carbon content of energy transformation, especially due to the increased penetration of renewables in electricity generation and reduced oil refining activity.

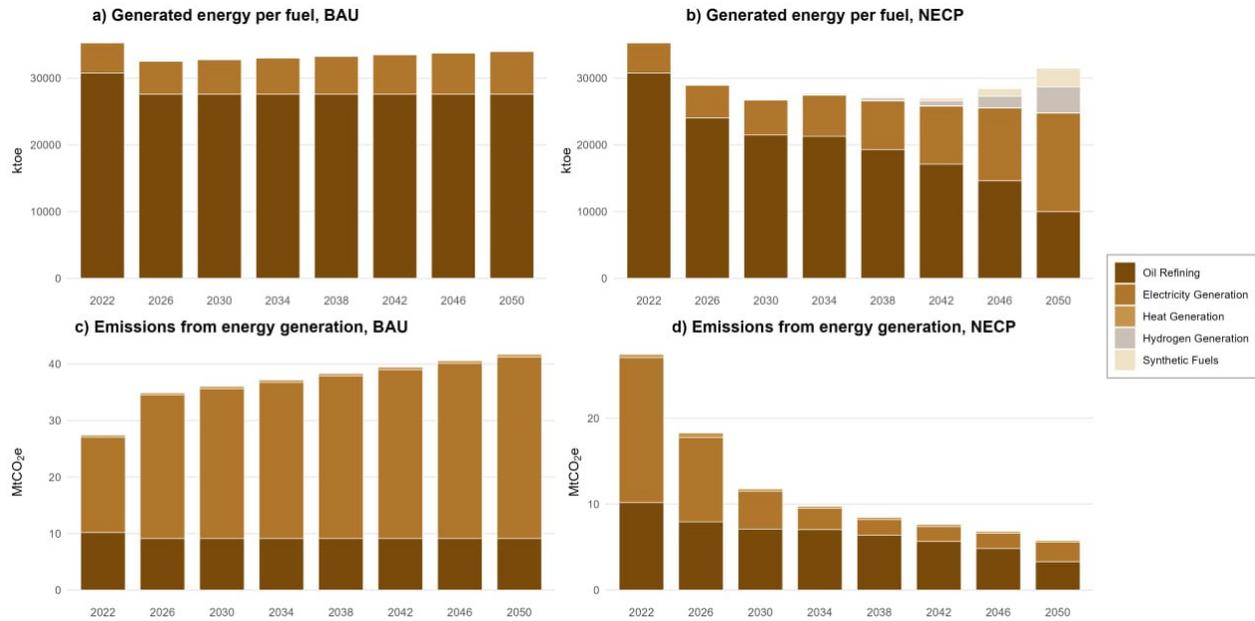


Figure 6. The generated energy from the different feedstock fuels in Greece for the BAU (a), and the NC scenario (b), with the respective GHG emissions (100-Year GWP) from these energy generation processes, for the BAU (c), and the NC scenario (d).

In Cyprus, the energy transformation-side is dominated by power generation dynamics. Under BAU, supply-side energy output and emissions are broadly flat, while NC shows higher conversion output (about +79%) alongside a substantial emissions reduction (about -81%), reflecting rising electricity requirements under electrification and a strong decline in power-sector carbon intensity. This is particularly relevant given Cyprus’ tourism-related growth in air transport and services. Even if aviation fuels remain difficult to fully decarbonize, a cleaner and larger electricity system can still deliver large economy-wide emissions reductions and reduce the indirect emissions footprint of tourism-related services (accommodation, retail, ancillary activities).

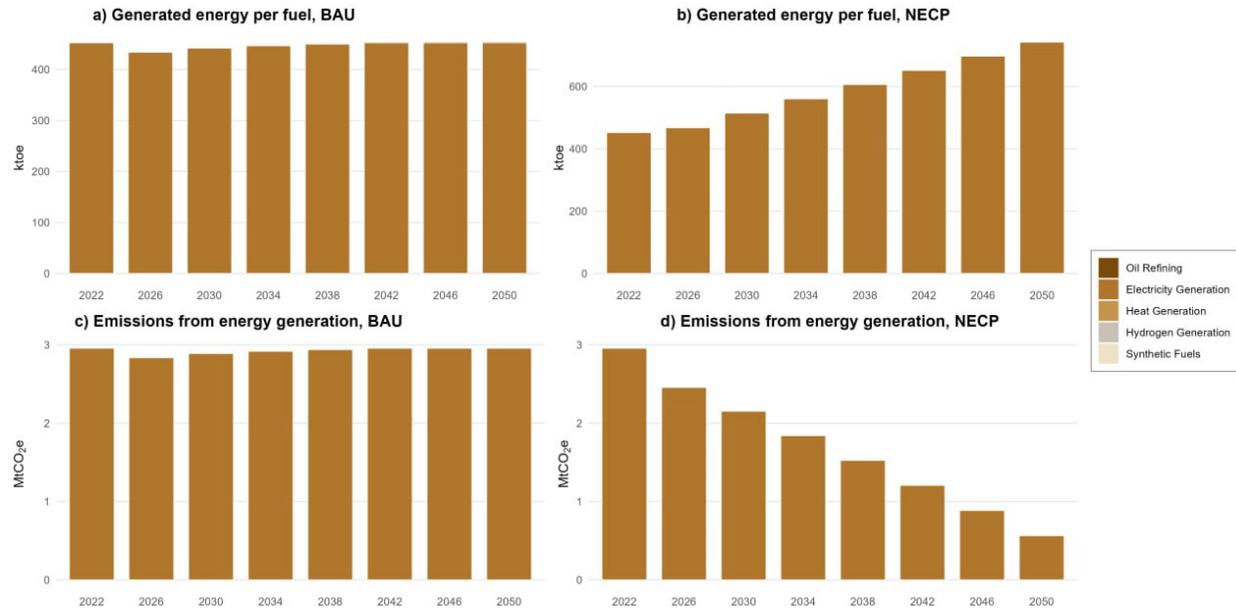


Figure 7. The generated energy from the different feedstock fuels in Cyprus for the BAU (a), and the NC scenario (b), with the respective GHG emissions (100-Year GWP) from these energy generation processes, for the BAU (c), and the NC scenario (d).

Overall, the decline in total GHG emissions in both countries is mainly driven by a substantial reduction in fossil fuel consumption in all sectors, an objective that sits at the heart of the NC. Further cuts come from increasing the share of renewables in power generation, along with the uptake of hydrogen and synthetic fuels, especially in water and air transport.

Figures 8 and 9 illustrate, for 2025 and 2050 (under NC), how feedstock fuels enter energy transformation pathways and are converted into final fuels serving different end uses.

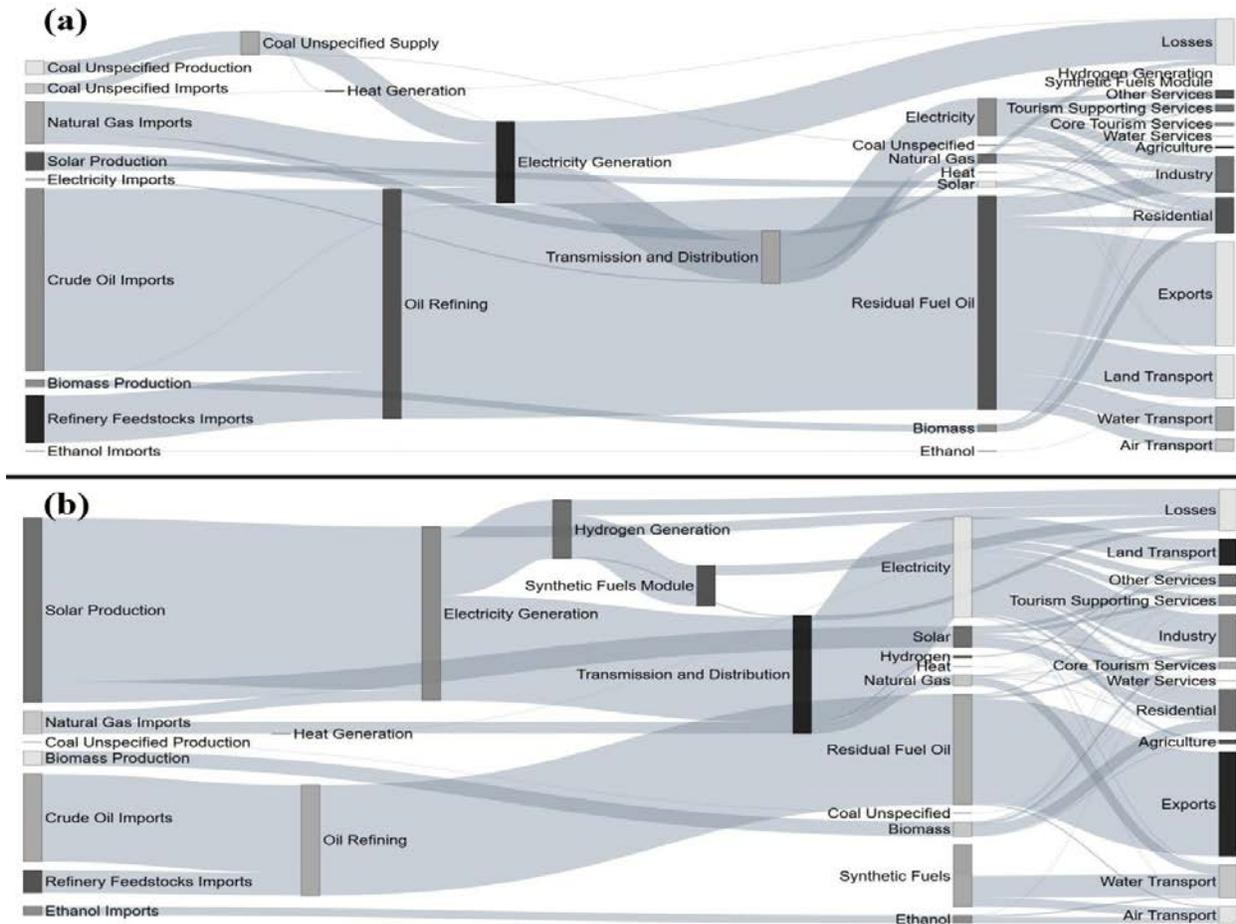


Figure 8. Sankey diagrams for the energy generation and consumption flows in Greece, for the BAU (a) and the NC scenario (b).

As noted, the shift toward cleaner fuels is clear. The two Sankey diagrams also show that the model maintains a consistent production-transformation-consumption balance over the full simulation horizon.

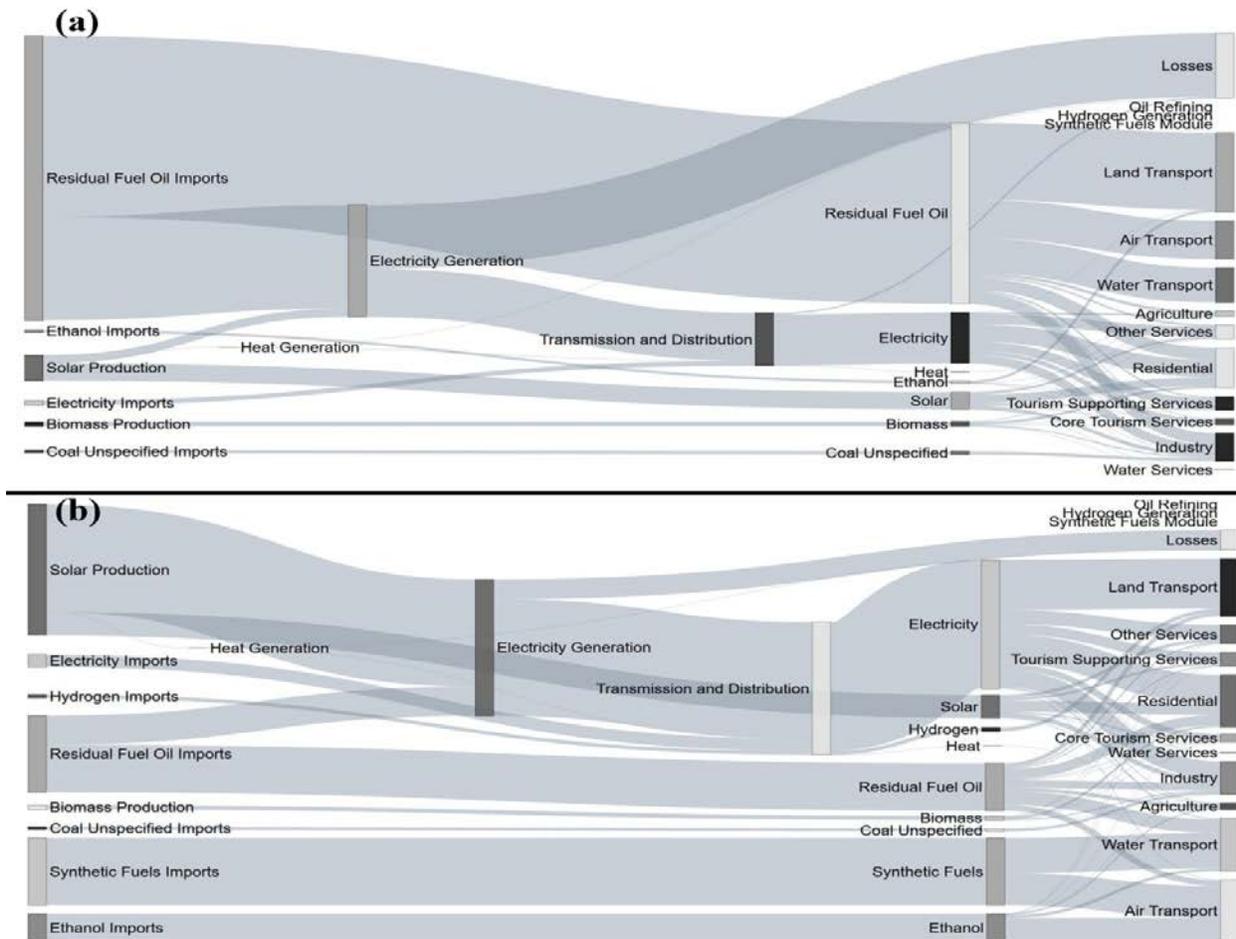


Figure 9. Sankey diagrams for the energy generation and consumption flows in Cyprus, for the BAU (a) and the NC scenario (b).

To validate the soft link between the economy-wide and energy system representations, we compare 2050 GHG emissions implied by GTAP-E’s energy-emissions accounting with the corresponding LEAP results under BAU. We find that the two estimates are very close, supporting consistency of the activity-intensity mapping used for coupling.

Seasonality pressures

Figures 10 and 11 provide a more operational view of overtourism by translating tourism seasonality into monthly energy-demand profiles for the five tourism-related sectors. Across both countries, the comparison between BAU_2025, BAU_2050, and NC_2050 highlights that decarbonization and efficiency policies reduce annual energy consumption, but they do not automatically remove peak-load stress, because seasonal demand spikes persist (and in several cases remain close to, or above, today’s peak levels). This distinction matters for resilience because systems can be on track toward net-zero while still facing summer (or late-summer) periods in which infrastructure capacity, security of supply, and water-energy interdependencies are under the greatest strain.

For Greece (Fig. 10), the seasonal signal is strongest in air and water transport, and the two tourism-services sectors. Air transport exhibits a clear tourism season from May to October, with pronounced peaks in June-August. Notably, BAU_2050 dominates throughout the year, and especially during summer, indicating that activity-driven growth can substantially raise peak demand absent additional measures. By contrast, NC_2050 is close to BAU_2025, implying that, despite ambitious interventions, the peak-month energy burden associated with aviation remains comparable to today's level. A similar pattern emerges for water transport, where the season starts in April and extends to October, with a very sharp peak in August (and elevated demand in July-September). The persistence of high peak energy demand under NC_2050 is particularly important in this sector because maritime activity often co-locates with island systems and port infrastructure where energy and water constraints are already tight. In core tourism services and tourism-supporting services, the seasonality resembles air transport: a broad May-October season with a distinct crest over June-September, again with BAU_2050 highest and NC_2050 close to present-day levels. Finally, land transport shows comparatively weak seasonality, with only a mild summer uplift, while NC_2050 achieves the lowest levels of energy consumption in all months, indicating that NC measures are highly effective in lowering energy use in this sector and that terrestrial mobility is not as strongly driven by tourism seasonality as other tourism-related activities.

Seasonality in Energy Consumption Greece

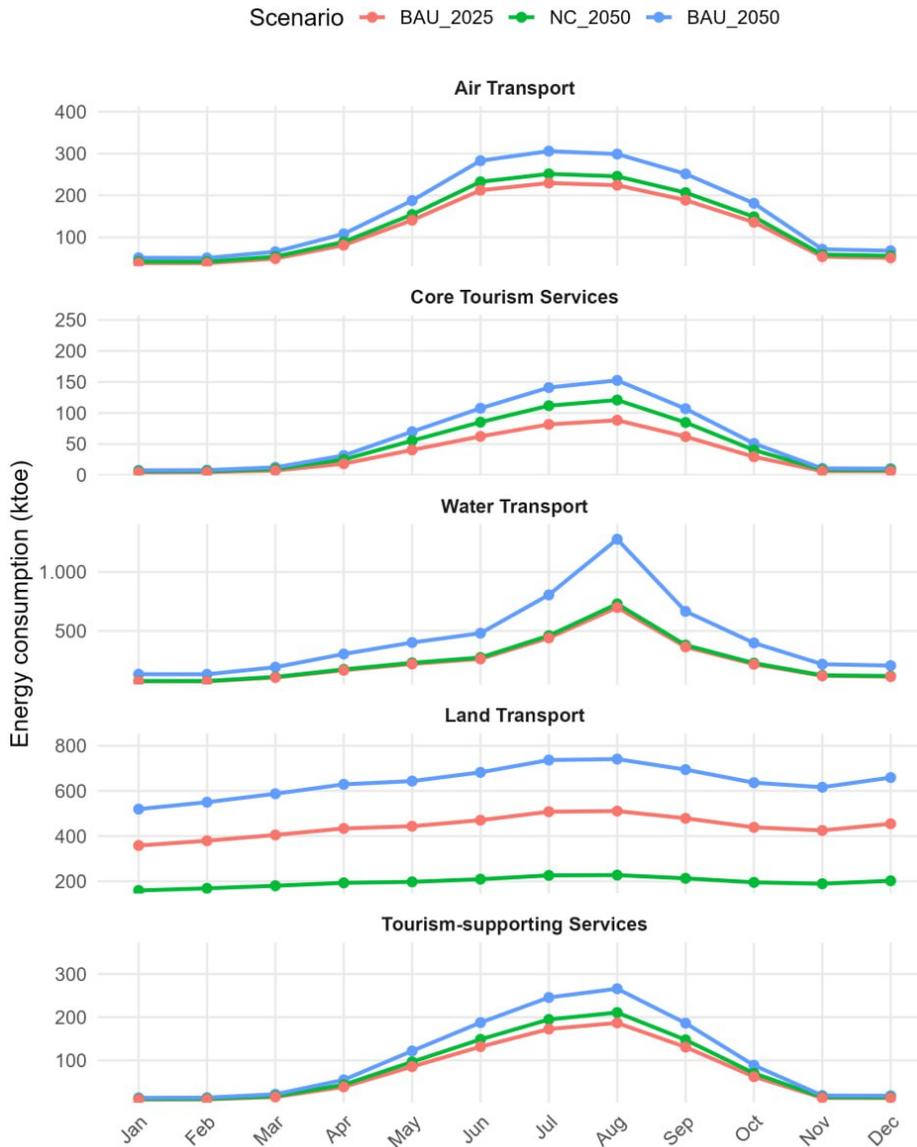


Figure 10. Seasonality in energy consumption by sector in Greece.

For Cyprus (Figure 11), the key differences are a longer tourism season and a more even distribution of activity across months, consistent with Cyprus' positioning and climate. Air transport exhibits a season starting as early as March and extending to October, with peaks in July-September. As in the case of Greece, BAU_2050 is systematically the highest, while NC_2050 remains close to BAU_2025, implying that peak-month energy demands associated with air travel are not eliminated by decarbonization policies alone. In water transport, seasonality runs broadly from April to November with a pronounced late-summer/early-autumn peak (reported as strongest around September-October), reinforcing the idea that peak pressure may shift later in the year in Cyprus relative to Greece, which is an important consideration for planning capacity and maintenance cycles. In core tourism services, the season spans March-

November, with a clear peak in June-August (especially July), while in tourism-supporting services the seasonal peak is again centered on June-August (mainly July).

Seasonality in Energy Consumption Cyprus

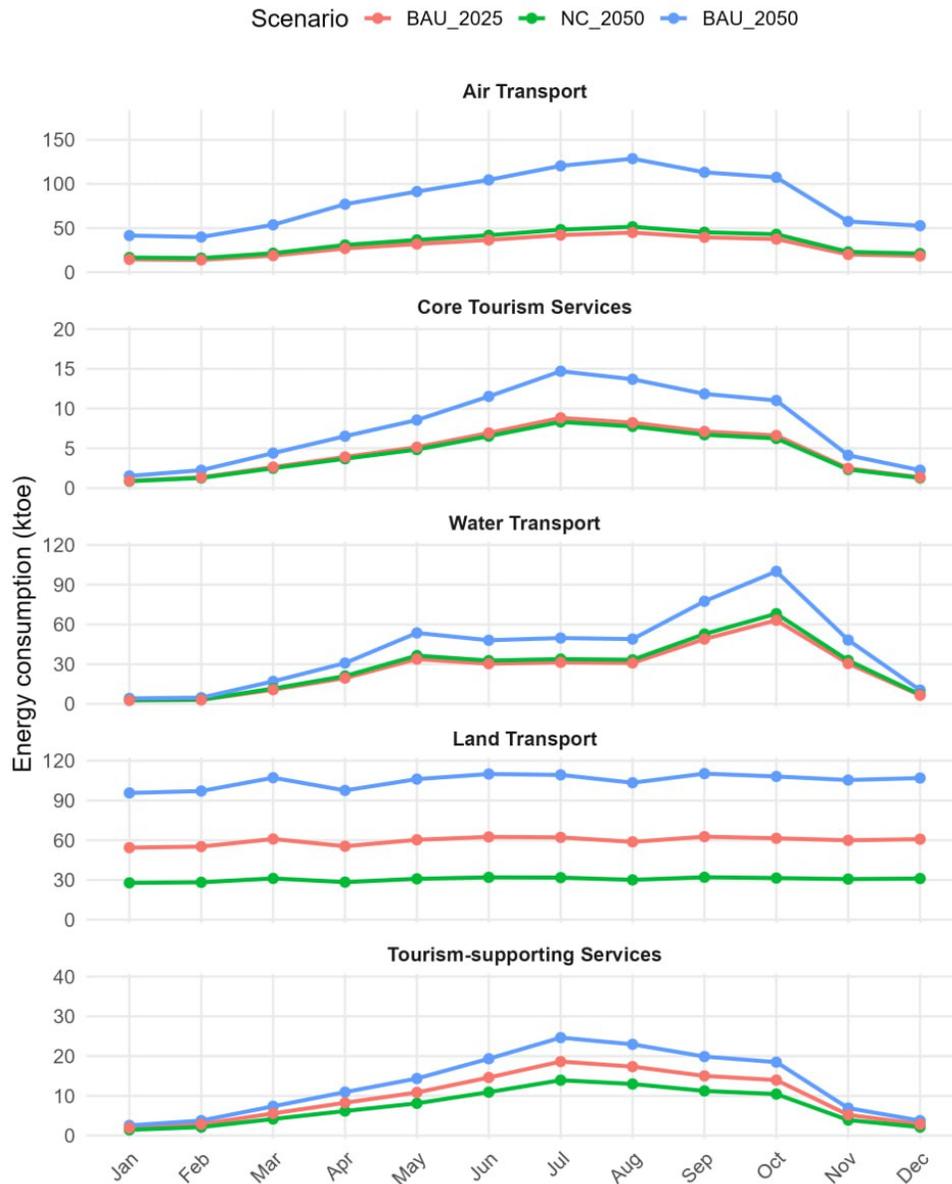


Figure 11. Seasonality in energy consumption by sector in Cyprus.

Taken together, Figures 10 and 11 suggest that overtourism risks are not only about annual growth, but about peak-load governance. The BAU_2050 profiles imply that, without additional action, seasonal peaks intensify as tourism-related sectors expand. Meanwhile, NC_2050 profiles indicate that even strong decarbonization pathways may leave peak energy demand at or near today's levels in several key tourism

sectors, especially air transport and core tourism services, meaning that a net-zero compliant pathway can still be vulnerable to peak-season operational stress. The comparative evidence also points to an important design implication. Because Cyprus has a longer season with more evenly distributed monthly shares, there may be relatively more scope to manage pressure through temporal rebalancing and product diversification, whereas Greece's sharper summer peaks underscore the need for targeted peak-management tools (e.g., demand response and grid flexibility in islands, capacity management in ports/airports, and measures that explicitly reward shoulder-season visitation).

[Water withdrawals, seasonality and Water Stress](#)

The results of the WaterReqGCH model show intense water pressures for both countries. Figures 12 and 13 summarize the evolution of annual freshwater withdrawals by sector and the corresponding monthly (seasonalized) withdrawal profiles derived from the disaggregation procedure described in the Methods section. Across both countries, the annual picture is dominated by structurally water-intensive uses (notably irrigation and municipal supply), while tourism's importance is revealed primarily through intra-annual peaks rather than its annual share, an effect that is masked in annual-only water accounts.

In Greece, total withdrawals are highest in sectors linked to irrigation and municipal supply, with industry and tourism contributing smaller annual totals but exhibiting sharper seasonal signatures. The monthly profiles show a pronounced summer concentration, with the national withdrawal curve rising from late spring and cresting in July–August, consistent with the coincidence of peak irrigation requirements and peak tourist presence. In the tourism component specifically, the seasonal peak is steep relative to shoulder months, indicating that tourism acts as a peak-amplifier for municipal/service withdrawals even when its annual total remains below irrigation. This reinforces the key distinction highlighted earlier for energy: decarbonization pathways can improve annual metrics, but they do not automatically eliminate seasonal system stress if peak drivers persist.

Water withdrawals-Greece

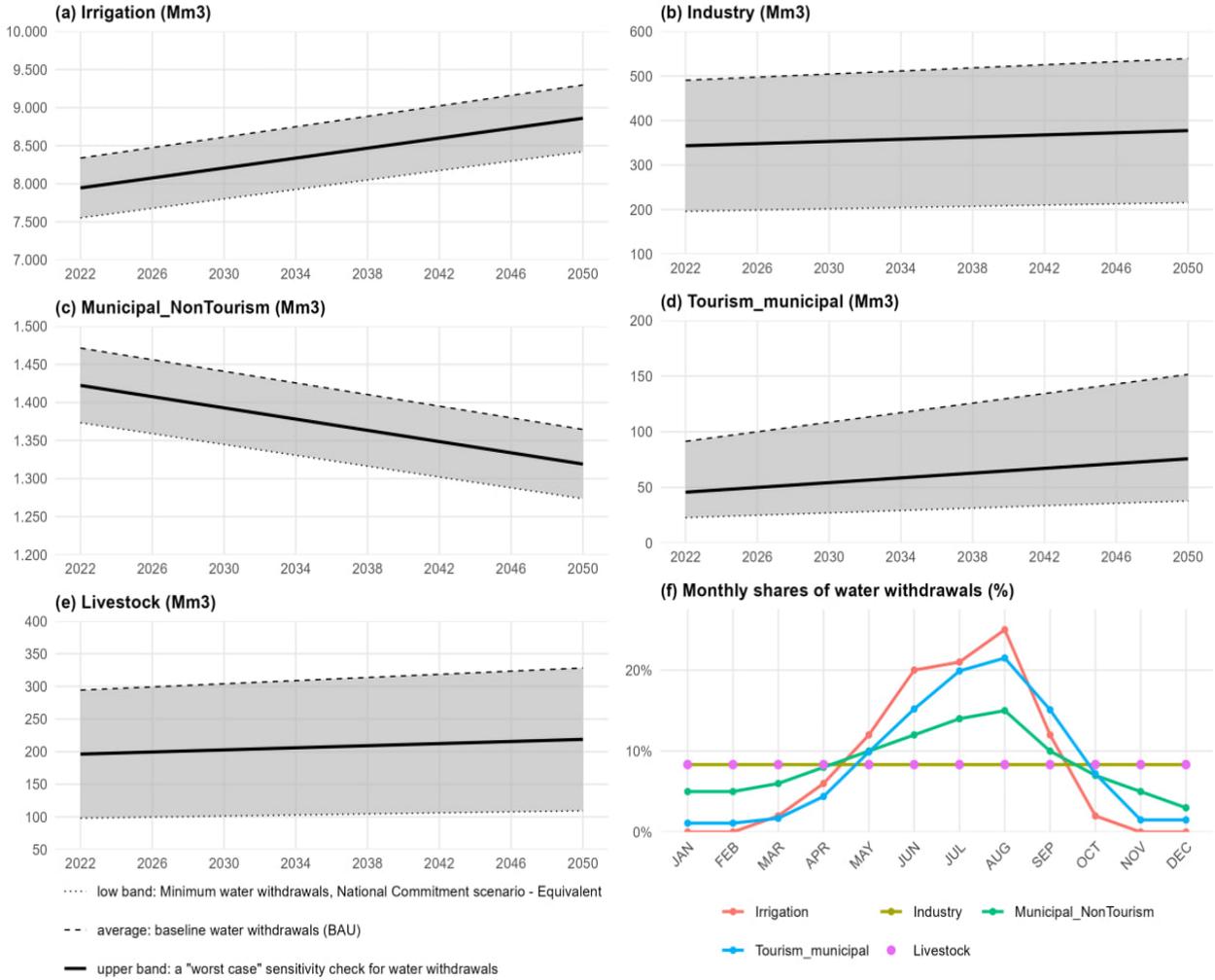


Figure 12. Water withdrawals per sector, for Greece (a)-(e), and typical monthly allocation per use.

Cyprus exhibits a different but equally policy-relevant pattern: withdrawals are concentrated in municipal and irrigation-related uses, but the relative importance of summer service demand is higher and the season extends longer into the year. The monthly curves show a broader high-demand period spanning late spring to early autumn, with peak pressure often appearing in late summer/early autumn (e.g., August–September), consistent with the longer tourism season described in the energy seasonality results. Because Cyprus is a smaller, more water-constrained system, the same absolute increase in peak-season withdrawals can translate into a larger proportional stress signal, making the seasonal peak particularly salient for operational planning (storage management, desalination scheduling, and drought contingency measures).

Water withdrawals-Cyprus

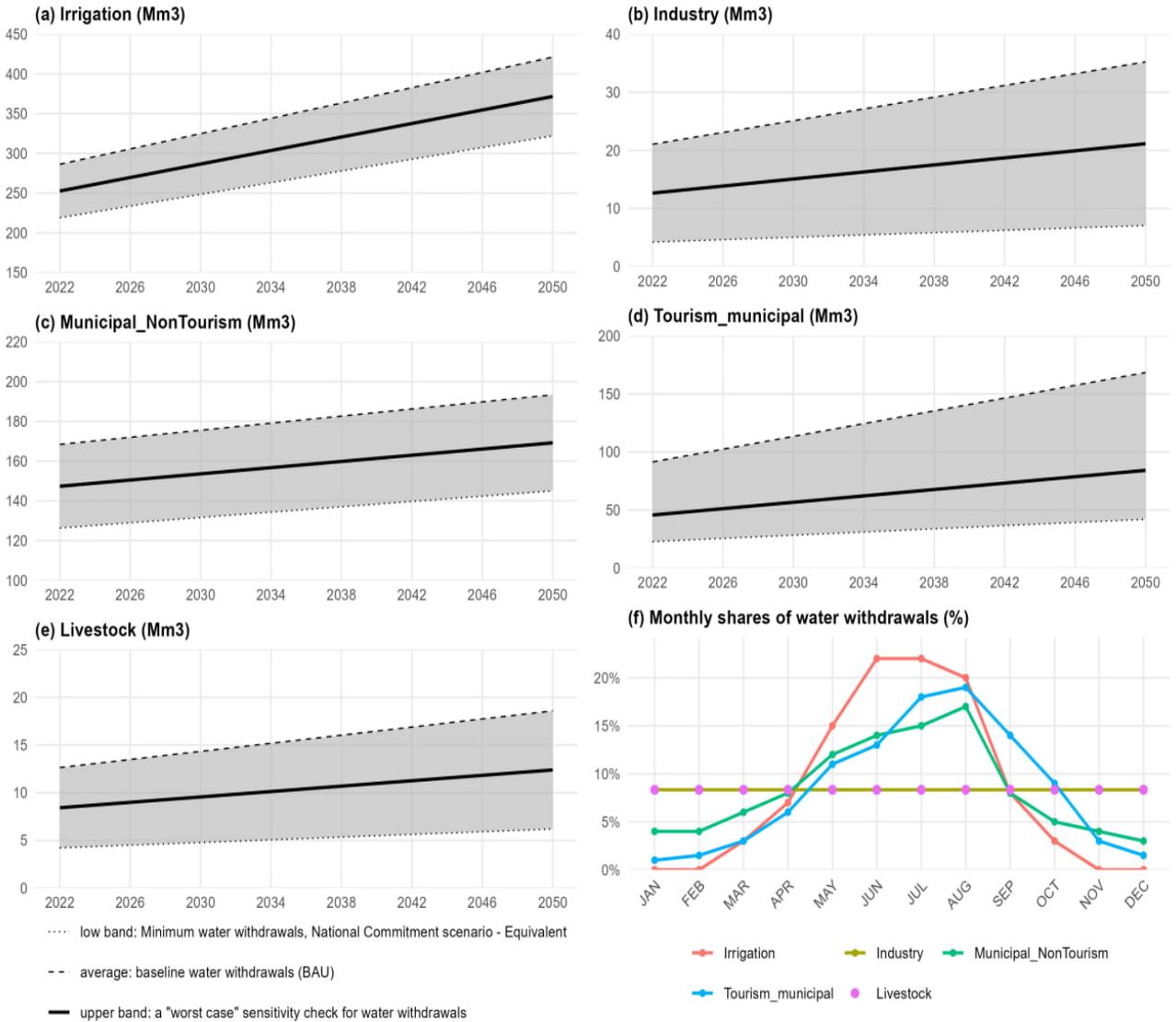


Figure 13. Water withdrawals per sector, for Cyprus (a)-(e), and typical monthly allocation per use.

Such patterns further justify the arguments about holistic design and planning, considering cross-sectoral feedbacks (Angelos Alamanos et al., 2021) as well as the need for effective and targeted awareness-raising about the different forms of water scarcity (Sarpong et al., 2024b, 2024a).

Monthly Water Stress

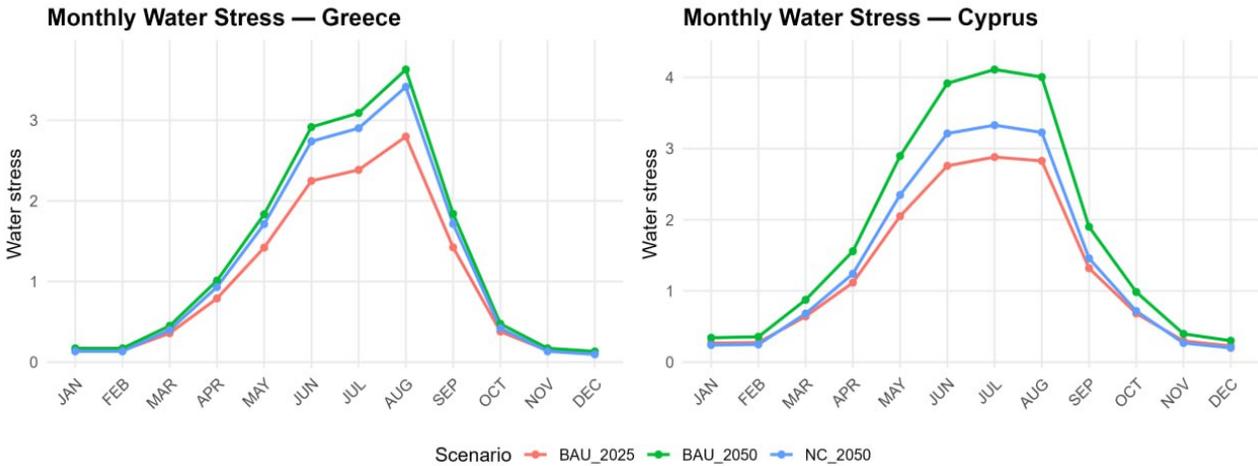


Figure 14. Water stress, monthly, for Greece (a) and Cyprus (b), per scenario explored.

The water stress results (Fig.14) express the ratio of withdrawals to renewable blue-water availability. First, we observe that stress indicators based on annual averages can materially understate periods of tightness, because the stress signal is driven by the coincidence of peak withdrawals with seasonal lows in availability and heat-driven demand (and this is where the tourism isolation matters operationally, rather than relying on annualized indicators alone).

Second, the timing and sharpness of peaks differ: Greece tends to show a more acute mid-summer peak, while Cyprus shows a longer plateau of elevated stress, implying different “best response” portfolios (Greece: targeted peak management, leakage reduction and island/port-area measures; Cyprus: sustained summer supply management, desalination and demand-side measures across a longer season).

The results on these monthly pressures are more worrying given the heavy reliance of Southern European countries (including Greece) on groundwater, to cope with the extensive irrigation in arid zones. Desalination and reuse are significant shares of water supply sources in Cyprus. Below are the results of our previous works for Europe, listing in detail water use shares and supply sources, as well as pan-European water balances (Figures 15 and 16).

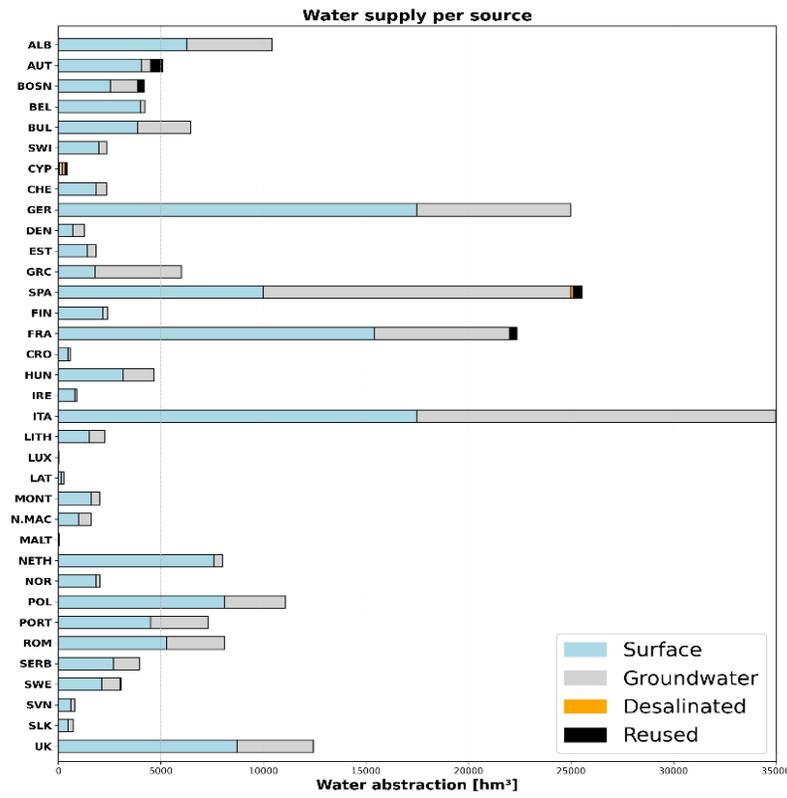
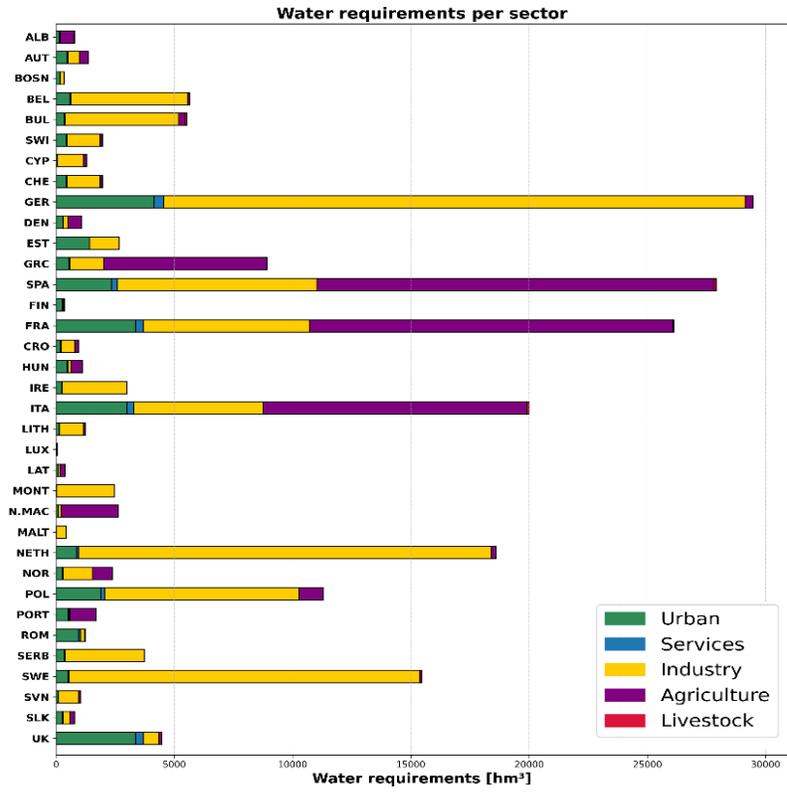


Figure 15. Typical annual water consumption (average for the period 1970-2022) per sector (upper), and per supply source (lower). Source: (Koundouri et al., 2025a).

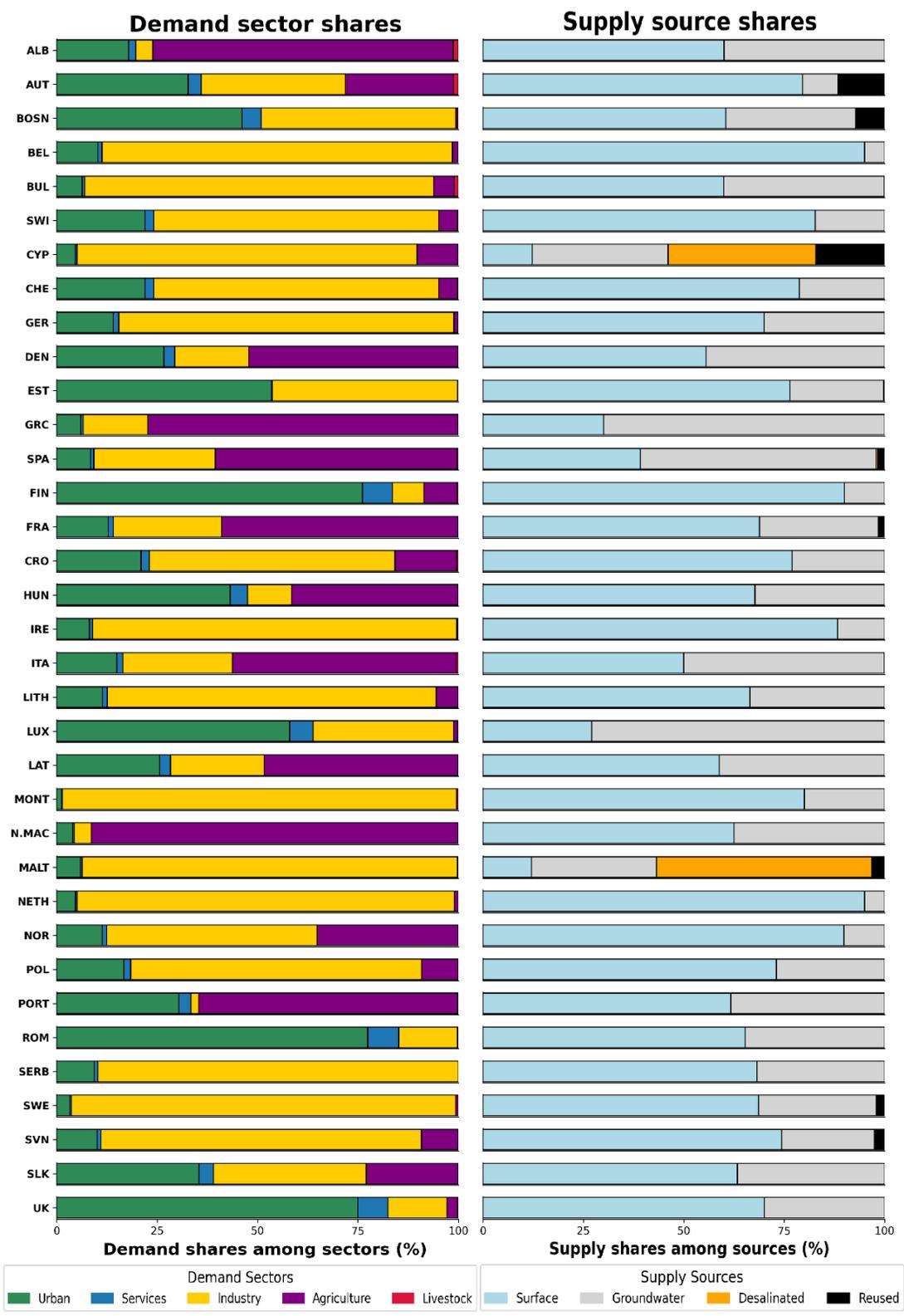


Figure 16. Percentage shares of the typical annual water consumption (average for the period 1970-2022) per sector and supply sources. Source: (Koundouri et al., 2025a).

We show these figures here, in order to put our findings for Greece and Cyprus in a European “urgency” context: Greece faces major agricultural pressures, threatening its groundwater resources; Cyprus is facing industry (including tourism) and agricultural pressures, trying to cope with costly desalination supply increases; while both countries are at the high-end of water stress compared to other European countries (Cleridou et al., 2014b; Hartfiel et al., 2020).

5. Discussion: Limitations, Planning Gaps and Policy Implications

This study set out to make tourism-driven seasonality operational within a national decarbonization and water-stress assessment for Greece and Cyprus by linking (i) an economy-wide baseline (GTAP-E) that yields sectoral activity trajectories to 2050, (ii) a detailed energy–emissions model (LEAP) calibrated to national energy balances, and (iii) a water-withdrawal and stress module that converts annual sectoral withdrawals into monthly profiles using observed seasonality factors. The key finding is that NC-consistent decarbonization can substantially reduce annual energy use and emissions, yet does not automatically eliminate peak-season pressures, because tourism-related activity growth and intra-annual concentration persist and can keep peak loads close to present-day levels in several tourism-related sectors—particularly in transport and core tourism services. Extending this logic to water, the seasonal disaggregation framework highlights why annual totals alone are insufficient to characterize resource stress in Mediterranean systems where peak demand coincides with the warm/dry season.

Integrated planning relevance of findings

The coupled results show a consistent narrative across modules. The GTAP-E baseline indicates pronounced growth in tourism-connected sectors (especially transport and core tourism services) in both countries to 2050, with Cyprus showing particularly strong expansion in aviation-related activity. When these activity trajectories drive LEAP, BAU outcomes translate growth into higher annual final energy and demand-side emissions; under NECP assumptions, technology and efficiency measures decouple activity from annual totals, yielding strong reductions in emissions and modest reductions in final energy. However, the seasonality results demonstrate that annual decoupling does not guarantee peak relief: monthly profiles show summer (and, in Cyprus, extended-season) peaks remain material in air transport, water transport, and tourism services even under the NC pathways.

The water module’s results reveal the same distinction (annual vs peak-season stress) by calibrating annual withdrawals to national totals and then distributing withdrawals to months using sector-specific seasonality shares, including explicit tourism profiles. This is crucial for Mediterranean planning because the months that concentrate tourism activity also typically coincide with higher irrigation requirements and greater municipal/service loads, and thus are the months where water stress and operational vulnerability are expected to emerge first.

Potential gaps in policy framing

A central motivation for this work is the observation that national decarbonization planning (NECP-style) is generally framed around annual targets (energy shares, cumulative emissions, long-run technology

shifts). The results here show why that framing can miss a binding constraint for Greece and Cyprus: system adequacy and resilience are governed by peaks, and those peaks are strongly shaped by tourism-related seasonality. In practice, this means a country can be “on track” in annual emissions metrics while still facing heightened seasonal stress in the infrastructures that underpin service provision (electricity networks, ports/airports, and water supply systems).

Following this logic and observation, a subsequent policy-relevant gap is fragmented planning across energy–emissions, economy, and water. Even within a single study, it is non-trivial to maintain consistency of sectoral definitions, baselines, and scenario assumptions across these domains; our framework was built explicitly to do so, with sectoral activity generated in GTAP-E, mapped into LEAP branches, and used again in the water module. The need for this alignment highlights why, in many policy processes, economy, energy, and water are still assessed in parallel rather than jointly (yet the results indicate that joint assessment is precisely what is needed to understand peak-season trade-offs).

The study highlights a “country-specific effects” gap. The seasonality outcomes differ between Greece and Cyprus (sharper peaks vs a longer season), implying that a one-size-fits-all horizontal policy lens can overlook local stress mechanisms even under the same EU policy architecture. This is not a claim about NECP text quality per se; it is an inference from the modelling outputs that peak dynamics and binding constraints are location- and structure-specific and should be reflected in scenario testing.

Limitations

This assessment is designed to be policy-relevant and internally consistent, based on an ambitious multi-model linking framework, but it does not come with some limitations arising from necessary assumptions.

The coupling uses GTAP-E to produce sectoral output trajectories that drive energy and water demand, which preserves economy-wide consistency but does not account for potential responses and improvements of the energy and water systems. Consequently, the results should be interpreted as “stress and vulnerability diagnostics under consistent scenarios”, rather than a fully endogenous co-optimization of the economy–energy–water system. Second, the NC scenario assumes the full implementation of the NECP and water-improvement measures, which is an intentionally optimistic assumption, in order to isolate “technology-policy” effects, and show how challenging is to fully decarbonize within environmental limits, rather than forecasting an actual future. Finally, water withdrawals are computed nationally by sector and compared to blue-water availability under the Aqueduct approach. This is the most commonly used approach, as it captures national seasonal stress signals, but does not resolve sub-national basin heterogeneity. So, one should keep in mind that this approach is most appropriate for national screening and scenario comparison, and should be complemented by basin-scale studies where local infrastructure choices are being made.

Policy implications of the findings

The results support several practical implications for Greece and Cyprus that follow directly from the modelled distinctions between annual outcomes and seasonal stress. These are summarized below:

1. There is a clear need to add peak-season stress tests to decarbonization planning. Because NECP-style measures substantially reduce annual emissions but can leave peak seasonal loads near current levels in key tourism sectors, policy evaluation should include explicit indicators of peak-month pressures (e.g., peak electricity demand in tourism services and transport; peak-month water withdrawals and stress).
2. Planning must target sector-specific peak drivers, not only annual efficiency. The seasonal results indicate that peak burdens are most persistent in specific tourism-linked sectors (especially aviation-related activity and core tourism services). This points to the need for targeted peak measures (demand response, temporal load shifting in accommodation/services, port/airport energy management), rather than relying solely on economy-wide annual efficiency gains.
3. Energy and water operational planning should be integrated where peaks co-locate. The modelling framework is built precisely because peak stress is cross-sectoral: tourism seasonality can simultaneously increase energy loads and water withdrawals. For islands and coastal nodes, coordinated planning (infrastructure sizing, maintenance windows, contingency management) becomes central: annual decarbonization success does not remove the need for operational resilience in peak months.
4. For large scale, or continental planning, country-specific seasonality shapes must be used as planning inputs. Greece and Cyprus show different seasonal “signatures” (sharper peaks versus a longer plateau), which implies that the most effective mix of measures may differ even under a shared EU policy framework. Peak-management tools should therefore be calibrated to each country’s observed seasonality profile and the specific sectors that dominate its peaks.

While the analysis is grounded in Greece and Cyprus, the mechanism it isolates (service-sector seasonality amplifying peak resource stress under decarbonization) is likely to apply to other tourism-intensive, climate-exposed coastal and island systems where summer demand coincides with water scarcity risk, so these recommendations are generally useful.

6. Recommendations

Drawing upon the findings of this assessment, we summarize the main policy recommendations in Table 4. The results indicate that annual decarbonization success does not automatically remove peak-season stress, because tourism-linked activity growth and intra-annual concentration persist in both Greece and Cyprus. Recommendations are therefore structured around (i) sectoral peak drivers, (ii) country-specific stress profiles, and (iii) regulatory framework alignment, reflecting what the coupled economy–energy–water modelling reveals.

Table 4. Policy recommendations concerning sectors (first colour-block), countries (second colour-block), and regulatory frameworks (third colour-block). The final (white-colour) block refers to monitoring and data priorities (to sustain the modelling approach and allow similar and more detailed analyses and solutions). The order is indicative, and all recommendations are complementary.

Category	Recommendation
1. Core tourism services (accommodation /food/recreation)	The peak-demand management should be listed as a decarbonization measure . Introduce summer-peak programmes targeted at hotels and tourism services: mandatory energy audits, accelerated retrofit schedules, heat-pump deployment and cooling-efficiency standards, smart controls, and demand-response participation (tariffs that reward load shifting). This directly follows the finding that NECP measures reduce annual totals but may leave peak tourism-month loads near present levels.
2. Aviation and ports	Such transport nodes should be treated as “seasonal critical infrastructure.” Because air and water transport show the strongest seasonal signals, prioritize airport/port electrification, shore power, electrified ground-support equipment, and peak-capacity management (including storage and flexible demand at nodes). This recommendation is anchored in the persistence of seasonal peaks in tourism-linked transport sectors under the NC scenario.
3. Grid flexibility and adequacy	Peak resilience must be a goal alongside emissions reduction. Translate NECP technology pathways into explicit adequacy metrics for summer peaks: strengthen demand response, storage and local flexibility (especially in island/coastal systems), and align maintenance/outage planning with seasonal peaks. This is a direct operational implication of the study’s peak/annual distinction.
4. Water demand management	Move from annual averages to seasonal targets , as they are the real stressors. Adopt seasonal water-efficiency measures that reflect peak-month stress: leakage reduction and pressure management in municipal networks, seasonal pricing/communication for peak months, and targeted water-efficiency requirements in tourism facilities (e.g., reuse systems, water-efficient fixtures, landscaping standards). This follows from the monthly withdrawal/stress design of the study and its emphasis on peak pressure.
5. Greece-specific	Greece is bigger and more heterogenous. Sharp summer peak governance and island/coastal hotspots should be prioritized. Greece displays more acute summer concentration in tourism-linked sectors, peak-month measures should focus on June–September stress management, with emphasis on island grids and port/airport systems where seasonal surges are concentrated. Interventions should be designed for “short, high peaks”: rapid demand response, temporary capacity reinforcement, and targeted tourism-facility efficiency upgrades ahead of summer.
6. Cyprus-specific	The key is to plan for a longer high-demand season and water–energy operational coupling . Cyprus shows a longer tourism season and strong growth in aviation-linked activity, implying a need for measures that sustain performance across an extended period (spring through autumn): stable demand response programmes, longer seasonal tariffs, and coordinated water–energy operational planning (especially where electricity demand and water-supply operations coincide in peak months)..
7. NECPs	Add peak-stress indicators and require seasonal stress tests:

	Complement annual NECP indicators with required reporting on (i) peak-month electricity demand in tourism-linked sectors, (ii) peak system adequacy metrics (capacity margin / stress hours), and (iii) peak-month emissions intensity where relevant. This recommendation follows directly from the study’s finding that NECP-style decarbonization can leave peak loads persistent.
8. River Basin Management Plans	<u>Incorporate scenario-consistent sectoral demand pathways and seasonality:</u> RBMP updates should not rely only on annual withdrawal totals; they should integrate sectoral activity baselines and explicitly include peak-month stress diagnostics. Use seasonal indicators as triggers for drought measures, and explicitly evaluate tourism-facility demand management alongside agriculture and municipal measures. This aligns with the study’s monthly disaggregation approach.
9. Integrated planning requirement	<u>Institutionalize an energy–water (and even tourism) coordination layer.</u> Create a formal coordination process (or technical annex) linking NECP implementation planning with RBMP programmes of measures for peak-season months, using consistent scenarios and sector definitions. The study’s linked framework demonstrates the value of aligning economy-driven sectoral growth, energy pathways, and water stress evaluation under common assumptions.
10. Monitoring and data priorities	<ul style="list-style-type: none"> • Maintain high-frequency tourism indicators as planning inputs: Institutionalize the use of monthly indicators (nights spent, passenger/port flows) to monitor tourism-driven peaks and update stress tests annually. This is needed because seasonality is central to peak pressure in the results • Improve sectoral water-use accounting for tourism and services: Strengthen separation between non-tourism municipal withdrawals and tourism-related service demand to avoid masking tourism peaks inside broad aggregates, consistent with the study’s goal of isolating tourism seasonality effects

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The **SDSN Global Climate Hub** is a global initiative of the **UN Sustainable Development Solutions Network (SDSN)**, dedicated to advancing science-based solutions that help countries achieve climate neutrality and resilience by 2050.

Established in 2022 and hosted in Athens by the **Athens University of Economics and Business** and the **ATHENA Research Center**, the Hub is led by **Prof. Phoebe Koundouri**.

The Hub's mission is to produce scientifically grounded and publicly supported pathways toward sustainable development. Its work is structured around **9 research units**, each representing a critical stage in designing and implementing integrated, cross-sectoral plans for climate neutrality and resilience.

