SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

AE4RIA
Alliance of Excellence for Research and Innovation on Aephoria

SDSN Global Climate Hub

Integrated Systems Modelling and Assessment of the Global National Commitments

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Report:

Integrated systems modelling and assessment of the global National Commitments

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The Global Climate Hub

The AE4RIA [UN SDSN 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. 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.

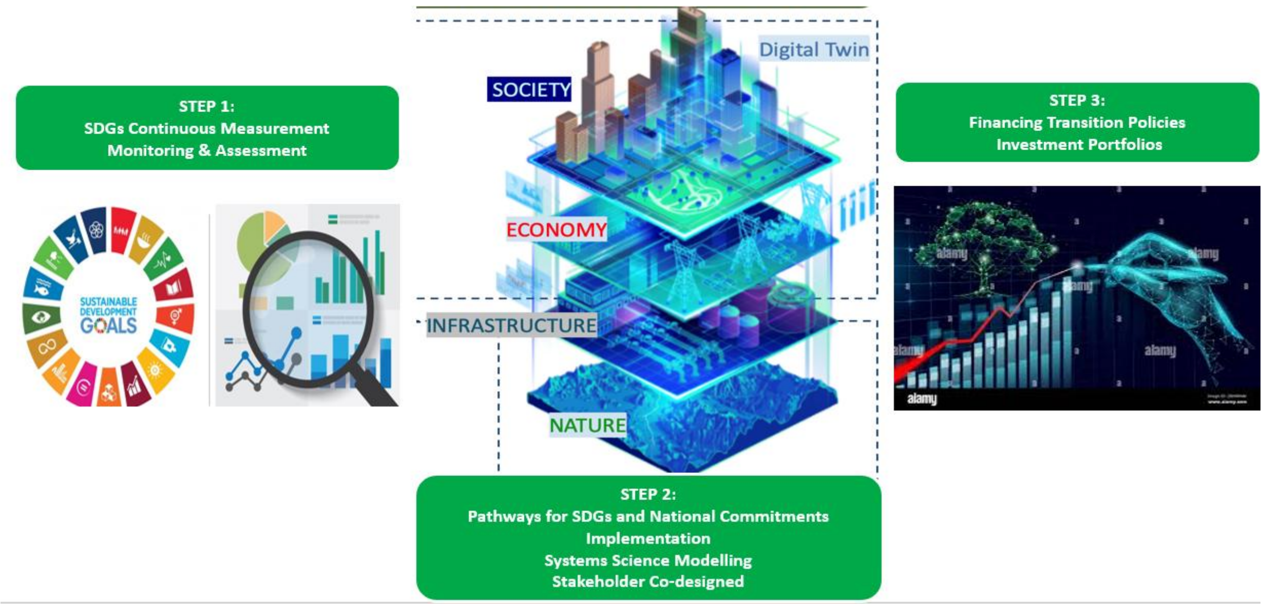


Figure a. The 3-step approach of the GCH: A Global Commons vision for SDGs Implementation. First, we implement advanced monitoring approaches for SDGs Continuous Measurement, Monitoring & Assessment. The 2nd stage refers to the systems modelling, creation of multi-sectoral digital twins and the development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

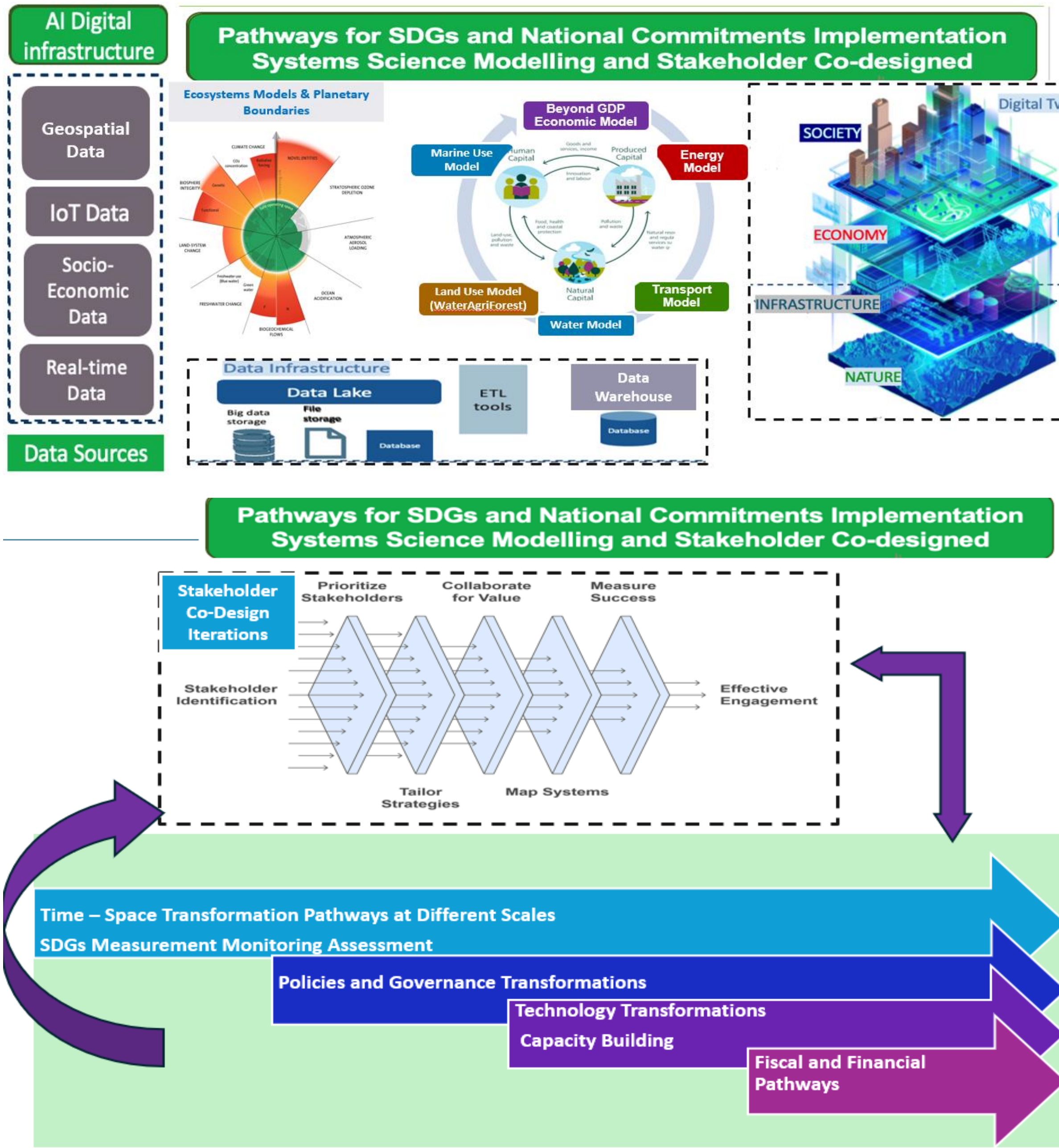


Figure b. The systemic innovation of the GCH, integrating multi-data through AI-supported infrastructure, multi-model assessments and pathways simulations, with digital twins, stakeholder engagement and co-designed sustainability pathways. Integrated models are used/developed, which are coupled and updated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

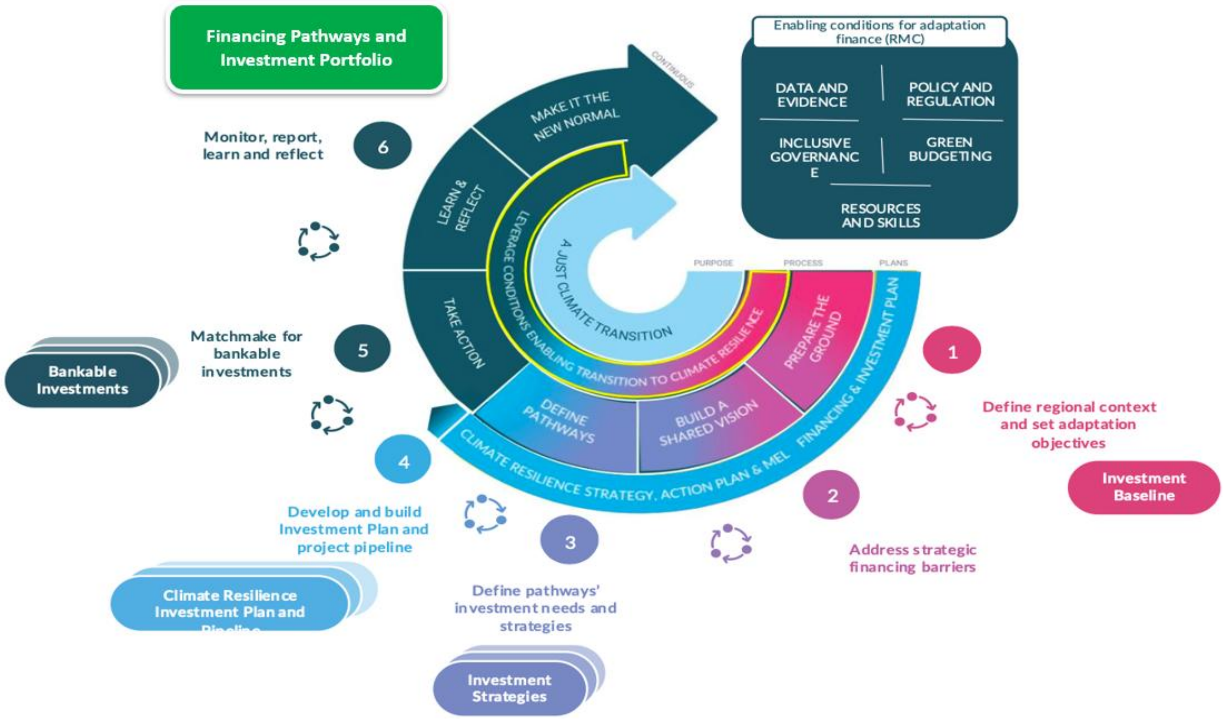


Figure c. The 3rd stage of the GCH approach includes the financing of pathways through investment portfolios.

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.

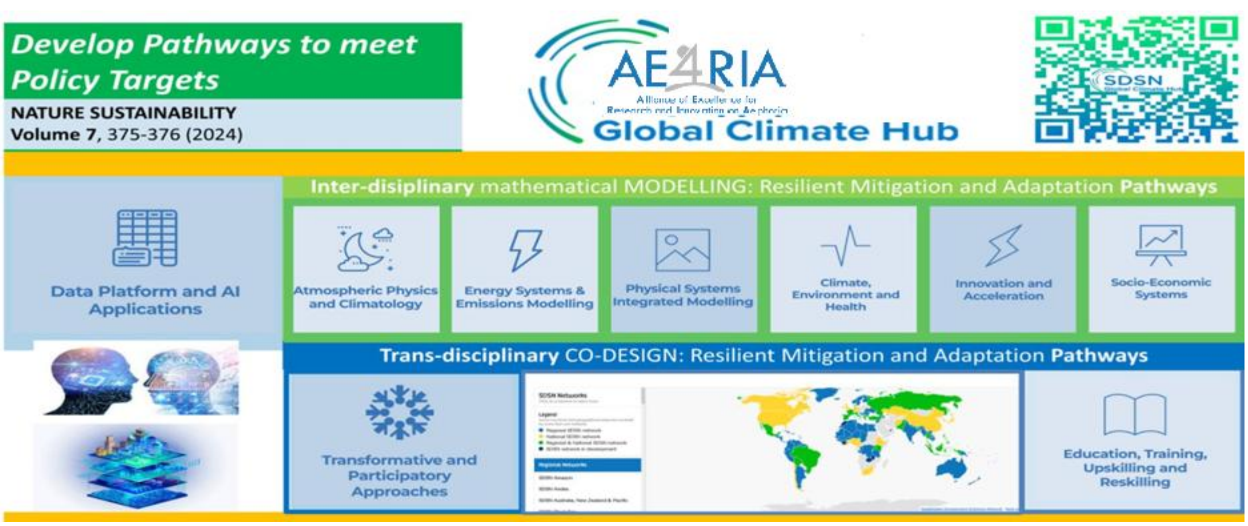


Figure d. The 9 units of the Global Climate Hub.

EXECUTIVE ABSTRACT

Every country now has a climate plan. This report asks what those plans add up to. It translates the national commitments of 128 countries, their Nationally Determined Contributions, long-term strategies and national energy and climate plans, into inputs for four linked models of land use, energy, water and the economy, and simulates them to 2050 against a common baseline in which no new commitments are implemented. The models, data and results are freely available on the GCH online platform, so that any country can explore their pathways, reproduce the analysis and ultimately use it in its own planning.

The commitments change the direction of travel, but they do not reach net zero. Fully implemented, they cut energy-related CO_2 emissions in 2050 by 64% relative to the baseline and by 46% relative to 2017, instead of the 47% increase the baseline implies. About 15 $GtCO_2$ remain in 2050, almost half in China and India, and emissions still grow in 38 of the 127 countries, mostly developing economies whose pledges allow growth from a low base.

Mitigation comes from decarbonising a growing energy system, not from shrinking it. Final energy consumption in 2050 is 28% below the baseline but above today's level: it falls in industrialised economies and rises in developing ones. Renewable electricity expands almost everywhere, fossil power generation and oil refining contract where commitments bind, and green hydrogen appears in 44 countries.

Land and water change as side effects, not as objectives. Forest area, which declines under the baseline, increases by about 1.5 million km^2 under the commitments, while cropland and tree crops continue to expand, mainly at the expense of grassland. No country sets a quantified water target. Water use changes only through land and economic decisions: withdrawals fall in most hotspots, but too little to change the map of water stress. Diets and higher yields would save more water than the land-related commitments do.

The economic effect is a reallocation, with clear winners and losers. Output and labour shift from fossil fuel industries towards electricity, energy-intensive industries and transport. Welfare losses of several percent of GDP are concentrated in fossil fuel exporters, while most importers gain; these estimates exclude avoided climate damages and health co-benefits, so they understate the value of acting.

The pledges cannot be compared, or simulated, as they are written. Targets use different baselines, gases, sectors and horizons, the treatment of land use is often unclear, and long-term commitments sit outside the NDC. Making them model-ready required a documented procedure applied identically to every country; clearer submissions would remove much of this uncertainty. Five priorities follow for policy:

- Make commitments quantifiable: absolute targets with stated baselines and scope, and the energy, land and water they imply.
- Align the horizons and cycles of climate, energy, agricultural and water plans, and make one body responsible for their intersections.
- Plan renewables, grids and electrification, and the decline of fossil fuel industries, as one programme with retraining and regional support.
- Use diets, agricultural productivity and forest protection as climate and water levers.
- Support fossil fuel exporters and vulnerable households, finance implementation on fair terms, and report welfare, natural capital and distribution alongside GDP.

CONTENTS

1. Policy frameworks: from global commitments to national delivery

Climate targets are now a fixed point of the policy landscape: they have been agreed internationally and, in Europe, written into law. Every country has also produced a plan to deliver them. This report therefore does not revisit whether the targets are appropriate. It asks a narrower and more practical question: are the plans written to deliver them internally consistent, physically feasible and fair? Put simply, every country has a plan; do the plans add up, and who pays for them?

The question is approached through three layers of policy: *what the world agreed* (treaties and decisions of the Conference of the Parties, COP, which set direction and reporting duties but deliver nothing by themselves); *what countries planned* (national laws, targets and plans, where legal force actually resides); and *what can be built* (the land, water, grid capacity, finance and workforce that implementation requires, and who bears the cost when these prove scarce). Sections 1.1 and 1.2 review the international agreements and the main national policy models. Section 1.3 examines how Nationally Determined Contributions (NDCs), National Energy and Climate Plans (NECPs) and just energy transition (JET) strategies connect in practice, Section 1.4 what it takes to translate commitments into implementable pathways, and Section 1.5 the implementation gap addressed in the remainder of the report.

1.1 International agreements

1.1.1 From Kyoto to Paris

The international climate regime rests on three agreements. The United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1992, has near-universal membership. It establishes a shared objective, the stabilisation of greenhouse gas (GHG) concentrations at a level that would prevent dangerous anthropogenic interference with the climate system, and a permanent forum for negotiation, but sets no quantified targets [1]. The Kyoto Protocol of 1997 was top-down: binding emission targets were negotiated centrally and assigned to developed countries only [2]. The United States signed it but never ratified it.

The Paris Agreement of 2015 reversed this logic [3]. It is bottom-up: every Party pledges, but each determines its own contribution. Its long-term goals are to hold the increase in global average temperature well below 2 °C above pre-industrial levels while pursuing efforts to limit it to 1.5 °C (Art. 2.1a), and to achieve a balance between anthropogenic emissions and removals in the second half of the century (Art. 4.1), which is the origin of the "net zero" concept. The shift can be summarised in one line: *Kyoto handed countries their targets; Paris asks countries to write their own.* Universal participation was bought with national discretion over ambition, format and timing. This was arguably the only politically available bargain, but it is also the root of the comparability and consistency problems examined in this report.

1.1.2 How the Paris Agreement operates

The Agreement operates through a set of procedural instruments [3]:

- **NDCs (Art. 4):** communicated every five years, with each successive NDC expected to represent a progression beyond the previous one (no backsliding).

- **Long-term low-emission development strategies, LT-LEDS (Art. 4.19):** mid-century strategies, typically to 2050.
- **Enhanced Transparency Framework (Art. 13):** Biennial Transparency Reports, the first of which were due by the end of 2024 [4].
- **Global Stocktake (Art. 14):** a collective assessment every five years; the first concluded in 2023 [5].
- **Articles 6 to 9:** cooperative approaches and carbon markets (Art. 6), adaptation and the Global Goal on Adaptation (Art. 7), loss and damage (Art. 8) and finance (Art. 9).

The central obligation is procedural. Parties must prepare, communicate and maintain an NDC, pursue domestic measures towards it and report on progress; they are not legally bound to achieve it, and there is no penalty for missing it. Paris is a transparency-and-peer-pressure regime rather than an enforcement regime, and its effectiveness depends on national law, national budgets and national permitting rules. Whether a country will deliver can therefore only be judged by reading its NDC together with the national plan meant to implement it, which is the approach taken in this report.

1.1.3 Just transition in the COP process

Just transition has followed a distinct trajectory through the COP process (Table 1.1).

Table 1.1. COP milestones relevant to a just transition.

Year	COP	What it added
2015	Paris (COP21)	Preamble reference to "a just transition of the workforce and the creation of decent work and quality jobs" [3]
2018	Katowice (COP24)	Solidarity and Just Transition Silesia Declaration [6]
2021	Glasgow (COP26)	Article 6 rulebook; call to phase down unabated coal power [7]; first Just Energy Transition Partnership, with South Africa [8]
2022	Sharm el-Sheikh (COP27)	Funding arrangements for loss and damage, including a dedicated fund; Just Transition Work Programme established [9]
2023	Dubai (COP28)	First Global Stocktake: transitioning away from fossil fuels in energy systems "in a just, orderly and equitable manner"; tripling renewable capacity and doubling energy-efficiency improvements by 2030 [5]
2024	Baku (COP29)	New Collective Quantified Goal on climate finance: at least USD 300 bn per year by 2035, with a call to scale up to USD 1.3 tn per year; Article 6 rules finalised [10]
2025	Belém (COP30)	Decision to develop a just transition mechanism, widely referred to as the Belém Action Mechanism [11]; call to at least triple adaptation finance by 2035; Global Implementation Accelerator [12]

Within a decade, just transition moved from a single preambular clause to an institutional mechanism. Two caveats apply: the Belém decision *develops* rather than *establishes* the mechanism, deferring its operationalisation to COP31 (Antalya, November 2026) [11]; and COP30 did not deliver a negotiated roadmap for transitioning away from fossil fuels, which, despite the backing of more than 80 countries, was left to a presidency-led initiative outside the formal decisions. The just transition decision nevertheless carries the strongest rights-based language adopted in the UNFCCC process to date, including labour and human rights, the rights of Indigenous Peoples and free, prior and informed consent, and stresses that support should avoid exacerbating debt burdens. This vocabulary is likely to shape the conditions attached to future just transition finance.

1.1.4 Just Energy Transition Partnerships

Just Energy Transition Partnerships (JETPs) are country platforms that bundle a national transition plan, concessional finance and a social dialogue process. Partnerships have been agreed with South Africa (2021; initially about USD 8.5 bn), Indonesia (2022; about USD 20 bn), Viet Nam (2022; about USD 15.5 bn) and Senegal (2023; about EUR 2.5 bn) [8]. They are the closest existing approximation to an operational just transition instrument at national scale and a reference point for the new UNFCCC mechanism, but they also illustrate its risks: they are donor-dependent, slow to disburse and dominated by loans rather than grants, and the United States withdrew as a partner in March 2025 [8].

The international layer thus sets direction and reporting duties, but does not deliver; everything concrete happens in national plans.

1.2 National policies

This section maps three contrasting governance models, namely the European Union, the United States, and China with the wider Asian region, as context for the analysis that follows rather than as a comparative assessment.

1.2.1 European Union

The EU has the most codified climate governance system in the world. The European Climate Law sets in law a net GHG reduction of at least 55% by 2030 relative to 1990 and climate neutrality by 2050 [13]. Its 2026 amendment adds a binding intermediate target of a 90% net reduction by 2040 [14]. At least 85% must be achieved domestically, with high-quality international credits of up to 5% of 1990 net emissions usable from 2036; the amendment also introduces a biennial review and postpones the start of the second emissions trading system (ETS2), covering buildings and road transport, from 2027 to 2028. The headline target thus became stronger while the delivery route became more flexible, an indication of the political strain the target carries. The EU's NDC sets an indicative 2035 reduction of 66.25–72.5% [15].

The Governance Regulation turns these targets into an administrative planning obligation [16]. Member States prepare ten-year integrated NECPs, report on progress every two years and submit long-term strategies (LTS) with a 30-year perspective; final updated NECPs were due by 30 June 2024. Implementation relies on the Fit for 55 package, including the EU Emissions Trading System (ETS) and ETS2, the Carbon Border Adjustment Mechanism (CBAM), the revised renewable energy, energy efficiency and buildings directives, and the Social Climate Fund [17], together with the Clean Industrial Deal [18]. Two further frameworks constrain the same physical system without being climate policies: the Common Agricultural Policy (CAP), implemented through national CAP Strategic Plans, governs much of the land [19], and the Water Framework Directive (WFD), implemented through River Basin Management Plans (RBMPs), governs water [20]. The main JET instrument is the Just Transition Fund (JTF), which requires Territorial Just Transition Plans (TJTPs) for the most affected regions [21].

The EU is the case study of this report not because its system is the best, but because it is the only setting in which dozens of national plans are prepared to a common template and can therefore be compared side by side.

1.2.2 United States

US climate policy has oscillated. The United States ratified the UNFCCC in 1992, signed but never ratified the Kyoto Protocol, joined the Paris Agreement in 2016, withdrew (announced in 2017, effective in 2020), rejoined in 2021 and in 2022 enacted the Inflation Reduction Act, with roughly USD 370 bn in clean energy incentives [22]. In 2025 it initiated a second withdrawal from the Paris Agreement, effective 27 January 2026 [23]; the One Big Beautiful Bill Act curtailed tax credits for wind, solar and electric vehicles [24]; and in January 2026 the administration announced its withdrawal from the UNFCCC itself [25]. US emissions are now projected to fall by 26–35% below 2005 levels by 2035, compared with 38–56% under the policy set in place a year earlier [26].

The main lesson is financial rather than political: policy volatility is priced by investors. A long-lived asset financed against a tax credit that can be repealed in a budget bill carries a risk premium, raising the cost of capital and reducing deployment. This is the strongest argument for anchoring targets in binding law, as the EU does, and a reason to watch the review clauses and flexibilities of the EU 2040 framework, through which volatility can re-enter.

1.2.3 China and Asia

China frames its policy as "dual carbon": peaking CO_2 emissions before 2030 and achieving carbon neutrality before 2060, implemented through the "1+N" system of an overarching guidance document and sectoral action plans. Its 2035 NDC introduces the country's first economy-wide absolute target, a 7–10% reduction in net GHG emissions from peak, together with a non-fossil share above 30% of energy consumption and more than 3,600 GW of wind and solar capacity [27]. The 15th Five-Year Plan (2026–2030) sets a 17% reduction in carbon intensity and a 25% non-fossil share by 2030, and signals a move from "dual control" of energy to "dual control" of carbon, combining intensity and total emissions [28]. The national ETS has been extended beyond power to steel, cement and aluminium, and the sectoral renewable energy plan targets about 3,500 GW of renewable capacity by 2030, of which more than 2,800 GW is wind and solar [29].

Elsewhere in Asia, India targets net zero by 2070 [30] and 500 GW of non-fossil capacity by 2030, and Japan pursues its Green Transformation (GX) strategy with a 2035 target of 60% below FY2013 levels [31], alongside regional initiatives such as the ASEAN Power Grid and the Indonesian and Vietnamese JETPs.

Two features stand out. China is the one large economy in which the climate plan and the industrial plan are effectively the same document, framing decarbonisation as competitiveness and energy security rather than as an environmental cost. And its metric is moving from intensity towards absolute emissions, the point at which a plan becomes checkable, since an intensity target can be met while emissions still rise.

1.2.4 Three models, one shared weakness

Table 1.2. Three governance models for climate policy.

	European Union	United States	China / Asia
Main instrument	Binding law and mandatory plans	Tax incentives	Five-year plans and industrial policy
Stability	High, with review clauses	Volatile	High
Framing	Climate and competitiveness	Energy dominance and cost	Energy security and industrial upgrading

The three systems differ in legal tradition, politics and instruments, yet share one structural weakness: whatever the governance model, plans are written sector by sector and ministry by ministry. The energy chapter assumes a certain amount of new solar capacity, the agriculture chapter assumes a certain amount of farmland, and nobody checks whether they refer to the same fields. Energy plans rarely account for the land, water, food and materials they consume. This is a testable claim, and Section 1.3 summarises how it was tested on 35 European plans.

1.3 Connecting NDCs, NECPs and JET strategies

1.3.1 The planning stack

In principle, the planning instruments form a coherent hierarchy: the NDC is the sum, the NECP is the translation and just transition plans are the social layer. In practice they are written separately, on different calendars, by different authorities and using different data (Table 1.3).

Table 1.3. The planning stack in European countries: different clocks and owners for one physical system.

Instrument	Scope	Cycle / horizon	Typical owner
NDC (Paris Agreement)	Whole economy	5-year cycle	Foreign affairs and environment ministries
European Climate Law	EU-wide binding targets	2030 / 2040 / 2050	EU institutions
NECP and long-term strategy	Energy and climate	10-year plan with biennial progress reports; LTS to 2050	Energy or environment ministry
CAP Strategic Plan	Agriculture and land	7-year policy period (to 2027)	Agriculture ministry
River Basin Management Plan	Water	6-year cycle (third cycle to 2027)	River basin or regional authorities
Transport plans	Transport	Varies	Transport ministry
Territorial Just Transition Plan	Affected regions	Programme period (to 2027)	Regional authorities, under the JTF

These documents rarely cite one another's numbers. An NECP seldom refers to the land assumptions of the CAP Strategic Plan, and an RBMP seldom accounts for the water an energy plan will need for cooling, hydrogen or bioenergy. A ten-year energy plan, a seven-year agricultural policy, a six-year water plan and a five-year international pledge cannot be synchronised by accident; alignment has to be deliberate, and no institution is currently mandated to achieve it.

1.3.2 Evidence from the assessment of 35 European plans

The integrated assessment of European national commitments for climate neutrality by Koundouri et al. [32] tested these claims for 35 countries: the EU-27, five Western Balkan countries, Norway, Switzerland and the United Kingdom. Two scenarios were simulated to 2050 at an annual time step: Business-as-Usual (BAU), in which current conditions persist, and National Commitments (NC), in which every NECP, CAP and WFD obligation is implemented fully and on time. The analysis linked the FABLE Calculator (agri-food systems and land use), LEAP (energy) and three tools developed by the Global Climate Hub (BiofuelGCH, LandReqCalcGCH and WaterReqGCH, for biofuel potential, land requirements of renewables and water balance), following the nexus approach previously applied to Greece [33], and reviewed all 35 NECPs against seven criteria. The NC scenario is deliberately generous: if the plans do not reconcile under full implementation, partial implementation cannot rescue them, so all findings represent a floor on the problem. Prices, cross-border trade and economic feedbacks were not modelled, because the NECPs themselves do not contain them. Four findings are relevant here.

Finding 1: the plans are not comparable. Only 28 of the 35 countries had submitted a final NECP; seven remained in draft despite the June 2024 deadline. Nineteen plans extend to 2050, ten to 2040 and six only to 2030, with 2050 addressed in a separate strategy. Nineteen balance supply and demand, nine focus on demand, six on supply, and one (Norway) reports emissions only. Seven are very detailed, nine are descriptive only and nine provide insufficient data for modelling. Detail runs inversely to national wealth: Southern and Eastern European states tend to write data-rich plans that demonstrate absorption capacity for EU funds, while wealthier states write narrative plans and keep the detail in separate national strategies. Plans with different end years, baselines and resolution cannot be aggregated arithmetically, which reflects the design of the template rather than the work of the officials who followed it.

Finding 2: even fully implemented, the plans do not close. Under NC, supply-side emissions fall from about 1,000 MtCO_2e in 2022 to about 200 MtCO_2e in 2050, a major transformation but not net zero. Agricultural emissions fall by only 15% (from about 600 to 510 MtCO_2e) and remain essentially flat under BAU. The aggregate European electricity deficit more than doubles, from 54 TWh in 2025 to 115 TWh in 2050, and the green hydrogen deficit grows from 11 to 79 TWh. Many plans assume imports from neighbours that are themselves planning to import: each plan is individually reasonable, but summed, they require Europe to import more electricity and hydrogen from itself than it produces. Planned capacity, generation, consumption and trade do not reconcile within the plans of Croatia, Denmark, Lithuania and Poland, and the Dutch plan contains an unreconciled switch from net importer to net exporter. Europe also remains a net biofuel importer, about 2–5 Mtoe short: Germany, France, Spain and Italy import, while Bulgaria, Romania, Hungary and Croatia hold unused surplus potential.

Finding 3: the plans ignore the resources they consume. No NECP estimates the land its own renewable targets require. New centralised solar capacity would occupy about 1,500 km^2 in Italy, 1,453 km^2 in France and 1,332 km^2 in Germany, well under 1% of national territory, but about 986 km^2 (≈3%) in Belgium and 667 km^2 in the Netherlands, where it competes directly with farmland and protected landscapes. The associated land costs range from about €0.35 bn (Finland) to €2.2 bn (Italy, France) and weigh proportionally more on Belgium (≈€1.48 bn) and Greece (≈€1.01 bn). For water, no NECP and no RBMP sets an enforceable, sector-specific water-use target, since the WFD sets ecological status objectives rather than consumption limits; there was therefore no policy to simulate. In Southern Europe, agriculture dominates withdrawals (about 16,800 hm^3 in Spain and 11,200 hm^3 in Italy) amid heavy groundwater dependence and severe irrigation deficits, yet the CAP-aligned productivity increase is water-intensive precisely in these countries. Land and water are where distributional conflict materialises (people object not to a megawatt, but to the loss of a field, a view, a well or an irrigation quota), and they are exactly the two dimensions the plans do not quantify.

Finding 4: fragmentation is the cause, not the symptom. The instruments in Table 1.3 have different owners, cycles and data, and no shared accounting. This is a failure of architecture rather than of ambition or expertise: each document is prepared competently to its own mandate, but nobody owns the intersections. Trade-offs between documents are therefore never made explicit, quantified or negotiated, and they surface years later as permitting disputes, local protests or litigation.

1.4 Translating commitments into implementable pathways

1.4.1 When does a commitment become a pathway?

A commitment becomes an implementable pathway when five questions can be answered:

1. **What, where, when:** which sector, which technology, which year.
2. **With what:** how much land, water, material, grid capacity and finance.
3. **Who pays, who is displaced:** the distribution of costs and benefits.
4. **Who is accountable:** which ministry, agency or authority owns delivery.
5. **How is it measured:** which indicator, against which baseline, reported to whom.

Measured against this checklist, most NECPs answer the first question partially, the second barely, the third hardly at all, and the fourth and fifth inconsistently. This is a consequence of a template that never asked for the second and third. The checklist can be applied to any strategy document without the need for a model.

1.4.2 Examples of partial good practice

Several national frameworks perform well on at least one of the five questions (Table 1.4).

Table 1.4. Examples of partial good practice.

Country / instrument	Strength
Greece	Data-rich NECP linked to a national integrated assessment covering energy, land, water and biofuels in one frame [33]
Germany	Federal Climate Change Act with sectoral emission budgets (assessed across sectors since the 2024 amendment) and an independent Council of Experts on Climate Change [34]; the detailed granularity sits outside the NECP
Denmark	Climate Act with a binding 2030 target and five-yearly target setting [35]; government goal of a 110% reduction by 2050; first national CO_2e levy on livestock emissions, from 2030 [36]

Country / instrument	Strength
Spain	Just Transition Agreements for coal regions and a dedicated Institute for Just Transition, negotiated with unions and municipalities [37]
Poland, Czechia	Territorial Just Transition Plans (e.g. for Silesia and Ústí) as a condition for Just Transition Fund support [21]
JETPs	Country platforms in South Africa, Indonesia, Viet Nam and Senegal combining plan, finance and social dialogue [8]

Spain offers the clearest European example of the third question answered institutionally, and Denmark and Germany of the fourth and fifth. Yet each is strong on one dimension, and none integrates energy, land, water, food and distribution in a single consistent frame.

1.4.3 Why integrated assessment remains rare

One structural reason lies in the modelling toolkit. The review of 20 global Integrated Assessment Models (IAMs) presented in Chapter 3 finds that 16 have an endogenous energy system, but only two endogenise water allocation alongside energy and land, none represents critical minerals, all use GDP as their sole welfare metric, and none resolves distribution within a country. When a model has no water module, water constraints do not appear as a risk; they do not appear at all. The tools most cited in international climate assessment are therefore structurally unable to answer just transition questions at national level. This motivates the approach of this report: a modular stack of specialist models, designed for country-level analysis and able to take an actual NECP as input.

1.4.4 From diagnosis to recommendations

The 35-country assessment translated its findings into 20 recommendations organised along the same fault lines, as *sectoral*, *country-specific* and *regulatory* measures [32]. Among the regulatory ones, a unified 2050 horizon for all NECPs is a precondition for coordination, since plans ending in 2030 are invisible in any long-run European aggregate; enforceable water-use targets tied to CAP irrigation standards would close the largest regulatory gap identified, within existing legal instruments; and creative land use, such as agrivoltaics, brownfield solar and agro-pastoral wind, addresses land constraints in dense countries while keeping land productive and farmers within the value chain.

1.5 The implementation gap

1.5.1 Four gaps, not one

The term "implementation gap" is often used loosely to mean that progress is too slow. A sharper taxonomy distinguishes four gaps (Table 1.5).

Table 1.5. Four dimensions of the implementation gap.

#	Gap	Between	Who measures it
1	Ambition	Pledges and the 1.5 °C goal	UNEP Emissions Gap Report [38]
2	Implementation	Pledges and policies actually adopted	Climate Action Tracker [39]; European

#	Gap	Between	Who measures it
			Environment Agency [40]
3	Delivery / feasibility	Adopted policies and what can physically be built, given land, water, materials, grid, permitting and labour	Very few assessments; the focus of the modelling in this report
4	Equity / legitimacy	Who bears the costs and who receives the benefits	Almost nobody, quantitatively

Gaps 1 and 2 are tracked annually by established institutions. Gaps 3 and 4 decide whether a plan survives contact with reality, and they are linked: if the equity gap opens, the other three widen, as the transition is slowed, litigated, protested and eventually reversed at the ballot box. This is a delivery argument as much as a moral one.

1.5.2 How the gap manifests across sectors

The gap is not concentrated in one difficult sector; it is distributed across all of them and takes a different form in each (Table 1.6).

Table 1.6. Sectoral character of the implementation gap in European plans.

Sector	Nature of the gap	Main issues
Buildings	Finance and tenure	Renovation rate must double or triple; split incentives between landlords and tenants; energy poverty; heat decarbonisation; together with services, over one-third of EU energy-related emissions
Industry	Roadmaps	No sub-sector roadmaps in most NECPs; single-technology solutions; cost and competitiveness pressure; interaction with CBAM
Transport	Ambition	Largest emitting sector, with emissions flat or rising; NECP measures insufficient for 2030 and 2050; modal shift barely addressed; freight and aviation deferred
Agriculture and land	Scope	Shallow NECP sections; dietary change largely ignored; heavy reliance on LULUCF removals; land competition with renewables unquantified
Water	Regulation	No enforceable targets; irrigation deficits in Southern Europe; infringement proceedings over late RBMPs
Power, grid and hydrogen	Coordination	Aggregate import deficits; interconnection, storage and flexibility not planned jointly

Across all sectors, plans also rely on assumed behavioural change and social acceptance that is rarely examined. There is therefore no single lever.

1.5.3 Closing the gap

Five measures, all administratively available without new legislation, treaties or funding, would address the structural causes identified in this chapter:

1. **Align horizons and baselines** across the NECP, CAP Strategic Plan, RBMPs and long-term strategy within one common 2050 frame.
2. **Publish a physical resource account** alongside every capacity target: km^2 of land, hm^3 of water, tonnes of materials and euros of investment.
3. **Make cross-border assumptions explicit** and reconcile them with neighbours, so that no plan assumes an import that another plan does not supply.
4. **Create a standing cross-ministerial body** with a shared model and shared data, enabling integrated analysis rather than sequential consultation.
5. **Attach a distributional annex to every measure**, stating who gains, who loses, who is compensated and from which fund (e.g. the Just Transition Fund, the Social Climate Fund or the Modernisation Fund).

The evidence reviewed in this chapter shows that national plans do not close, either physically or across borders, and that they break mainly where resources are not counted and costs are not allocated. This leaves open the question with which the chapter began: who pays? The following chapters turn to the tools available for assessing the economic, social and environmental consequences of the transition, and to whether they can answer it.

2. Assessing the implications of the transition: tools and modelling approaches

Chapter 1 showed that national plans, even if fully implemented, do not add up. Judging their consequences requires tools that can trace effects across three dimensions: *economic* (money, jobs, growth, prices and public finance), *social* (who benefits, who is harmed and who is left out) and *environmental* (land, water, air, nature and the resources the transition itself consumes). This chapter introduces the main assessment tools and modelling approaches used for this purpose, and what each can and cannot represent. The distinction matters in practice, because knowing which tool produced a number also tells us what that number cannot include. Section 2.1 reviews the traditional approaches and the core vocabulary of assessment; Sections 2.2 and 2.3 outline how jobs and inequality are treated; and Section 2.4 introduces cross-system interactions. A systematic review of Integrated Assessment Models follows in Chapter 3, and the modelling framework applied in this report is presented in Chapter 4.

2.1 Traditional approaches to assessment

2.1.1 Baselines and scenarios

To assess a policy is to compare a world in which the policy is implemented with a world in which it is not. Two ingredients are needed: a *baseline* (also called the counterfactual or business-as-usual), describing what would have happened anyway, and a *scenario*, describing what happens if the policy goes ahead. Since only one of these worlds can ever be observed, the other has to be constructed, and that construction is the model. Every dispute about whether a policy "worked" is, at root, a dispute about the baseline. The Business-as-Usual and National Commitments scenarios of the 35-country assessment discussed in Chapter 1 are an example of two such constructed worlds [32].

2.1.2 Four families of tools

Assessment tools can be grouped into four families, which differ in scope, in the questions they answer and in what they leave out (Table 2.1).

Table 2.1. Main families of assessment tools.

Family	Tool	What it does	Main limitation
Appraisal (one project or policy)	Cost–Benefit Analysis (CBA)	Monetises all costs and benefits over time, using a discount rate, to test whether the net result is positive; the standard method for public investment appraisal, including for major EU co-financed projects [41]	Everything must be converted to money; a high discount rate makes far-future damage almost disappear
	Cost-Effectiveness Analysis (CEA)	Finds the cheapest way to reach a fixed target	Takes the target as given; fits climate policy, where targets are set in law
	Multi-Criteria Analysis (MCA)	Scores options against weighted criteria without monetisation	Results depend on the choice of criteria and weights
	Marginal Abatement Cost Curve (MACC)	Ranks measures by cost per tonne of CO_2 avoided	Treats measures as independent and hides who pays

Family	Tool	What it does	Main limitation
Economy-wide	Input–Output (IO) analysis	Traces spending through inter-industry transactions to estimate output and employment multipliers	Fixed technology and prices, no resource constraints; tends to overestimate effects
	Computable General Equilibrium (CGE)	Represents all markets at once, with prices adjusting until supply meets demand; captures knock-on effects across sectors	Typically assumes market clearing and a single representative household
	Macro-econometric models (e.g. E3ME)	Estimate economic relationships statistically from historical data, without assuming markets clear	Can show unemployment and path dependence, but rely on past relationships holding
	Partial equilibrium	Represents one sector in detail, holding the rest of the economy fixed	Misses economy-wide feedbacks
Systems and engineering	Energy system models (e.g. LEAP, TIMES, OSeMOSYS, Balmorel); land and food models (e.g. FABLE, GLOBIOM); hydrological and water allocation models	Represent physical systems technology by technology, fuel by fuel, crop by crop or basin by basin, by simulation or optimisation	Usually cover one system; others enter as exogenous assumptions
Integrated Assessment Models (IAMs)	Global IAMs	Couple an economy, an energy system, land use and a simplified climate model to produce long-run global scenarios, typically to 2100	Breadth comes at the expense of sectoral and spatial detail

Two distinctions cut across these families. *Simulation* models ask "what happens if we do X?", whereas *optimisation* models ask "what is the cheapest way to reach Y?". Variables are *endogenous* when they are determined inside the model and *exogenous* when they are fed in from outside as fixed assumptions. The second distinction is the more consequential for policy: if water availability is exogenous, water can never constrain the result, and the model will return a pathway that implicitly assumes all the water it needs. Anything exogenous is an assumption presented in the form of a result.

IAMs deserve particular attention because of their institutional reach. They produce the mitigation pathways assessed by the IPCC [42] and the standard global socio-economic scenarios used as common reference points [43], and many national NDCs and long-term strategies are built on, or benchmarked against, their outputs. Their blind spots therefore tend to become the blind spots of policy. A related methodological choice is between a single *monolithic* model, in which all components are solved together, and a *modular* chain of specialist models linked by passing outputs from one as inputs to another (soft-linking). The former suits global scenario screening; the latter is better suited to country-specific nexus and just transition assessments. Both issues are examined in Chapters 3 and 4.

2.1.3 Beyond GDP

Most economy-wide models and IAMs measure welfare through Gross Domestic Product (GDP), the market value of goods and services produced in a year. GDP is a measure of transactions and has well-known blind spots: a forest counts only when it is cut down; cleaning up an oil spill adds to GDP; unpaid work such as care or subsistence farming is invisible; and the indicator says nothing about who receives the income. Three concepts address these gaps. *Natural capital* is the stock of nature (soils, water, forests, fish, pollinators); *ecosystem services* are the flows of benefits that this stock provides (clean water, flood protection, pollination, carbon storage); and *non-market valuation* assigns values to goods without a market price, either by inferring them from behaviour (revealed preference, e.g. travel costs to a wetland or house prices near a park) or by asking people in structured surveys (stated preference, e.g. willingness to pay). The rationale is simple: a value that is not estimated is treated as zero in appraisal, and zero is always the wrong number. Alternative metrics such as Inclusive Wealth, the Genuine Progress Indicator and the Human Development Index build on this logic, backed by the Stiglitz–Sen–Fitoussi Commission [44], the Dasgupta Review [45], the UN System of Environmental-Economic Accounting [46] and the UN Pact for the Future, which calls for measures of progress that complement GDP [47].

In CGE models, beyond-GDP considerations can enter through three routes of increasing difficulty. The first, *satellite accounts*, converts physical model outputs (tonnes, hectares, cubic metres) into value estimates after the run; it is easy, but environmental damage never feeds back into the economy. The second treats *ecosystem services as inputs to production*, so that degrading clean water, soil fertility or pollination reduces output; this makes nature constrain the economy but requires credible valuation. The third *extends the welfare measure itself*, adding non-market goods and distributional weights to the household side and reporting welfare changes by income group; it is the most demanding, as it requires disaggregated households (Section 2.3). Without such extensions, a pathway optimised for GDP can appear cheapest while depleting the natural capital on which GDP depends.

2.1.4 Synergies, trade-offs, co-benefits and distributional impacts

Four terms structure the interpretation of any assessment (Table 2.2).

Table 2.2. Core terms for interpreting assessment results.

Term	Definition	Example
Synergy	Doing A also helps B	Building retrofits cut emissions, energy bills and winter illness
Trade-off	Doing A costs B	Bioenergy cuts emissions but uses land and water needed for food
Co-benefit	A benefit that was not the aim, often larger and sooner than the intended one	Coal phase-out cuts CO_2 (global, slow) and particulate air pollution deaths (local, immediate)
Distributional impact	Who receives the synergy and who bears the trade-off	Rooftop solar subsidies mainly reach homeowners, while renters contribute through levies

An assessment framed only in terms of aggregate cost and benefit tends to undervalue co-benefits, which accrue to other ministries' budgets, and to hide trade-offs, which fall on other sectors. Timing and concentration matter as well: a synergy in 2050 is not comparable with a trade-off in 2027, and 10,000 people each losing €50 represent the same total cost as 50 people each losing €10,000, but very different politics.

2.2 Job creation and workforce development

Employment is the most politically decisive figure in any transition and the one most often quoted loosely. Green jobs are those that reduce environmental harm, for example by protecting ecosystems, reducing energy, material and water use, decarbonising or avoiding waste [48]; brown jobs are in highly polluting activities; and jobs are counted in full-time equivalents (FTE) to account for part-time and seasonal work. "Skills" problems also differ in kind, and each calls for a different remedy: a skill *shortage* requires new training capacity, a skill *gap* on-the-job upskilling, *underskilling* targeted retraining, and a *mismatch* (the right skills in the wrong place or sector) mobility support or relocation of industry.

Recent evidence shows that most change consists of existing jobs acquiring green content rather than new occupations, and that fear of job losses can hold up transitions regardless of the net figures [49]. Where and how decarbonisation is targeted matters: for the Hungarian economy, a 20% emissions cut achieved by targeting firms according to their position in supply networks costs about 2% of jobs and output, against 28% of jobs and 33% of output when the largest emitters are targeted first [50]. Geography also binds, as US fossil fuel workers are largely not located where green employment is growing [51]. The relationship runs both ways: environmental degradation undermines employment in water-, land- and air-dependent activities [52], while well-designed transitions can raise productivity and create greener jobs when supported by education and training [53]. At the skills level, the share of occupations requiring both green and digital skills is rising, and green skills risk reaching only those who already access training unless disadvantaged groups are targeted explicitly [54]. The aggregate net-jobs number is therefore of limited use; what matters for policy is which jobs, where, for whom and when.

2.3 Vulnerable communities, welfare and inequality

Distributional analysis asks who gains and who loses, rather than how much in total. A policy is *regressive* when its costs take a larger share of income from poorer households, as most energy taxes do by default, and *progressive* in the opposite case; income *deciles* allow effects on, for example, the poorest 10% to be isolated. Harm depends on *exposure* (being in harm's way), *vulnerability* (how badly one is affected) and *adaptive capacity* (the ability to cope and recover), which is why identical hazards produce very different outcomes. *Energy poverty* denotes the inability to afford adequate energy services, a problem of affordability in higher-income countries and of access in lower-income ones [53].

The evidence shows why averages mislead. Carbon emissions are highly concentrated with wealth [55], while lifting people out of extreme poverty would barely change global emissions [56]. The distributional effects of carbon pricing vary strongly with policy design, and returning revenues as equal per-capita transfers can more than compensate the poorest households [57]. More than half of 5,097 energy transition mineral projects worldwide are located on or near the lands of Indigenous and peasant peoples [58]. In a modelled San Francisco Bay Area earthquake, poorer households bear 19% of asset losses but 41% of well-being losses [59], a strong argument for measuring welfare rather than assets alone.

Standard CGE models and IAMs typically represent each region through a single representative household and therefore cannot, by construction, show who pays. Answering distributional questions requires disaggregated households, micro-simulation based on household survey data, and the coupling of physical models with econometric evidence on people's preferences and livelihoods, so that measures are designed to be socially acceptable rather than only technically optimal [60]. Even then, behaviour and acceptance remain assumptions, which is why participatory approaches, in which stakeholders contribute knowledge that models lack, are an integral part of credible assessment.

2.4 Cross-system interactions

2.4.1 The nexus

The *nexus* is the set of connections between systems that are normally managed separately, namely water, energy, food, land and the economy. The term does not merely state that everything is connected; it means that the connections are strong enough to change the answer. A decision taken in one of these systems is a decision in all of them, whether intended or not. Ministries, budgets, data and careers are organised by sector; the physical world is not.

2.4.2 How a local problem propagates

A stylised example shows how a local inequality can reach every sector. It starts with smallholder farmers in a southern region who lack access to affordable irrigation, an apparently local and agricultural equity issue:

1. Farmers over-abstract groundwater, lowering an aquifer that also supplies the nearby town and cools a thermal power plant.
2. Yields fall and become volatile, food prices rise, and the problem reaches poor urban households.
3. Farm incomes fall and land is sold, offering cheap sites to solar developers.
4. Renewables concentrate in the area, and the community experiences the transition as something imposed on it.
5. Reduced hydropower and cooling water constrain summer electricity supply, raising prices and energy poverty in the same region.
6. Industry relocates or lobbies for exemptions, and the NECP misses its sectoral targets.
7. Local opposition delays permitting, slowing renewable deployment nationally and worsening the affordability problem that started the chain.

Seven steps involve at least seven ministries (agriculture, water, energy, environment, industry, planning and social affairs), none of which is accountable for the loop. Sector-by-sector analysis sees seven unrelated problems; integrated analysis sees one. The cheapest intervention lies at the starting point (affordable, efficient irrigation combined with enforceable abstraction limits), yet it would be booked as agricultural spending, invisible to the energy ministry that bears the consequences later.

2.4.3 Documented cases

Such interactions are well documented. Global mitigation policies that target land-use-change emissions can increase water demands and stress in African river basins, with knock-on effects on irrigation and hydropower [61]. Globally, irrigated biomass plantations deployed to limit warming to 1.5 °C could double the area and population under severe water stress, exceeding the water impact of the climate change they are meant to avoid [62]. Mitigation pathways relying on bioenergy produce larger fertiliser-driven increases in river nitrogen loads than even the highest-emissions pathway, with the largest increases projected in lower-income regions [63]. The IPCC Special Report on Climate Change and Land highlighted the interactions between land-based mitigation, food security, water and biodiversity that sector-specific assessment overlooks [64]. In none of these cases was the carbon accounting wrong; the frame was too small. National-scale nexus assessments, such as the one conducted for Greece, show that the same trade-offs emerge between energy, land and water policies within individual countries [33].

Regional studies show how such problems escalate from the local to the national and international level. In Thessaly, Greece's driest region and largest agricultural supplier, competition among farmers and uncontrolled abstraction through unregistered wells turned a local irrigation issue into a persistent political and governance problem, marked by individual political interests and a lack of transparency, with overexploited aquifers, environmental degradation and rising costs for agricultural production [65]. In agricultural catchments of Greece, Canada and Ireland, diffuse pollution from farming has degraded lakes and rivers used for irrigation and drinking water, turning the practices of individual farms into a problem of national water quality and, in Greece and Ireland, of compliance with the EU Water Framework Directive [66]. In the Omo-Turkana basin, multi-sectoral competition for scarce water within Ethiopia and Kenya feeds international tension between the two countries, with consequences for production and economic growth on both sides [67]. In Northwest China, the rapid expansion of wastewater treatment improved river water quality, while water scarcity and its burden remain unequally distributed among provinces [68].

Four lessons follow for the remainder of this report. An assessment is only as good as its counterfactual and its coverage, and what a model cannot represent it implicitly values at zero. Aggregate figures, whether for jobs or welfare, conceal the distribution that decides whether a transition is accepted. Inequality is not a side effect of the transition but a mechanism that propagates through every other system. And integrated analysis does not mean a bigger model, but a discipline: one scenario, one base year and consistent handovers between tools. A constraint left outside the frame does not disappear; it re-enters elsewhere, usually at higher cost and as a political rather than a technical problem. Chapter 3 examines how far the global IAMs that underpin climate policy meet these requirements.

3. Comparative assessment of global Integrated Assessment Models (IAMs) for energy–economy–natural resources analysis: A literature review and benchmarking against a multi-model approach

3.1 Introduction

Global challenges like climate change mitigation, food security, water stress, and land degradation are deeply interconnected through what is commonly referred to as the water-energy-food (WEF) or, more broadly, the energy-water-land (EWL) nexus, including the economy [69–71]. Policy decisions in one domain of the nexus routinely cascade into the others, creating competitions, shifts and reshapes [33, 72]. Integrated Assessment Models (IAMs) have become the principal quantitative tools for exploring these interdependencies, underpinning the scenario analyses of the Intergovernmental Panel on Climate Change (IPCC), Nationally Determined Contributions (NDCs), and long-term low-emission development strategies [43, 73, 74]. Yet no single IAM covers all nexus dimensions with equal depth. Most of the process-based IAMs that dominate IPCC assessments originated as energy-system or energy-economy models and only subsequently extended their scope to land use, agriculture, or natural resources such as water or minerals [75–78]. Such asymmetries matter because a growing body of evidence demonstrates that poor consideration of one component of the nexus in planning can produce unintended negative consequences for the others, even when the primary policy objective is met. Examples show that global climate mitigation policies targeting land-use-change emissions can increase water stress [61]; biomass plantations under a 1.5 °C scenario could double the global area and population under severe water stress exceeding the impact of the very climate change that such plantations are designed to mitigate [62]; bioenergy-associated fertilizer applications in climate mitigation scenarios lead to larger nitrogen-load increases [63]. The important caveats of sector-siloed modelling and their sub-optimal policy implications were also flagged explicitly by the IPCC [64].

Despite the proliferation of IAMs and the recognized importance of nexus-aware modelling, there is no systematic, practitioner-oriented review that evaluates the major global IAMs specifically through a water-energy-food-economy nexus lens. Existing model intercomparison exercises (e.g., SSP/IPCC AR6 scenario ensembles) [79–82] compare scenario outputs but rarely assess structural capabilities, sectoral blind spots, data requirements, or coupling compatibility side by side. As a result, a practitioner seeking to understand which model can endogenously represent water constraints on energy decisions, or which framework can accommodate country-level policy detail, must navigate dozens of separate model documentation pages and technical reports without a unified evaluative framework. The closest related work by Johnson et al. [76] on the water-energy-land nexus in global models, Vinca et al. [77] on CLEW models across scales, and Bardazzi and Bosello [83] on WEFE in macroeconomic models, either focuses on a subset of models, organizes the analysis by spatial scale rather than by evaluation criteria, or reviews model classes rather than named models under a uniform framework. The review paper by Johnson et al. [76] assessed how global models cover the W-E-L nexus, however, it was not focusing only on IAMs, but also on global hydrological models, agro-economic, hydro-economic models, and it aimed more to guide future modelling improvements, rather than practitioner-oriented insights for model selection. No work to our knowledge compares established IAMs against alternative multi-model architectures, combining different tools, as practitioners tend to prefer [84–86]. This gap is especially consequential because a growing number of research teams and policy institutions are now designing custom multi-model frameworks rather than relying on a single IAM, as no off-the-shelf tool fully covers the nexus dimensions they need [87]. Such examples are the WEAP-LEAP coupling [88, 89], the GTAP-based CGE models linking with biophysical land and energy tools for economy-wide assessments [90], the CLEWs framework built on OSeMOSYS for climate-land-energy-water analysis [91], and the SDSN Global Climate Hub (GCH) combining different sectoral models [32, 72, 92]. These bespoke architectures offer the advantage of specialist depth per sector and flexibility in model selection, but they introduce challenges of their own, such as ensuring consistency across component models that were not designed to communicate with each other, harmonizing spatial and temporal resolutions, aligning commodity and sector definitions, and managing iterative convergence [77, 93]. Crucially, there is no established guidance on when a monolithic IAM is preferable to a modular multi-model pipeline, or vice versa, for specific analytical purposes such as nexus assessments, national policy evaluation, or SDG trade-off analysis. The literature has called for such comparative guidance [94, 95], but it has not yet been systematically provided.

This chapter aims to contribute to filling this gap by presenting a structured comparative assessment of 20 globally scoped IAMs and their key couplings, evaluated against a uniform set of criteria relevant to energy-economy-natural resources analysis. We then provide a comparison of such approaches against custom multi-model frameworks, which link dedicated specialist tools into an integrated pipeline. As a concrete benchmarking example, we use the multi-model framework of the SDSN GCH, which links specialist tools for land-use, computable general equilibrium modelling, energy-emissions analysis, and hydrological tools into a sequential pipeline for integrated country-level assessments. The aim of this comparison is twofold: i) to identify the structural strengths, weaknesses, and complementarities of existing IAMs for nexus analysis; and ii) to assess the role and added value of a modular, multi-model architecture relative to monolithic IAM frameworks, providing practitioners with guidance on when each approach is most appropriate for such purposes.

3.2 Materials and Methods

3.2.1 Model selection and scope

The models included in this review were selected according to three criteria. First, each model must have a global or multi-regional scope, meaning it can in principle represent the world economy, energy system, or land surface, not solely a single country or continent. This criterion ensures comparability across frameworks and relevance to the global-scale scenarios that inform IPCC assessments and international climate negotiations [43, 73]. Models that have been developed with a purely regional or continental scope (e.g., PRIMES for the EU, Euro-Calliope for Europe) were excluded, even where they are technically sophisticated, because they cannot be meaningfully compared against global IAMs on the nexus dimensions under the scope of this review. Second, each model must have the documented capacity to address at least two of the four nexus domains central to this review, namely energy, economy, land use, and water resources. This threshold is deliberately inclusive as it allows the review to capture both highly integrated IAMs that span all four domains and specialized models (e.g., energy-only or land-only) that contribute to nexus analysis through coupling, a distinction that is itself analytically informative. Third, the model must be documented in peer-reviewed literature or official technical documentation of sufficient detail to support the evaluation criteria defined in Section 3.2.3. The existence and quality of documentation is itself a criterion of inclusion, following established practice in model review studies [78, 96, 97]. Undocumented or proprietary models for which structural characteristics cannot be independently verified were excluded.

Applying these criteria resulted in a set of 20 model entries, comprising 16 standalone models or frameworks (REMIND, MAgPIE, IMAGE, MESSAGEix, GCAM, DEMETER, WITCH, AIM/CGE, POLES, TIAM-UCL, DICE/PAGE/FUND, GLOBIOM, EPPA, E3ME, IMACLIM-R, OSeMOSYS/CLEWs) and 4 documented couplings of these models that are treated as distinct analytical configurations (MESSAGEix-GLOBIOM full stack, REMIND-MAgPIE, MAgPIE-LPJmL, GCAM-DEMETER). The coupled configurations are included separately because their nexus capabilities, data requirements, and practical limitations differ substantially from those of their component models in isolation, a point emphasized in the literature on model-linking challenges [77, 98]. General-purpose computable general equilibrium frameworks and databases (e.g., the GTAP standard model, GEM-E3, ENV-Linkages, DART) were excluded because they function primarily as economy-wide tools without endogenous representation of land, water, or climate systems, and would therefore score identically on the nexus evaluation criteria; their inclusion would expand the review substantially without adding analytical differentiation. The CGE paradigm is nonetheless represented through four models that have been specifically extended toward climate and resource analysis (AIM/CGE, EPPA, E3ME, IMACLIM-R). We acknowledge that the boundary between "global" and "regional" is not always sharp, and some models (e.g., POLES, E3ME) cover many individual countries, but all included entries are designed for and documented as global or multi-regional frameworks. Finally, we note that GCAM, AIM/CGE, MESSAGEix-GLOBIOM, and other frequently cited nexus-relevant models are fully included in the review; our selection criteria were designed to capture precisely the models that feature most prominently in IPCC and SSP scenario exercises [43, 80].

3.2.2 Data sources and review methodology

The review follows a documentation-based, qualitative comparative approach, which is an established methodology for assessing and comparing energy, environmental, and integrated assessment modelling tools [97, 99, 100]. Rather than comparing model outputs (as in model intercomparison projects), this approach evaluates model structures, assumptions, and capabilities based on their documentation, allowing practitioners to assess fitness-for-purpose before committing to a specific tool. The primary sources for this review are: i) the IAMC wiki [101], which provides a standardized, wiki-based documentation platform used consistently across a range of IAMs and allows for direct comparison of model features; ii) official technical reports and model manuals published by the developing institutions (e.g., the MESSAGEix-GLOBIOM documentation by Krey et al. [102]; the E3ME manual by Dwesar et al. [103]; the GLOBIOM documentation by Havlík et al. [104]); and iii) flagship application papers that describe the models in the context of their major use cases, particularly the Shared Socioeconomic Pathways quantification [43, 105, 106] and IPCC AR6 scenario contributions. In addition, we consulted peer-reviewed papers describing recent model extensions that alter a model's nexus capabilities, most notably the MESSAGEix-GLOBIOM water nexus module [107] and the GCAM v5.1 water module documentation [106]. Finally, supplementary web-based searches were conducted to identify the latest developments in GitHub repositories and community resources. Each of the 20 model entries was assessed against the predefined evaluation framework (Section 3.2.3), using a standardized template that maps directly to the overall evaluation table columns. This ensures internal consistency, which is a recognized requirement for documentation-based model reviews where subjective judgement is unavoidable [78, 97]. The resulting assessments were compiled into a single comparative table (Table 3.A.1, Appendix 3.A) designed for side-by-side inspection.

3.2.3 Evaluation framework

The evaluation framework comprises 17 criteria organized into four groups (Table 3.1). These were designed to capture not only what each model does but also what it cannot do, where its blind spots lie, and how practically accessible it is. These are dimensions that are critical for practitioners selecting or designing modelling frameworks, but that are rarely presented systematically in the literature. The criteria map directly to the columns of the comparison table (Table 3.A.1, Appendix 3.A) but include additional dimensions identified during the review process as important for nexus assessment.

Table 3.1. The main criteria of the evaluation framework followed along with their description/justification.

Evaluation angle	Description
A. Structural and methodological characteristics: These criteria capture the model's fundamental architecture.	
(1) Model paradigm	whether the model is based on optimization (linear or nonlinear programming), simulation, computable general equilibrium (CGE), econometric estimation, or a hybrid of these approaches. This is a primary determinant of what questions a model can meaningfully answer [75].
(2) Temporal dynamics	whether the model uses intertemporal optimization with perfect foresight, recursive-dynamic (myopic) updating, or pure simulation, which determines how it treats expectations, investment decisions, and policy anticipation.
(3) Spatial granularity	the number and nature of spatial units (world regions, countries, grid cells), whether outputs are spatially explicit, and whether the model can feasibly be configured for country-level analysis.
(4) Time horizon and step size	the base year, end year, step resolution (annual, 5-year, 10-year), and whether sub-annual time-slices (e.g., for electricity dispatch) are available.
B. Sectoral coverage/nexus dimensions: These criteria directly assess each model's treatment of the resource domains that constitute the nexus.	
(5) Energy system	the depth of technology representation on both the supply and demand sides, fuel detail, and whether the model endogenously determines the energy mix.
(6) Economy and macroeconomic feedbacks	whether the model includes a full CGE, partial equilibrium, reduced-form macroeconomic closure, or no economic feedback at all.
(7) Land use and agriculture	whether land allocation is endogenous, the level of crop, livestock, and forestry detail, and whether bioenergy production is represented.
(8) Water resources	whether the model includes endogenous water allocation, hydrological constraints, water–energy feedbacks (e.g., cooling water, hydropower), or irrigation demand, and at what spatial resolution.
(9) Minerals and critical materials	whether the model represents non-energy natural resources such as critical minerals, metals, or phosphorus. This criterion was included because of the growing recognition of mineral supply constraints for the energy transition [108].
(10) Climate module	whether the model includes an endogenous climate response (temperature, radiative forcing), a damage function, or treats climate externally (emissions as output only).
C. Cross-cutting capabilities: These criteria assess how sectors interact within the model and what policy questions can be addressed.	
(11) Nexus integration depth	which cross-sector feedbacks are endogenous (resolved within the optimization or equilibrium), which are soft-linked (exchanged iteratively between models), and which

	are absent. This is assessed for each pairwise nexus linkage: energy↔land, energy↔water, land↔water, and the three-way nexus.
(12) Policy instrument coverage	the range of policy levers the model can represent, including carbon pricing, sectoral regulations, technology mandates, NDC/NECP-style targets, and subsidies.
(13) Uncertainty treatment	whether the model is deterministic only, supports stochastic programming, or handles uncertainty through scenario analysis, Monte Carlo methods, or probabilistic outputs.
D. Practical considerations: These criteria address the barriers and enablers of model adoption - factors that are decisive for practitioners but often overlooked in model descriptions	
(14) Openness and reproducibility	the model's software license, the availability of source code, dependency on commercial solvers (GAMS, CPLEX, CONOPT), and whether input data are publicly accessible.
(15) Data requirements and scarcity tolerance	the volume and specificity of input data required, and whether the model can produce credible results in data-scarce contexts (e.g., developing countries) or requires full national calibration.
(16) Coupling compatibility	how easily the model can be linked to external tools, whether documented coupling interfaces or APIs exist, and whether the model has been used in multi-model pipelines.
(17) Computational cost	approximate run times and hardware requirements, which determine feasibility for large scenario ensembles and sensitivity analyses.

3.3 Results

3.3.1 Taxonomy of reviewed models

The 20 model entries collected, span six methodological paradigms and six primary domain orientations, revealing a landscape that is both diverse and unevenly populated (Figure 3.1). The majority of models cluster in the optimization paradigm (REMIND, MESSAGEix, TIAM-UCL, OSeMOSYS, MAgPIE, GLOBIOM, GCAM, and their couplings), reflecting the historical dominance of cost-minimization and surplus-maximization approaches in energy and land-use modelling [75]. A smaller but important group uses computable general equilibrium frameworks (AIM/CGE, EPPA), while single representatives occupy the econometric (E3ME), hybrid (IMACLIM-R, WITCH), simulation (IMAGE, POLES), and aggregate cost-benefit (DICE/PAGE/FUND) paradigms. This diversity matters: optimization-based models identify cost-efficient pathways but assume a central-planner perspective; CGE models capture economy-wide feedbacks but often simplify technology representation; econometric models empirically ground their parameters but cannot identify "optimal" trajectories; and cost-benefit models provide aggregate welfare insights but lack the sectoral resolution needed for nexus analysis.

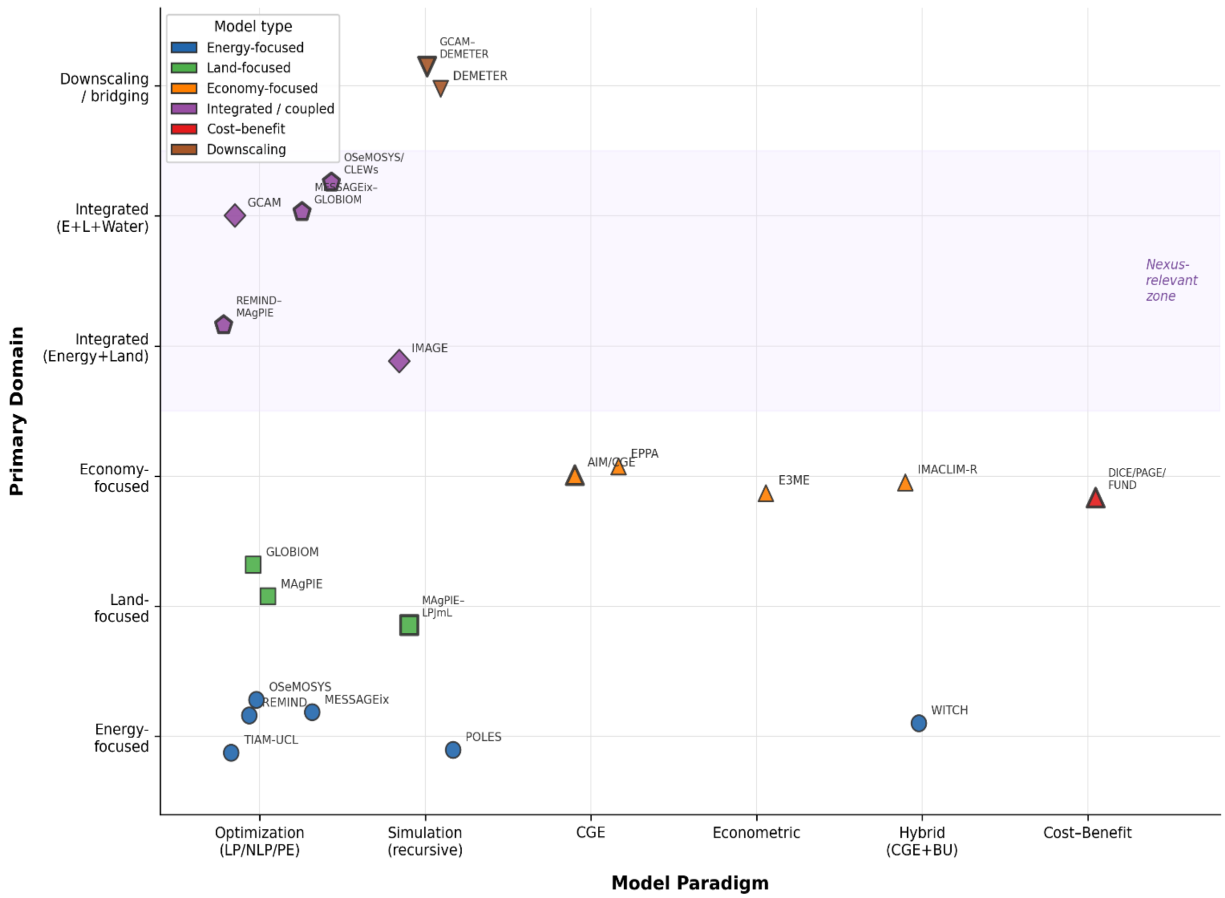


Figure 3.1. Taxonomy of 20 reviewed models by methodological paradigm (x-axis) and primary domain orientation (y-axis). Colours indicate the model's core sectoral focus: energy (blue), land (green), economy (orange), integrated or coupled (purple), cost-benefit (red), and downscaling (brown). Coupled model systems are shown with larger markers and thicker borders. The shaded band highlights the "nexus-relevant zone", i.e. the domain space where models span at least three resource sectors (energy, land, and water). Most models cluster in the bottom-left quadrant (energy-focused optimization), and only five entries occupy the integrated zone.

In terms of primary domain, the reviewed models fall into three broad categories: energy-focused tools (REMIND, MESSAGEix, TIAM-UCL, POLES, WITCH, OSeMOSYS), land-focused tools (MAgPIE, GLOBIOM, DEMETER), and economy-focused tools (AIM/CGE, EPPA, E3ME, IMACLIM-R, DICE/PAGE/FUND). A fourth, smaller category (integrated or coupled systems) is the most nexus-relevant: only GCAM, IMAGE, MESSAGEix–GLOBIOM (full stack), REMIND-MAgPIE, and OSeMOSYS/CLEWs span at least three nexus domains, and only two (GCAM, MESSAGEix-GLOBIOM with the nexus module) include endogenous water allocation alongside energy and land. Figure 3.1 positions each model along both axes, highlighting the "nexus-relevant zone", i.e., the space where integrated or coupled models operate. It also shows how sparsely it is populated relative to the single-domain tools that dominate the landscape.

3.3.2 Sectoral coverage comparison

Figure 3.2 presents another core finding of this review, namely a nexus coverage matrix in which each model is evaluated across six sectoral dimensions (energy, macroeconomy, land use, water, minerals, and climate), with coverage rated as endogenous (■), soft-linked or iterated (◧), post-processed or exogenous input (○), or absent (—).

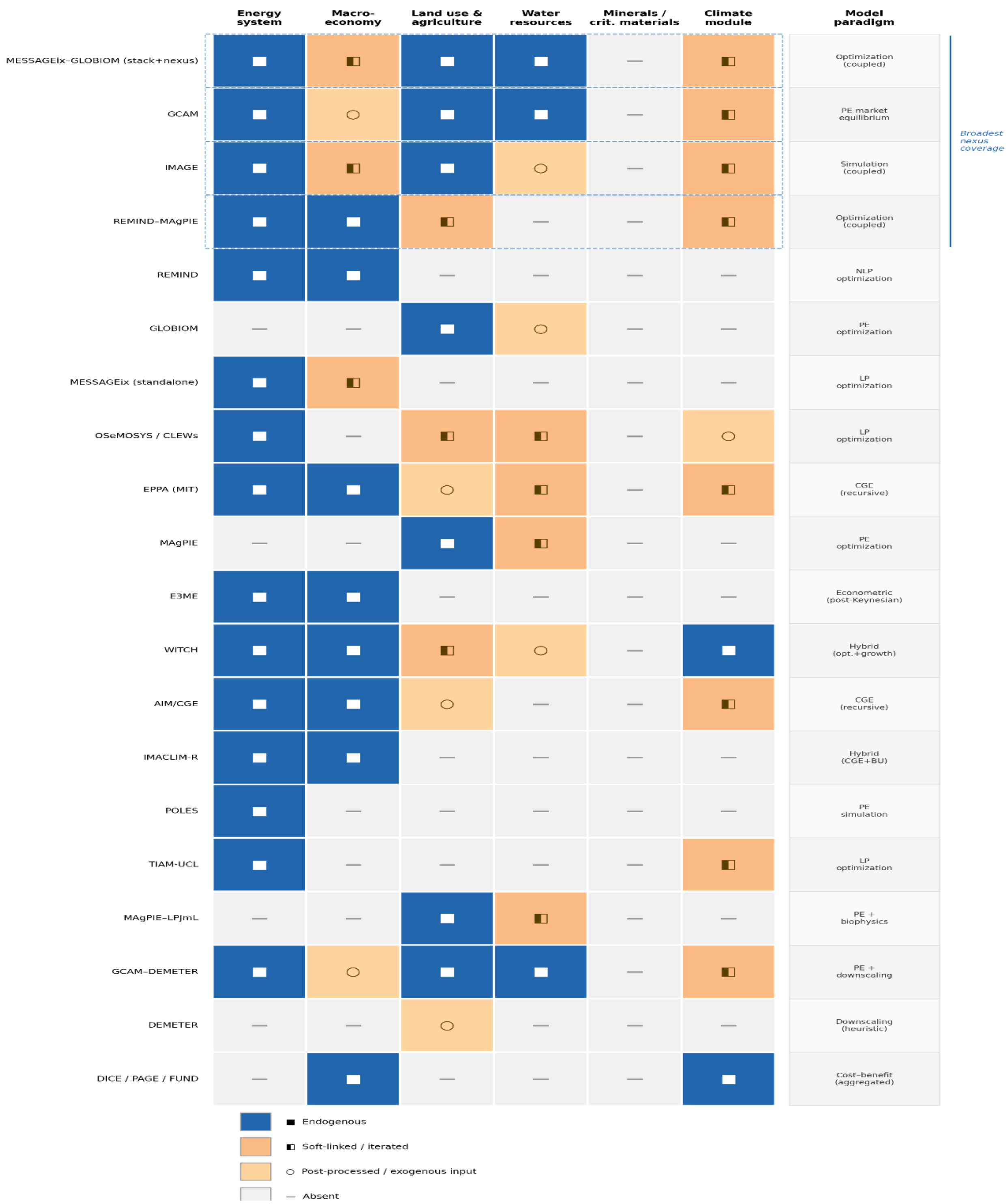


Figure 3.2. Sectoral nexus coverage of 20 reviewed IAMs across six dimensions: energy system, macroeconomy, land use and agriculture, water resources, minerals and critical materials, and climate

module. The rightmost column indicates the model paradigm. Each cell is coded as: endogenous (■, dark blue = the sector is resolved within the model's optimization or equilibrium), soft-linked or iterated (◧, medium orange = information is exchanged with an external model), post-processed or exogenous input (○, light orange = the sector is represented via prescribed data or accounting), or absent (—, grey). Dashed borders highlight the four models with the broadest nexus coverage. The minerals column is universally empty, and only three model configurations include endogenous water allocation, revealing the two most significant structural gaps for nexus-oriented analysis.

Three patterns emerge immediately. First, the energy column is the most uniformly populated: 16 of 20 entries include an endogenous energy system, confirming that the IAM landscape remains rooted in energy-climate analysis. Second, the water column is the most sparsely covered: only three entries (MESSAGEix-GLOBIOM with the nexus module, GCAM, and GCAM-DEMETER which inherits GCAM's water) treat water endogenously, while six more include it as a soft-linked or post-processed variable and the remaining eleven omit it entirely. This asymmetry of robust energy coverage alongside weak water coverage, is the single most important structural gap revealed by the heatmap, and it has direct implications for the credibility of nexus assessments [76]. Third, the minerals column is universally empty: no reviewed model includes endogenous representation of critical materials, rare earths, or phosphorus, despite the growing recognition that mineral supply constraints may significantly shape the feasibility and cost of energy transitions [108].

3.3.3 Energy-Water-Land (EWL) nexus evaluation

Moving beyond the sectoral inventory, this section evaluates how models represent the linkages between nexus domains (beyond the economy), which is ultimately more important than whether each sector is present in isolation.

- Energy ↔ Land. The bioenergy-land competition is the most widely represented nexus linkage. GCAM resolves it endogenously through its market-equilibrium framework, where bioenergy competes with food and forestry for land at the regional level [106]. REMIND-MAgPIE captures it through iterative coupling, with bioenergy demand from REMIND influencing land allocation in MAgPIE [109]. IMAGE, MESSAGEix-GLOBIOM, and WITCH represent this linkage through soft-links to their respective land models (MAGNET, GLOBIOM, GLOBIOM). However, a less-discussed dimension is the land requirements for renewable energy infrastructure (solar farms, wind parks), which is rarely represented endogenously. Most models treat the land footprint of renewables as negligible or exogenous, despite evidence that large-scale solar and wind deployment can conflict with agricultural and conservation land uses [110].
- Energy ↔ Water. This is the weakest pairwise linkage across the reviewed models. Only two frameworks endogenize bidirectional water-energy feedbacks: GCAM, which includes water constraints at the basin level affecting both agricultural and energy-sector decisions [106, 111]; and the MESSAGEix-GLOBIOM nexus module, which tracks cooling water for power plants, water for energy extraction, and irrigation water across 210 basins [107]. EPPA's IGSM-WRS coupling adds basin-level water but drives water demand from GDP and population projections rather than from endogenous technology choice, making it a softer linkage. IMAGE post-processes water stress indicators. All other reviewed models either omit water entirely or treat energy-sector water use as an accounting exercise with no feedback to energy decisions.

- Land ↔ Water. MAgPIE and GLOBIOM both represent irrigation water as a constraint on agricultural intensification, with MAgPIE drawing on LPJmL biophysics to constrain water availability at the clustered grid-cell level. GCAM includes irrigation demand within its water module. IMAGE incorporates hydrological information from LPJmL but does not use water availability as a decision variable for land allocation. The remaining models do not represent the land-water linkage.
- Three-way nexus. Only two model configurations currently allow simultaneous, endogenous feedbacks across all three domains: the MESSAGEix-GLOBIOM stack with the nexus module and GCAM. In both cases, energy decisions influence land (through bioenergy), land decisions influence water (through irrigation), water availability constrains both energy (cooling) and land (agricultural expansion), and prices or shadow values propagate these trade-offs across sectors. However, even in these models, the water representation remains coarser than the energy or land modules, and sub-annual water variability (crucial for drought and flood risk) is not captured. OSeMOSYS/CLEWs can in principle represent three-way feedbacks within a single optimisation framework, but its sectoral detail is shallower than that of the larger IAMs, and its global-scale implementation is less mature.

3.3.4 Methodological trade-offs

The reviewed models embody several fundamental methodological trade-offs that practitioners must navigate.

- Perfect foresight vs. myopic dynamics. Intertemporal optimisation with perfect foresight (REMIND, MESSAGEix, TIAM-UCL, WITCH) yields cost-efficient pathways but assumes that agents perfectly anticipate future prices, technologies, and policies, which is an assumption that systematically underestimates transition frictions, stranded assets, and policy uncertainty. Recursive-dynamic models (GCAM, AIM/CGE, EPPA, MAgPIE) avoid this assumption but cannot represent anticipatory investment behaviour. E3ME and IMACLIM-R take a third route, grounding dynamics in empirically estimated parameters that embed historical path dependence but may not hold under deep structural transformation [112]. For nexus analysis, the choice matters: perfect foresight tends to find smoother, cheaper transitions because the model can "see" the full future price trajectory, while myopic dynamics may produce more abrupt shifts and higher costs that better reflect real-world decision-making under uncertainty [113].
- Technology detail vs. economic generality. Bottom-up energy models (REMIND, MESSAGEix, TIAM-UCL, OSeMOSYS) represent hundreds of individual technologies but lack economy-wide feedbacks. Top-down CGEs (AIM/CGE, EPPA) capture sectoral reallocation and trade effects but represent technologies through aggregate production functions. Hybrid approaches (IMACLIM-R, WITCH) attempt to bridge this gap but at the cost of increased complexity and reduced transparency. For practitioners, this trade-off means that technology-rich models are better suited for questions about energy system design, while CGEs are better suited for questions about macroeconomic costs, employment, and trade impacts while no single model excels at both.
- Spatial aggregation vs. computational feasibility. Global IAMs typically operate at 10-37 regions, which is insufficient to resolve within-country distributional effects, basin-level water dynamics, or the spatial heterogeneity of renewable energy resources. Higher-resolution models exist (POLES covers 54 countries; OSeMOSYS can be configured nationally) but at increased data and computational costs. This trade-off is particularly acute for water, where basin-level resolution is

physically necessary but computationally expensive to maintain within a global optimization framework.

3.3.5 Openness, data requirements, and accessibility

Practical accessibility varies enormously across the reviewed models. At one extreme, GCAM and OSeMOSYS are fully open-source with no commercial solver dependency, active user communities, and free educational materials, making them the most accessible entry points for new users and data-scarce contexts. At the other extreme, POLES, TIAM-UCL, and IMACLIM-R are proprietary or require institutional affiliation, and several nominally open-source models (REMIND, MESSAGEix, MAgPIE, GLOBIOM) depend on GAMS combined with commercial solvers such as CPLEX, GUROBI, or CONOPT, representing annual license costs that can exceed €10,000 and creating a reproducibility barrier for research groups without institutional licenses.

Data intensity follows a broadly predictable pattern: technology-rich energy models and detailed land-use models (TIAM-UCL, MAgPIE, GLOBIOM) require the most granular input data (individual technology costs, crop-level yield parameters, livestock system characterizations), while aggregate economic models (DICE/PAGE/FUND) and CGEs calibrated to GTAP require comparatively standardized macroeconomic datasets. For data-scarce developing countries, OSeMOSYS/CLEWs is the most data-scarcity-tolerant framework by design, while full-scale IAMs like MESSAGEix-GLOBIOM require substantial calibration effort that has been completed for only a limited number of national applications.

3.3.6 Gaps and limitations across all reviewed IAMs

The comparative assessment reveals seven systemic gaps that are shared across virtually all reviewed models, regardless of paradigm or domain focus.

- Minerals and critical materials are universally absent. No reviewed model endogenously represents the supply, demand, or price dynamics of lithium, cobalt, rare earths, copper, or phosphorus. Despite the IEA's finding that clean energy transitions could require up to six times more mineral inputs by 2040 [108], this is arguably the largest structural blind spot in the current IAM landscape.
- Sub-annual water variability is not captured. Even the most advanced water modules (in GCAM and MESSAGEix-GLOBIOM) operate at annual resolution, which cannot represent seasonal droughts, flood events, or the intra-annual timing mismatches between water demand (irrigation peaks, cooling demand in summer) and supply (snowmelt, monsoon patterns). This limitation is significant given that climate impacts on water are predominantly expressed through changes in variability and extremes, not annual means.
- Climate-impact feedbacks on resource systems are underrepresented. Most reviewed IAMs treat climate as one-directional output: the model computes emissions, which feed a climate module (e.g., MAGICC) to estimate temperature change, but temperature and precipitation changes do not feed back to reshape energy demand, water availability, or crop yields within the same optimisation. Only the MESSAGEix-GLOBIOM nexus module [107] and, partially, IMAGE incorporate biophysical climate impacts on energy and land systems. This omission matters because extreme events like droughts reducing hydropower and cooling-water availability, heatwaves spiking electricity demand, floods disrupting supply chains, can fundamentally alter

the cost-optimal resource mix. Without such feedbacks, IAM pathways may overestimate the feasibility of strategies that depend on climate-sensitive resources [114, 115].

- Distributional and equity impacts within regions are invisible. All reviewed global IAMs aggregate economic agents into representative regional households or sectors, precluding analysis of how climate policies affect income groups, rural vs. urban populations, or vulnerable communities, which are dimensions that are central to the just-transition agenda and to Sustainability Science as a discipline.
- Relatedly, all reviewed models use GDP as their primary measure of economic performance and welfare, with no model incorporating beyond-GDP metrics such as the Genuine Progress Indicator (GPI), the Human Development Index (HDI), or inclusive wealth accounts. This is a significant omission given the growing consensus as reflected in the Dasgupta Review [45], the Stiglitz-Sen-Fitoussi Commission [44], and the UN's recent adoption of a resolution on beyond-GDP measures [47], that GDP alone fails to capture the depletion of natural capital, social inequality, and non-market ecosystem services that are central to sustainability assessment. For nexus analysis specifically, GDP-based welfare measures cannot value the ecosystem services provided by intact watersheds, forests, or biodiversity, meaning that pathways optimized for GDP growth may systematically undervalue the natural resource base on which long-term prosperity depends [45, 116].
- Behavioural realism remains limited. With the exception of E3ME's econometric approach and IMACLIM-R's second-best economics, the reviewed models assume either optimizing agents (optimization-based IAMs) or representative-agent equilibrium behaviour (CGEs). Consumer heterogeneity, bounded rationality, political economy constraints, and social acceptance dynamics that critically shape the pace and direction of energy and land-use transitions, are at best handled through exogenous scenario assumptions [117].
- Systematic validation against historical data is limited. Wilson et al. [78] note that historical simulation is an underused evaluation method for IAMs, and our review confirms this: most model documentation focuses on structural description and scenario results rather than on demonstrating the model's ability to reproduce observed historical dynamics. This is a particular concern for water and land modules, where historical datasets could in principle support validation but are rarely used for this purpose within IAMs themselves.

3.4 Alternative architectures based on multi-model approaches: the GCH example

3.4.1 Overview of the GCH modelling suite

The SDSN GCH adopts a modular “digital twin” architecture that chains specialised models for land, economy, energy and water [118], and is designed for country-level application from the outset. Its core components are: a land-use module (LandReqGCH), which projects land-use change on the basis of historical land-use data and estimates the land required for renewable energy infrastructure and the potential for biofuel production [119, 120]; a multi-region computable general equilibrium model (GTAP-CGE), which captures price, trade, output and welfare responses across all sectors [121, 122]; the LEAP energy–emissions model, which simulates, or optimises, fuel mixes, technology deployment and emissions [123]; and a water module (WaterReqGCH) based on Aqueduct, which estimates basin-level water availability, sectoral withdrawals and water stress [124].

The modules are linked so that the outputs of one become inputs or constraints for the others: land allocated to bioenergy caps biofuel supply in the energy model, and economic growth and sectoral output drive energy demand; in the optimisation set-up under development, land and water availability also enter as constraints on energy and agricultural demands. The land component is validated against historical data and the water component is calibrated to national water accounts, and the framework is openly accessible. The architecture thus pursues the "end goal" of nexus modelling identified by Johnson et al. [76], namely frameworks that capture trade-offs and synergies among water, food and energy systems, and supports the exploration of pathways consistent with the Sustainable Development Goals [125]. The model chain and methodology applied in this report are described in detail in Chapter 4.

3.4.2 Comparison: multi-model assessments vs. monolithic IAMs

Unlike a "monolithic" IAM (e.g., GCAM, IMAGE, REMIND) that models all sectors within one unified code, the GCH uses a "modular" stack of sector-specialist models. The distinction is better understood as a spectrum than a binary, since several of the reviewed IAMs are themselves internally modular: IMAGE chains energy, agro-economic, vegetation–hydrology and climate modules through iterative soft-links [126], REMIND-MAgPIE couples an energy-economy optimisation with a land-use model through bioenergy price iteration, and the MESSAGEix-GLOBIOM stack links five independently developed models. What distinguishes such institutional "IAM stacks" from custom multi-model frameworks is mainly the degree of institutional integration: their components are maintained by the same institute, share a common data infrastructure and have co-evolved to ensure consistency, whereas a custom pipeline assembles tools from different institutions, offering greater flexibility in model selection but requiring the user to resolve coupling, harmonisation and convergence.

Each approach has trade-offs. A single IAM solves an integrated optimisation or equilibrium, which is elegant and computationally efficient but often coarse outside its core sectors; land and water are typically represented with less granularity than in stand-alone modules, and energy–land links are often reduced to simplified bioenergy supply curves [76]. Multi-model assessments can instead use detailed sectoral logic and bespoke resolution in each domain, at the cost of greater calibration effort and feedbacks that may require manual iteration. Most IAMs still treat energy-sector water use exogenously, and only GCAM and MESSAGEix-GLOBIOM have recently introduced basin-level water constraints [76, 77]. A multi-model approach that integrates a dedicated hydrological module can enforce a two-way coupling, in which water scarcity affects agriculture and energy, and the resulting scarcity metrics feed back on energy and land decisions (Table 3.2).

Table 3.2. Summary of the main comparison dimensions between typical IAM (in the 'monolithic' sense) and a typical multi-model assessment approach.

Dimension	Monolithic IAMs (e.g., GCAM, IMAGE)	Multi-model assessment (e.g., GCH)
Integration	Internal consistency enforced by solver	Consistency ensured by sequential/iterative linking —risk of gaps but also flexibility
Sectoral depth	Trade-off: broad but often shallow in non-core sectors	Each component model is specialist — deeper treatment per sector
Water	Absent or simplified in most IAMs	Dedicated basin-level module (Aqueduct)
Economy	PE or simplified macro (except CGE-based IAMs)	Can get sectoral and trade detail (CGE)

Land	Varies (MAgPIE/GLOBIOM deep; most others shallow)	Can get detailed projections (LandReqGCH: validated historical + scenario projections; includes land requirements for renewables)
Energy	Often optimization-based, technology-rich	Can be either simulation or optimization-based, technology-rich
Transparency & openness	Varies widely (some open, some proprietary)	Depends on modelers
Country-level application	Typically requires re-regionalization and recalibration	Designed for country-level analysis (NECP/NDC assessment)
Policy specificity	Generic policy levers (carbon price, cap)	Can incorporate actual country-specific policies (NECPs, NDCs)
Minerals/critical materials	Absent	Can be included (e.g., as total factor productivity CGE inputs, and/or as optimization constraints expressing scarcity).

Overall, multi-model assessments trade the simplicity of one-code IAMs for the flexibility and depth of multiple specialised models. They occupy an intermediate space: richer than the default configuration of any single IAM and better able to provide country- and sector-specific policy insights, but more structured than ad hoc model linking and more demanding to develop and run than off-the-shelf tools. The GCH approach is open-access for transparency, although this is not yet standard practice among multi-model assessments.

3.5 Discussion on model selection

No single model fits all, nor covers the full energy-economy-land-water-minerals nexus. A key implication is that model choice must match the decision context. Global IAMs inherently simplify parts of the nexus due to scale and complexity, hence multi-model architectures (GCH, MESSAGEix-GLOBIOM stack, REMIND–MAgPIE) are increasingly necessary. The choice between monolithic and modular approaches depends on the research question: policy screening (monolithic, faster) vs. deep sectoral analysis (modular, flexible, can be more complex and slower).

A single IAM (e.g., MESSAGEix, GCAM, AIM/CGE) is often easier to run and benefits from large user communities. If a project is primarily about long-term global scenarios or if only coarse regional detail is needed, investing time to master one of these established IAMs can be efficient; they typically solve complex problems quickly and have well-defined best-practice workflows. However, they may force the studied problem into their existing structure. For instance, water use might be hard-coded as a fixed fraction or modeled only by sector, and fine-scale policies may not be representable. On the other hand, a multi-model approach requires learning or even developing multiple tools (e.g., an energy model, a CGE, an 'intermediate link' model) and writing the "glue" code to link them. This takes more up-front investment in model building, programming and understanding each model's inputs/outputs. But the payoff is depth and flexibility, tailoring each component to local data and policy levers. Also, in data-poor or rapidly changing contexts (e.g., developing countries), it might be necessary to calibrate models to local conditions, which is something that most global IAMs are not built for. In such cases, it makes sense to start from a modular base (multi-model approach) and further customize. The trade-off with customization, however, is that it is difficult to be reproducible. Conversely, if one simply needs consistent world-scale scenarios for high-level SDG planning, an existing IAM or an IAM ensemble may be the best option.

When the decision is to use a single IAM rather than a multi-model pipeline, practitioners still face the question of which IAM to select. Figures 3.1 and 3.2 provide direct guidance here. For questions centered on the energy-land-water nexus with endogenous cross-sector feedbacks, GCAM and MESSAGEix-GLOBIOM (with the nexus module) are the only options that currently resolve all three pairwise linkages (Figure 3.2). If the primary concern is economy-wide impacts of climate policy (e.g., GDP, trade, employment, sectoral reallocation), then a CGE-based model (AIM/CGE, EPPA) or an econometric model (E3ME) is more appropriate. Among these, E3ME is distinctive in that it does not assume market equilibrium, making it better suited to questions about unemployment, path dependence, and short-to-medium-term transition dynamics. For technology-rich energy-system analysis under carbon budgets, REMIND, MESSAGEix, and TIAM-UCL offer the greatest detail, though REMIND and MESSAGEix assume perfect foresight while TIAM-UCL provides sub-annual time-slices for power dispatch. For land-use and agricultural questions, MAgPIE and GLOBIOM are the two dominant global tools, with MAgPIE offering tighter biophysical coupling (via LPJmL) and GLOBIOM offering higher spatial resolution on the supply side. Where full openness and low entry barriers are paramount (particularly for capacity-building in data-scarce developing countries) OSeMOSYS/CLEWs is the clear choice, being the only reviewed framework that is fully open-source, solver-free, and explicitly designed for educational use. Finally, for aggregate cost-benefit analysis and social cost of carbon estimation, the DICE/PAGE/FUND family remains the standard tool, despite its well-documented limitations in sectoral and spatial resolution. In all cases, the selection should be guided by the specific research question, the available data and expertise, and critically an honest assessment of which nexus dimensions the chosen model cannot represent, so that these blind spots can be acknowledged or addressed through complementary analysis.

In practice, no matter the approach, certain principles must be kept (and these can also lead to the right model choices): i) clarity about scale and scope, like national detail depth or global consistency; ii) assessing data and expertise, often within the team, as it might narrow down the choices that are actually available (e.g., if there are strong hydrology skills but no macroeconomist, it may make sense to use a detailed water model linked to a simpler economy model, and so on); iii) plan for harmonization at the end, as mismatched regions or time steps can hinder integration. It is critical to ensure that all models in a stack speak the same "language" (e.g., compatible aggregations, sectors, base years, time intervals). Moreover, validation and openness considerations can also play an important role on modelling decisions. Furthermore, as the international community moves toward beyond-GDP frameworks for measuring progress [45, 47], the next generation of IAMs and multi-model assessments will need to report not only GDP and consumption but also natural-capital depletion, distributional outcomes, and inclusive wealth, which are metrics that no reviewed model currently provides endogenously.

3.6 Conclusion

This chapter has presented a structured comparative assessment of 20 globally scoped Integrated Assessment Models and their key couplings, evaluated through a water-energy-food-economy nexus lens against 17 criteria spanning structural characteristics, sectoral coverage, cross-cutting capabilities, and practical accessibility. The review was complemented by a comparison with the multi-model framework of the SDSN GCH, illustrating the trade-offs between monolithic IAM architectures and modular multi-model pipelines.

Five principal findings emerge. First, the IAM landscape remains structurally anchored in energy-climate analysis: 16 of 20 reviewed entries include an endogenous energy system, but only three endogenize water allocation, and no model represents critical minerals. This asymmetry means that IAM-derived pathways, including those informing IPCC assessments and national climate commitments, may systematically underestimate the resource constraints and cross-sector trade-offs involved in deep decarbonization. Second, the energy-water linkage is the weakest pairwise nexus connection across the reviewed models, with only GCAM and MESSAGEix-GLOBIOM (with the recent nexus module) offering endogenous bidirectional feedbacks between water availability and energy-system decisions. Third, multi-model frameworks, such as the GCH, offer a viable alternative when off-the-shelf IAMs do not cover the required nexus dimensions, providing specialist depth per sector and country-level flexibility, though at the cost of coupling complexity and consistency management. Fourth, practical barriers (commercial solver dependencies, data intensity, and limited documentation) remain significant obstacles to the broader adoption of nexus-aware modelling, particularly in developing-country contexts where the need is greatest and data more scarce. Fifth, all reviewed models rely exclusively on GDP as their measure of economic performance, leaving a critical gap as the international community moves toward beyond-GDP frameworks that account for natural-capital depletion, distributional equity, and inclusive wealth.

These findings lead to several recommendations for practitioners and model developers. For practitioners selecting a modelling approach: i) the choice between a single IAM and a multi-model pipeline should be driven by the research question; global scenario screening favours established IAMs, while country-specific nexus assessments increasingly require modular architectures; ii) whichever approach is chosen, the blind spots revealed by Figures 3.1 and 3.2 should be explicitly acknowledged and, where possible, addressed through complementary analysis or sensitivity testing; iii) open-source tools (GCAM, OSeMOSYS/CLEWs) should be preferred where reproducibility and capacity-building are priorities, as they lower the barriers to transparency and independent verification.

For model developers, this review identifies four priority directions for the next generation of integrated assessment tools. First, endogenizing water-energy feedbacks at basin-level resolution should become standard practice, building on the recent advances in GCAM and MESSAGEix-GLOBIOM. Second, critical minerals and materials must be incorporated into IAMs, not merely as resource accounting but as supply constraints that interact with energy technology choice and, through the water intensity of mining, with water stress. Third, standardized coupling interfaces, including harmonized commodity definitions, spatial mappings, and time-alignment protocols, are needed to reduce the friction of multi-model integration, enabling researchers to assemble bespoke nexus pipelines without reinventing the coupling infrastructure each time. Fourth, beyond-GDP metrics should be integrated into model reporting, so that pathways can be evaluated not only for their economic efficiency but also for their implications for natural capital, distributional equity, and long-term human wellbeing. Finally, we note a meta-level finding: the absence of a systematic, publicly available nexus-coverage database for IAMs has meant that practitioners must navigate dozens of separate documentation sources to assess model fitness-for-purpose. The comparison table and nexus heatmap presented in this chapter (Table 3.A.1 in Appendix 3.A, and Figures 3.1 and 3.2) are offered as a step toward filling this gap, and we encourage the IAM community particularly the IAMC, to maintain and update such a resource as models continue to evolve.

4. The GCH integrated modelling framework

This chapter describes the modelling framework used to simulate the Business-as-Usual (BAU) and National Commitments (NC) scenarios. The framework couples four models: a land-use model (LandReqGCH), an energy–emissions model (LEAP), a water model (WaterReqGCH) and a computable general equilibrium model of the global economy (GTAP-E). Section 4.1 presents the overall architecture and explains how the models operate as one interconnected simulation. Sections 4.2 to 4.5 document each model in turn, from the resource and energy systems, which are represented sector by sector, to the general equilibrium model that connects all sectors and production factors. Section 4.6 summarises how consistency, validation and uncertainty are handled across the framework. The translation of national commitments into model inputs is described in Chapter 5.

4.1 Overview of the modelling framework

4.1.1 A modular, country-level architecture

The SDSN Global Climate Hub (GCH) adopts a modular "digital twin" architecture that chains specialised models for land, energy, water and the economy [53, 118], following a systems-thinking approach to resource security [128]. The framework is designed for country-level application from the outset, and each component is validated against historical data where observations exist. Earlier versions have been applied to assess the European Green Deal [129], the climate-neutrality plans of Greece [33, 92], the national commitments of 35 European countries [32, 130], seasonal energy–water–economy pressures in Greece and Cyprus [72], and energy, water and decarbonisation stress in Rwanda [131]. Its four core components are:

- **LandReqGCH (land use):** projects annual land-use change for 229 states to 2050 from six decades of remote-sensing-based land-use data, using a time-varying Markov chain validated through hindcasting [119, 120, 132]. Two auxiliary modules convert renewable energy capacity into land requirements (km² and €) and estimate the biofuel production potential of crop residues (BiofuelGCH) [32].
- **LEAP (energy and emissions):** a bottom-up, demand-driven accounting model of energy demand, energy supply and transformation, and greenhouse gas (GHG) and air-pollutant emissions by sector and fuel [123].
- **WaterReqGCH (water):** combines renewable water supply from WRI Aqueduct 4.0 with sectoral water withdrawals estimated by the GCH from land-use and economic activity drivers, and computes water stress following the Aqueduct methodology [124, 133].
- **GTAP-E (economy):** a multi-region, multi-sector computable general equilibrium (CGE) model with an energy–environment extension, which provides economy-wide consistent trajectories of sectoral output [121, 122].

The general architecture and the main data exchanges are shown in Figure 4.1.

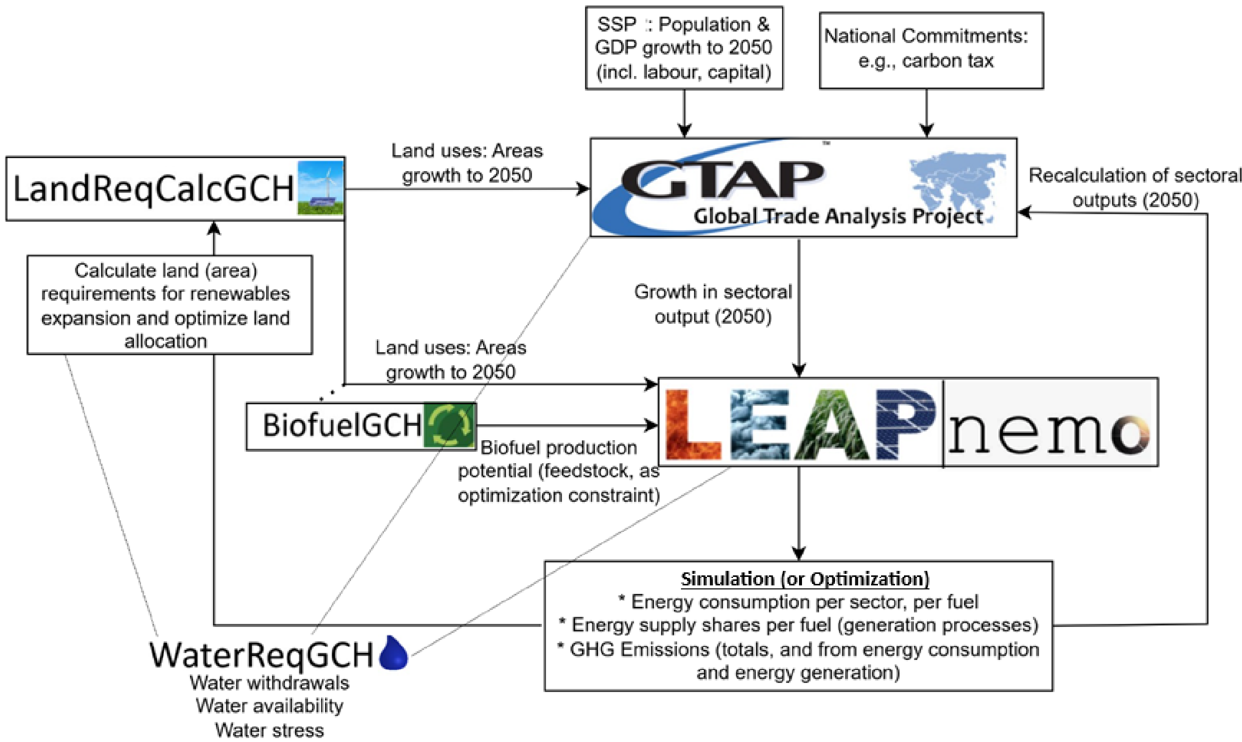


Figure 4.1. General architecture of the GCH multi-model framework and main data exchanges between LandReqGCH, GTAP-E, LEAP and WaterReqGCH. The optimisation components shown (least-cost energy optimisation with NEMO and land-allocation optimisation) are part of ongoing work and are not activated in the simulations of this report (Section 4.1.3).

4.1.2 One interconnected simulation

The four models are not applied as separate, sequential stages. They are run as one soft-linked system that shares a common scenario definition, a harmonised country and sector mapping, and a common horizon to 2050, so that the land, energy, water and economic results describe the same simulated future. The presentation order of this chapter (land, energy, water, economy) follows the flow from the partial, sector-specific representation of resources and energy to the general equilibrium that closes the system, but the exchanges run in both directions (Table 4.1):

- **Economy → energy and water.** GTAP-E translates macroeconomic drivers and scenario-specific policy shocks into sectoral output trajectories. These provide the activity levels of the LEAP demand branches and the activity drivers of industrial, energy-sector and service-related water withdrawals in WaterReqGCH.
- **Land → economy, energy and water.** LandReqGCH provides the areas of each land-use class. These drive irrigation and livestock water withdrawals in WaterReqGCH, inform the growth of land endowments in GTAP-E, cap the bioenergy feedstock available to LEAP through BiofuelGCH, and are used to test whether the land required for new solar and wind capacity is available.
- **Energy → economy.** In the optimisation set-up under development (Section 4.1.3), the energy balance, fuel mix and emissions simulated by LEAP are returned to GTAP-E, so that sectoral outputs are recalculated consistently with the energy system. In the simulations of this report the

exchange runs in one direction only, from GTAP-E to the sectoral models; consistency between the economic and energy representations is ensured instead by the common scenario definition and, in the NC scenario, by the same emissions constraints (Chapter 5).

Exchanges between models use relative growth indices rather than absolute levels. This allows each model to retain its own validated base year (2017 for the GTAP-E database, the 2022 current account in LEAP, 2020 for the land-use record, and the Aqueduct baseline period for water) while following a common trajectory. For a variable X produced by one model with values in its base year y_b and in 2050, the constant annual growth factor g and the activity A passed to a receiving model with base year y_0 are:

$$g_{s,c} = \left(\frac{X_{s,c,2050}}{X_{s,c,y_b}}\right)^{\frac{1}{2050-y_b}}, \qquad A_{s,c,y} = A_{s,c,y_0}\, g_{s,c}^{\,y-y_0} \qquad (4.1)$$

where s denotes the sector and c the country. In the runs of this report the sectoral outputs of GTAP-E are passed to LEAP and WaterReqGCH without a return loop; iterating the exchange until the transferred outputs are stable is part of the optimisation set-up under development (Sections 4.1.3 and 7.3.2).

Table 4.1. Main data exchanges between the models of the GCH framework.

From	To	Variable exchanged	Role in the receiving model
GTAP-E	LEAP	Growth of sectoral output (by aggregated sector)	Activity levels of energy demand branches
GTAP-E	WaterReqGCH	Growth of industrial, energy and service-sector output	Activity drivers of non-agricultural withdrawals
LandReqGCH	WaterReqGCH	Annual area of crops, tree crops and grassland	Drivers of irrigation and livestock withdrawals
LandReqGCH	GTAP-E	Growth of land-use areas to 2050	Land endowment trajectories
LandReqGCH (BiofuelGCH)	LEAP	Biofuel production potential	Upper bound on domestic bioenergy supply
LEAP	GTAP-E	Energy balance, fuel mix and emissions	Recalculation of sectoral outputs (optimisation set-up under development)

4.1.3 Simulation rather than optimisation

The framework is deliberately run in simulation mode. Its purpose is to reproduce the consequences of implementing national commitments as they are stated, and to compare them with a continuation of current trends, rather than to identify least-cost pathways towards a target. An optimisation would replace the commitments with pathways chosen by the model and would therefore no longer test what countries have actually pledged. Optimisation capabilities, including least-cost electricity generation with the NEMO module of LEAP [134, 135] and optimal land allocation, are part of ongoing work. Our future plans include to present optimized pathways, where national plans will be able to be achieved in an holistic and optimal way across all sectors, but in this report, we present the first step of this effort, the simulation of the BAU and NC situations.

The land and water components cover the whole globe, while the energy and economic components cover the 128 countries of the global run, which together account for about 87% of global energy-related CO_2 emissions (Section 5.1); harmonised international datasets are used for calibration throughout. For the European countries, a more detailed layer builds on the manual assessment of the National Energy and Climate Plans of 35 countries (the EU-27, five Western Balkan countries, Norway, Switzerland and the United Kingdom) and on Eurostat data [32, 130].

4.2 Land use: LandReqGCH

4.2.1 Data and land-use classes

LandReqGCH is built on the Historical Land Dynamics Assessment Plus (HILDA+) version 2.0 dataset, which reconstructs annual land use and land cover at 1 km² resolution from 1960 to 2020 by harmonising remote sensing products, national statistics and land-use inventories [119, 120]. The HILDA+ categories were grouped into seven classes: *Crops* (annual and perennial cropland), *TreeCrops* (permanent tree-crop plantations), *Forest* (natural and semi-natural forests), *Grassland* (natural grasslands, pastures and rangelands), *Urban* (built-up areas), *Water* (inland water bodies, rivers and wetlands) and *Other* (barren land, bare soil, ice and unclassified areas). These classes separate cropland, permanent crops, grazing land and natural ecosystems, which differ in economic function, emissions and water demand.

Country boundaries were taken from Natural Earth (version 5.1.1, 1:10 million scale), a public-domain dataset with consistent names and ISO codes [136]. Overlaying HILDA+ with these boundaries produced annual area series (km²) for the seven classes and 234 states over 1960–2020; projections are produced for the 229 states with sufficient coverage (Section 6.1.1).

4.2.2 Transition matrices

Land-use transitions were computed by tracking pixel-level changes between consecutive years. For an interval from t_1 to t_2, the area moving from class i to class j within a country is:

$$T_{ij}(t_1 \to t_2) = \sum_{p \in P} \mathbf{1}\left[L_p(t_1) = i \ \wedge \ L_p(t_2) = j\right] A_p \qquad (4.2)$$

where P is the set of pixels in the country, $L_p(t)$ the land-use class of pixel p at time t, A_p the pixel area (1 km²) and $\mathbf{1}[\cdot]$ the indicator function. The corresponding transition probabilities are:

$$P_{ij} = \frac{T_{ij}}{\sum_{k=1}^{n} T_{ik}}, \qquad \sum_{j=1}^{n} P_{ij} = 1 \qquad (4.3)$$

with $n = 7$ classes. Sixty annual matrices (1960–1961 to 2019–2020) were computed for each country. Matrices for three multi-year windows, a recent (2010–2020), a medium (2000–2020) and a long (1990–2020) window, were obtained by pooling the annual transitions within each window w, which yields average annual transition probabilities:

$$P_{ij}^{(w)} = \frac{\sum_{t \in w} T_{ij}\,(t \to t+1)}{\sum_{t \in w} \sum_{k=1}^{n} T_{ik}\,(t \to t+1)} \qquad (4.4)$$

4.2.3 Time-varying Markov chain projection

Land use is projected with a discrete-time, first-order Markov chain, in which the probability of moving to a future state depends only on the current state [86, 137–140]. With the land-use state of a country at time t written as the row vector $\mathbf{S}(t) = [s_1(t), \dots, s_n(t)]$ of class areas (km²), the annual projection and its multi-year form are:

$$\mathbf{S}(t+1) = \mathbf{S}(t)\,\mathbf{P}, \qquad \mathbf{S}(t+\Delta t) = \mathbf{S}(t)\,\mathbf{P}^{\Delta t} \qquad (4.5)$$

Annual projections from 2021 to 2050 are obtained by applying Equation (4.5) iteratively from the observed 2020 state. Because each row of $\mathbf{P}$ sums to one, the total country area is conserved by construction. The matrix also encodes competition between uses explicitly, for example whether cropland expands at the expense of forest or of grassland, and the approach uses the full annual record rather than two end points.

A single matrix fitted to 1960–2020 would mix periods with very different dynamics: global land-use change accelerated until the mid-2000s and slowed thereafter [119], while national trajectories shifted with deforestation, agricultural intensification, urbanisation and reforestation policies. Conversely, a matrix based only on the last year would over-fit short-term anomalies. The model therefore uses time-varying matrices, selecting for each country the most recent window that reproduces observed dynamics (Table 4.2).

Table 4.2. Hierarchy of transition-matrix windows used in LandReqGCH.

Tier	Window	Use	Typical cases
1	2010–2020 (recent)	Default	Reflects current policies, technologies and markets; benefits from improved satellite observation after 2000
2	2000–2020 (medium)	If Tier 1 fails validation	Countries with volatile recent trends, post-conflict reconstruction, climate-driven anomalies or policy discontinuities in the 2010s
3	1990–2020 (long)	If Tier 2 fails validation	Countries with persistent long-term trends, such as gradual forest transitions, continuous urbanisation or structural agricultural change

4.2.4 Hindcast validation and window selection

Each candidate matrix is subjected to a retrospective consistency test. The matrix of window (t_1, t_2) is applied from an earlier observed state at $t_0 < t_1$ to the validation year t_v (the end of the observed record), and the projected areas are compared with the observed ones for each class i:

$$\mathbf{S}_{\text{proj}}(t_v) = \mathbf{S}_{\text{obs}}(t_0)\mathbf{P}^{\,t_v - t_0}, \qquad e_i = \frac{\left|S_{i,\text{proj}}(t_v) - S_{i,\text{obs}}(t_v)\right|}{S_{i,\text{obs}}(t_v)} \times 100\% \qquad (4.6)$$

A window is accepted when all class errors are below class-specific tolerances, set according to the predictability of each class: 15% for Urban (highly persistent and practically irreversible growth), 20% for Crops, Forest and Water (major economic and natural assets with moderate variability), and 25% for TreeCrops, Grassland and Other (higher natural variability and classification uncertainty). The test starts with Tier 1 and proceeds to Tiers 2 and 3 only if the previous window fails. If no window meets all tolerances, the window with the lowest mean class error is retained and the country is flagged. In this way, states with stable recent dynamics follow the recent window, while states with volatile recent trends or long structural transitions fall back to longer averages; in this report, the long window was selected for about half of the states (Section 6.1.1).

Three physical constraints are enforced on all projections: total country area is conserved; urban area cannot decrease, $S_{\text{Urban}}(2050) \geq S_{\text{Urban}}(2020)$, with any projected contraction reallocated to Other (reflecting brownfield or peri-urban transitions); and inland water bodies may vary by at most ±20% of their 2020 area, which accommodates data uncertainty while preventing unrealistic reservoir construction or drainage. The model produces annual class areas for 2021–2050 for every country.

4.2.5 Robustness to measurement error

HILDA+ country series are derived from remote sensing and classification products and therefore combine true land-use change with year-to-year measurement noise. Because the transition matrices and projections depend directly on these series, we tested whether plausible measurement error could bias the projected 2050 areas enough to change the conclusions. Each country–class series is treated as the sum of a slowly varying signal x_t and noise e_t, the classical additive errors-in-variables formulation [141]:

$$y_t = x_t + e_t, \qquad E[e_t] = 0, \qquad \mathrm{Var}(e_t) = \sigma_e^2 \tag{4.7}$$

The signal was estimated with locally weighted scatterplot smoothing (LOWESS), a robust non-parametric smoother suitable for long series without an assumed functional form [142]. The residuals $\hat{e}_t = y_t - \hat{x}_t$ over the observed years provide an empirical estimate of the noise variance, which was cross-checked with a first-difference estimator. Since $\mathrm{Var}(\Delta y_t) = \mathrm{Var}(\Delta x_t) + 2\sigma_e^2$ for independent noise:

$$\hat{\sigma}_e^2 = \frac{1}{T-1}\sum_t \hat{e}_t^{\,2}, \qquad \hat{\sigma}_{e,\mathrm{fd}}^2 = \frac{1}{2}\max\{0,\ \mathrm{Var}(\Delta y_t) - \mathrm{Var}(\Delta \hat{x}_t)\} \tag{4.8}$$

Bias in the smoothed 2050 estimate $\hat{\theta}$ was then quantified with simulation–extrapolation (SIMEX) [143, 144]. In the simulation step, additional noise is added at levels $\lambda \in \{0.5, 1.0, 1.5, 2.0\}$ over R Monte Carlo replicates, and the estimator is recomputed and averaged:

$$y_t^{(\lambda,r)} = y_t + \sqrt{\lambda}\,\tilde{e}_t^{(r)}, \qquad \tilde{e}_t^{(r)} \sim \mathcal{N}(0, \hat{\sigma}_e^2), \qquad \hat{\theta}(\lambda) = \frac{1}{R}\sum_{r=1}^{R} \hat{\theta}^{(\lambda,r)} \tag{4.9}$$

In the extrapolation step, a quadratic function is fitted to $\{\lambda, \hat{\theta}(\lambda)\}$ and extrapolated to $\lambda = -1$, the zero-error limit:

$$\hat{\theta}(\lambda) \approx a + b\lambda + c\lambda^2, \qquad \hat{\theta}_{\mathrm{SIMEX}} = \hat{\theta}(-1) = a - b + c \tag{4.10}$$

Where country series were sufficiently informative, a Gaussian hidden Markov model (HMM) was also fitted to the vector of class areas to separate latent regimes from observation noise, with parameters estimated by the Baum–Welch algorithm [145, 146]; transition matrices were then recomputed on the de-noised trajectories. Diagonal or regularised covariances and k-means initialisation were used to avoid degenerate fits, and countries failing fit diagnostics were not de-noised. For classes with near-zero 2050 areas (below 1 km^2), absolute rather than percentage corrections were assessed.

The corrections are negligible for the vast majority of series. Of 1,603 country–class series, 27 (1.7%) show a SIMEX correction above 5% and 21 (1.3%) above 10% (Figure 4.2). At the global level, the corrected 2050 totals differ from the smoothed projections by −0.03% for Crops, +0.002% for Forest and +0.014% for Grassland (Figure 4.3), far below common thresholds of policy relevance. The largest absolute corrections occur in large countries, for example for grassland in the United States and tree crops in Brazil, but each represents about 0.01% of the global class total. Flagged series with material national-level corrections were recomputed with HMM de-noised transitions. Measurement error in the HILDA+ input therefore does not materially affect the projections used in this report.

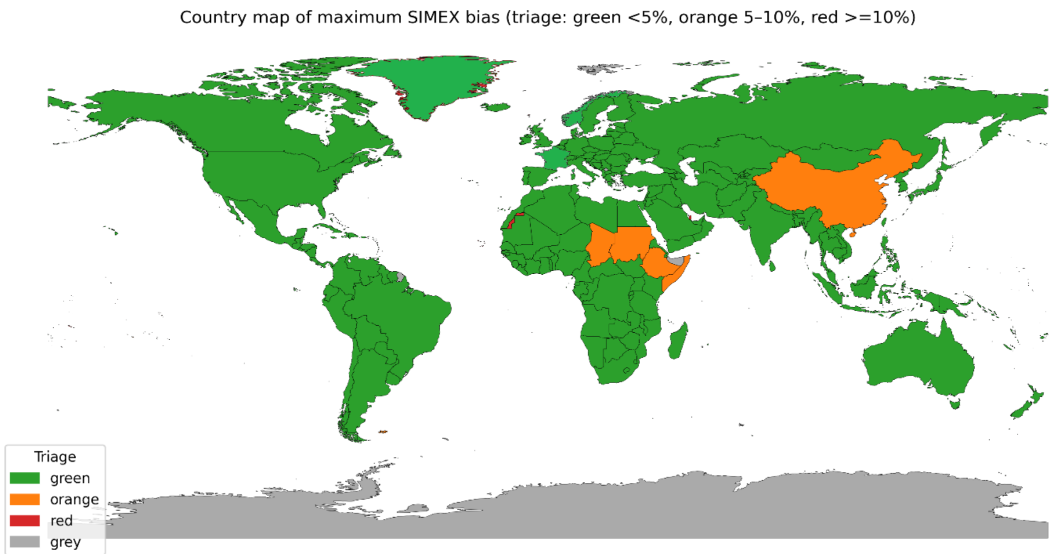


Figure 4.2. Maximum absolute SIMEX correction of the projected 2050 land-use areas across classes, by country (green: <5%; orange: 5–10%; red: ≥10%; grey: no data).

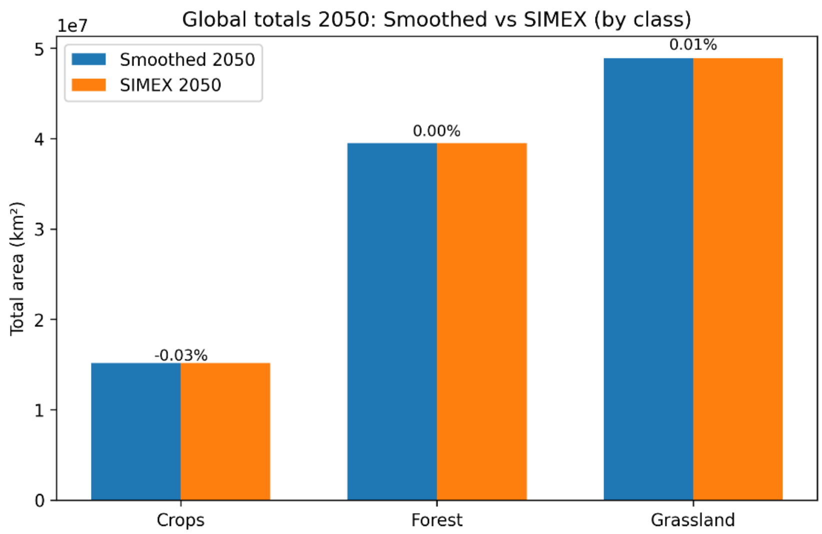


Figure 4.3. Global land-use areas in 2050 for Crops, Forest and Grassland: smoothed projections versus SIMEX-corrected estimates, with the percentage difference annotated.

4.2.6 Scenario implementation: BAU and NC

In the BAU scenario, land use follows the validated time-varying Markov projection described above, so that historical dynamics continue to 2050. LandReqGCH can also represent alternative diet and land-policy pathways, such as dietary shifts, bioenergy expansion, yield intensification, land retirement or afforestation, because dietary choices and land policies strongly affect the land area required for food, feed and forests [147]. In this report, the policy scenario is the NC scenario, in which countries implement their land-related commitments, mainly forest gain targets, while cropland may expand to supply bioenergy feedstock.

Few national commitments specify quantified, country-level land-use trajectories: land-sector contributions are often expressed qualitatively or through heterogeneous accounting approaches [148]. The NC scenario therefore combines two sources. Where a country's NDC or national plan quantifies a land-related target (for example an afforestation area or a land-based carbon sink, as recorded in the assessment described in Chapter 5), that target is applied directly. Otherwise, class-specific multipliers informed by global land-use scenario studies and agricultural outlooks are used [109, 147, 149–151] (Table 4.3). The multipliers express the net effect of policy, yields and bioenergy demand on each class relative to the BAU area in 2050.

Table 4.3. Land-use multipliers of the NC scenario relative to BAU areas in 2050 (central value and range).

Land-use class	NC multiplier
Crops	1.03 (±0.05)
TreeCrops	1.05 (±0.05)
Forest	1.07 (±0.05)
Grassland	0.98 (±0.03)
Urban	1.00
Water	1.00
Other	0.95 (±0.04)

For each class k of a country, the provisional NC target area in 2050 is the product of the multiplier m_k and the BAU area. The adjustment is phased in linearly over the implementation period 2026–2050, preserving the BAU dynamics up to 2025, and the residual needed to conserve the total country area A_{tot} is allocated to Other:

$$A_{k,2050}^{\text{NC}} = m_k\, A_{k,2050}^{\text{BAU}}, \qquad A_{k,t}^{\text{NC}} = A_{k,t}^{\text{BAU}} \left[1 + (m_k - 1)\,\frac{t - 2025}{2050 - 2025}\right] \tag{4.11}$$

$$A_{\text{Other},t}^{\text{NC}} = A_{\text{tot}} - \sum_{k \neq \text{Other}} A_{k,t}^{\text{NC}}, \qquad t = 2026, \dots, 2050 \tag{4.12}$$

Country-specific values are selected within the ranges of Table 4.3 according to national context, and the ranges also bound the sensitivity analysis. To ensure physical plausibility, the following caps are applied before rebalancing:

- in high-forest countries (forest above 50% of land area), $m_{\text{Forest}} \geq 0.99$, since large proportional forest losses are unlikely without major drivers;
- in very low-forest countries (forest below 5%), $m_{\text{Forest}} \leq 1.02$, unless the national commitment explicitly targets larger afforestation;
- in arid and water-limited countries (by aridity index), $m_{\text{Crops}} \leq 1.02$, reflecting water and soil constraints on cropland expansion;
- in countries where agricultural land exceeds half of the land area, wider adjustments of Crops and Grassland are allowed within predefined ranges;

- in small island states, absolute caps on area changes are applied, reflecting limited land availability.

This design preserves the empirically estimated dynamics up to 2025 and provides a transparent counterfactual for the implementation period. It is computationally efficient for many countries, but it does not represent spatially explicit transition paths or sub-national heterogeneity, and it is therefore suited to national, cross-country comparative analysis. Compared with approaches that treat land use as an equilibrium outcome of economic models or as an exogenous scenario target [152–154], LandReqGCH combines empirically derived remote-sensing transition matrices, validated baseline projections and country-level scenario targets, and links the resulting land-use trajectories directly to water withdrawals (Section 4.4).

4.2.7 Uncertainty and limitations

Uncertainty in the transition dynamics was propagated through a Monte Carlo analysis with 100 realisations, in which the transition probabilities were perturbed with Gaussian noise (5% standard deviation) and each row was renormalised to sum to one. Some drivers of land-use change remain outside the BAU projection. Armed conflicts, abrupt policy interventions and economic crises can create regime shifts not captured by pre-shock transition matrices; the hindcast test partly mitigates this by moving flagged countries to longer windows. Population growth, agricultural productivity, commodity prices, climate change and technological change are assumed to continue their historical trends in BAU, and their explicit representation through the coupling with GTAP-E is being extended in ongoing work.

4.3 Energy and emissions: LEAP

LEAP (Low Emissions Analysis Platform) is at the core of the energy–emissions component. Developed by the Stockholm Environment Institute over four decades, it is a scenario-based tool for long-term integrated energy, climate mitigation and air-pollution planning [123]. LEAP has been applied from municipal to national scales, including by countries preparing their NDCs [155], and it accommodates both bottom-up end-use accounting and top-down approaches, which makes it suitable for simulating specific policies and exploring decarbonisation pathways [156, 157]. In the GCH framework, LEAP simulates energy demand by sector, fuel supply and transformation, and the associated emissions, and it has been used to evaluate national energy and climate plans together with their water implications [33, 158].

4.3.1 Energy demand, supply and emissions

National commitments differ widely in the detail with which they describe planned interventions. To accommodate this heterogeneity, two modelling approaches were developed within LEAP (Table 4.4) to address in sufficient detail all countries, considering their data availability. The first follows LEAP's final energy intensity method, in which the energy demand D of a sector or end use is the product of an activity level AL and an energy intensity EI (energy use per unit of activity):

$$D_{s,y} = AL_{s,y} \cdot EI_{s,y} \qquad (4.13)$$

This approach represents multiple end uses within each core sector (residential, industry, agriculture, transport and services) and is used where sufficient data exist to examine sector-specific policies. The second approach, used under data scarcity, follows LEAP's total energy demand method, in which the main input is the total final energy consumption of each sector; it covers the same sectors with fewer end uses and fuel categories. In both approaches, sectoral activity levels grow according to the GTAP-E output trajectories (Equation 4.1).

The supply side represents primary and secondary energy resources and the transformation processes (electricity, heat and hydrogen generation, synthetic fuel production, oil refining, and transmission and distribution with the associated losses). Supply is balanced against the sectoral demand inputs and accounts for imports, exports and system losses.

Emissions are estimated from fuel use by sector and process with IPCC emission factors, and GHGs are aggregated to CO_2-equivalents with the 100-year global warming potentials of the IPCC Fifth Assessment Report [159]:

$$E_{g,y} = \sum_{s} \sum_{f} D_{s,f,y} \cdot EF_{s,f,g}, \qquad E_{y}^{\mathrm{CO_2e}} = \sum_{g} E_{g,y} \cdot GWP_{g} \tag{4.14}$$

where f denotes the fuel, g the gas or pollutant, EF the emission factor and GWP the global warming potential (t CO_2e per t of gas).

Table 4.4. Characteristics of the two LEAP modelling approaches followed for the global analysis.

Component	Approach 1 (data-rich)	Approach 2 (data-scarce)
Residential	Final energy intensity; activity: urban and rural population; uses: space heating, space cooling, water heating, cooking, lighting, appliances	Total energy demand; residential sector as a whole
Agriculture	Final energy intensity; activity: value added	Total energy demand
Industry	Final energy intensity; activity: value added; sub-sectors: food and tobacco, textiles and leather, wood products, paper, pulp and printing, chemicals, rubber and plastics, non-metallic minerals (excluding cement), basic metals (excluding steel), machinery, transport equipment, other manufacturing, mining, construction, cement, steel	Total energy demand; industry as a whole
Transport	Final energy intensity; activity: passenger-km and tonne-km; sub-sectors: cars and light trucks, freight trucks, motorcycles, buses, passenger and freight rail, domestic aviation, maritime	Total energy demand; sub-sectors: road and rail, aviation, maritime
Services	Total energy demand; services as a whole	Total energy demand; services as a whole
Primary resources	Solar, hydro, wind, geothermal, solid waste, biomass, crude oil, lignite, other coal, natural gas	Renewables (solar, hydro, wind, geothermal), biomass (including solid waste), crude oil, coal, natural gas
Secondary resources	Electricity, hydrogen, synthetic fuels, heat, biogas, refinery feedstocks, diesel, petroleum coke, fuel oil, kerosene, CNG, LPG, gasoline, other petroleum products	Electricity, hydrogen, synthetic fuels, heat, biogas, refinery feedstocks, petroleum products
Transformation	Transmission and distribution, synthetic fuels, hydrogen, electricity and heat generation, oil refining, with losses	As in Approach 1

Component	Approach 1 (data-rich)	Approach 2 (data-scarce)
Emissions	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, PM2.5, black carbon, organic carbon	As in Approach 1

4.3.2 Validation and robustness

For each country, the current account (2022) of energy consumption and fuel supply was validated against the IEA World Energy Balances [160], and, for the 35 European countries of the detailed layer, against Eurostat energy balances [161]. To ensure that conclusions do not depend on the choice of approach, both approaches were implemented for countries with sufficient data. The results remained qualitatively the same, in line with an earlier comparison of the two approaches [162] and with the Greek application [33]. The simpler approach is therefore not a weakness but a robust option under data scarcity. The specific commitments simulated in the NC scenario (for example renewable shares, efficiency improvements and fuel switching) are described in Chapter 5.

4.4 Water: WaterReqGCH

WaterReqGCH quantifies renewable water supply, sectoral water withdrawals and water stress for every country and sub-basin. It builds on hydro-economic and systems approaches developed for water-scarce and data-limited settings [128, 163–165], and it links water to the land, energy and economic trajectories of the other models, so that the water implications of national commitments can be assessed jointly with their emissions [166]. The resulting indicators are relevant to water policy and regulation, where withdrawal estimates inform allocation and governance decisions [167, 168]. Supply is taken from Aqueduct 4.0, withdrawals are estimated by the GCH, and stress is computed following the Aqueduct methodology.

4.4.1 Renewable water supply

Water supply is taken from WRI Aqueduct 4.0 [124], which is based on the global hydrological model PCR-GLOBWB 2 at a resolution of about 10 km (5 arc-minutes) [169]. Outputs are aggregated to about 16,400 HydroBASINS level-6 sub-basins [170]. For each sub-basin b, available blue water BA is the total renewable freshwater (surface runoff, interflow and groundwater recharge) generated in or flowing into the sub-basin, TB, minus the consumptive use upstream, UCU:

$$BA_{b,y} = TB_{b,y} - UCU_{b,y} \qquad (4.15)$$

The baseline (1979–2019) uses observed climate forcing. Future values for 2030 (window 2015–2045) and 2050 (window 2035–2065) are the median of simulations forced by five bias-corrected CMIP6 general circulation models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL), with long-term trends extracted with a 10-year moving average and Theil–Sen regression. Aqueduct provides projections under SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5. Both the BAU and the NC scenarios use the SSP3-RCP7.0 supply projections, so that differences in water stress between the scenarios arise from withdrawals; the SSP1-RCP2.6 and SSP5-RCP8.5 projections bound the sensitivity of the results to climate-driven supply.

4.4.2 Water withdrawals

Withdrawals (gross abstraction, as opposed to consumption) are estimated for four use categories: irrigation, livestock, industry (including the energy sector) and municipal use. Following an accounting structure analogous to energy demand in LEAP, the withdrawal of use u in country c and year y is the product of an activity driver D and a calibrated intensity I:

$$W_{u,c,y} = D_{u,c,y} \cdot I_{u,c}, \qquad I_{u,c} = \frac{W^{\text{obs}}_{u,c,y_0}}{D_{u,c,y_0}} \tag{4.16}$$

where W^{obs}_{u,c,y_0} is the observed withdrawal in the base year y_0. The drivers differ by use, and it is through them that the water model is connected to the other models (Table 4.5).

Land-based uses. Irrigation and livestock withdrawals are driven by the land-use areas projected by LandReqGCH. Per-area water-use intensities $\omega^0_{k,c}$ for crops, tree crops and grassland are derived from Aqueduct 4.0 sectoral demand, FAO AQUASTAT and crop water-footprint data [124, 171, 172], and are scaled by a country calibration factor κ_c so that base-year withdrawals match the reported national totals:

$$W^{\text{irr}}_{c,y} = \kappa_c \sum_{k\in\{\text{Crops},\text{TreeCrops}\}} \omega^0_{k,c}\, L_{k,c,y}, \qquad W^{\text{liv}}_{c,y} = \kappa_c\, \omega^0_{\text{Grassland},c}\, L_{\text{Grassland},c,y} \tag{4.17}$$

$$\kappa_c = \frac{W^{\text{obs}}_{\text{agr},c,y_0}}{\sum_k \omega^0_{k,c}\, L_{k,c,y_0}} \tag{4.18}$$

where $L_{k,c,y}$ is the area of class k and $W^{\text{obs}}_{\text{agr},c,y_0}$ the observed agricultural (irrigation and livestock) withdrawal in the base year.

Activity-based uses. Industrial and energy-sector withdrawals are driven by the output of the corresponding GTAP-E sectors, whose trajectories are consistent with the energy balance simulated in LEAP, and municipal withdrawals by population under SSP2 [43]. Base-year intensities are calibrated with Equation (4.16), and drivers evolve according to Equation (4.1). Total withdrawals are the sum over uses:

$$W_{c,y} = W^{\text{irr}}_{c,y} + W^{\text{liv}}_{c,y} + W^{\text{ind}}_{c,y} + W^{\text{mun}}_{c,y} \tag{4.19}$$

Table 4.5. Water-use categories, drivers and calibration data in WaterReqGCH.

Use	Activity driver	Source model	Base-year calibration and cross-checks
Irrigation	Area of Crops and TreeCrops (km²)	LandReqGCH	AQUASTAT, Eurostat water accounts, Aqueduct irrigation demand, crop water footprints
Livestock	Area of Grassland (km²)	LandReqGCH	AQUASTAT, Eurostat water accounts, Aqueduct livestock demand
Industry and energy	Output of industrial and energy sectors	GTAP-E (consistent with LEAP)	AQUASTAT, Eurostat water accounts, Aqueduct industrial demand
Municipal	Population (SSP2)	Exogenous driver shared with GTAP-E	AQUASTAT, Eurostat water accounts, Aqueduct domestic demand

Base-year totals and sectoral shares are taken from national water accounts compiled in FAO AQUASTAT [171] and, for the European countries, from Eurostat water statistics [173], expressed in million cubic metres (Mm³) [133]. The estimates are cross-checked against Aqueduct 4.0 gross demand aggregated to national level and against the reported national statistics; where sources diverge, for example because of different conventions for cooling-water returns, the differences are inspected and documented.

Connection with land use. Because irrigation and livestock withdrawals scale with the areas of crops, tree crops and grassland, every land-use change simulated in LandReqGCH propagates to water. In the NC scenario, the expansion of cropland for bioenergy increases irrigation withdrawals, whereas the conversion of grassland or other land to forest reduces livestock-related withdrawals, even when the total land area remains unchanged. The resulting change in withdrawals can therefore be decomposed by land-use class, which shows directly which land-related commitments drive water demand.

Temporal resolution. Withdrawals and stress are computed annually by default, consistent with Aqueduct. For countries and sectors of particular interest, annual withdrawals can be disaggregated into monthly profiles with sector-specific seasonal shares and compared with monthly supply, as demonstrated for tourism-driven seasonal peaks in Greece and Cyprus [72].

4.4.3 Water stress

Water stress follows the Aqueduct definition of baseline water stress, the ratio of total withdrawals to available renewable blue water [124, 174]. To preserve the basin-level character of the indicator, national withdrawals by use are distributed to the sub-basins of each country in proportion to the Aqueduct gross demand for that use, $WW_{u,b}^{\mathrm{Aq}}$. The stress of each sub-basin is then computed, and the national value is aggregated as a demand-weighted mean, so that sub-basins with more demand have more influence on the national score, as in Aqueduct:

$$W_{b,y} = \sum_{u} W_{u,c,y} \frac{WW_{u,b}^{\mathrm{Aq}}}{\sum_{b' \in c} WW_{u,b'}^{\mathrm{Aq}}}, \qquad WS_{b,y} = \frac{W_{b,y}}{BA_{b,y}} \tag{4.20}$$

$$WS_{c,y} = \frac{\sum_{b \in c} W_{b,y}\ WS_{b,y}}{\sum_{b \in c} W_{b,y}} \tag{4.21}$$

Stress values are classified with the Aqueduct categories (Table 4.6). Sub-basins where both water supply and withdrawals are very low are flagged as “arid and low water use” rather than assigned a stress category, because a ratio is not meaningful there. The ratio can also be expressed as a 0–5 score, $\min\{5, \max\{0,\ \log_2(WS/0.1) + 1\}\}$, which reproduces the category thresholds.

Table 4.6. Water stress categories following Aqueduct.

Category	Withdrawals as share of available blue water	Score
Low	<10%	0–1
Low–medium	10–20%	1–2
Medium–high	20–40%	2–3
High	40–80%	3–4
Extremely high	>80%	4–5
Arid and low water use	Very low supply and very low withdrawals	–

The indicator measures competition for renewable water at annual scale. It does not account explicitly for environmental flow requirements, water quality or intra-annual variability, which is why monthly analysis is applied where seasonal peaks matter.

4.5 Economy: GTAP-E

GTAP-E, the energy–environment extension of the Global Trade Analysis Project (GTAP) model, provides the economy-wide closure of the framework. GTAP is a multi-region, multi-sector CGE model widely used for trade and policy analysis. It assumes competitive markets and constant returns to scale, and it differentiates domestic from imported goods through the Armington assumption [121]. GTAP-E adds an explicit representation of energy commodities, with substitution between capital and energy and among fuels, and it links fossil-fuel combustion to CO_2 emissions, so that energy–economy interactions and carbon policies are resolved within the general equilibrium [122].

The model is calibrated to the GTAP Data Base version 11, with 2017 as the base year [175]. Population, GDP, labour and capital follow the SSP2 ("middle-of-the-road") pathway [43]; these trajectories are imposed as the long-run drivers of factor endowments and economic scale, and the model is solved for a 2050 equilibrium for all regions of the aggregation. The growth of land endowments is informed by the LandReqGCH trajectories, and, in the optimisation set-up under development, sectoral outputs are recalculated with the energy balance simulated in LEAP (Table 4.1). The representation of national commitments in the NC scenario is described in Chapter 5.

GTAP sectors are aggregated to a classification that matches the sectoral structure of the energy and water models (Table 4.7). The key variable transferred from GTAP-E is the growth of sectoral output, which is interpreted as the growth of the activity levels that drive final energy demand in the corresponding LEAP branches and non-agricultural water withdrawals in WaterReqGCH (Equation 4.1). Through this mapping, the energy and water trajectories reflect economy-wide structural change and international equilibrium effects, such as changes in trade and in the relative competitiveness of sectors.

Table 4.7. Sectoral aggregation used in the GTAP-E Model and corresponding GTAP sub-sectors.

Main sector	Subsectors
1. Fossil energy industries	Coal; Oil; Gas; Petroleum & coal products; Gas manufacture & distribution
2. Energy intensive industries	Paper products & publishing; Chemical products; Mineral products; Ferrous metals; Metals
3. Other industries	Other Extraction; Bovine meat products; Meat products; Vegetable oils and fats; Dairy products; Processed rice; Sugar; Food products; Beverages and tobacco products; Textiles; Wearing apparel; Leather products; Wood products; Basic pharmaceutical products; Rubber and plastic products; Metal products; Computer, electronic and optical products; Electrical equipment; Machinery and equipment; Motor vehicles and parts; Transport equipment; Manufactures
4. Electricity	Electricity generation, transmission and distribution, covering thermal, nuclear, hydro and renewable generation technologies
5. Terrestrial transport	Passenger and freight transport by rail and road (including buses, coaches, metro/tram systems, taxis and trucking), and transport via pipelines
6. Water transport	Passenger and freight transport by sea, coastal and inland waterways, including ferries, cruises, water taxis, barges and towing
7. Air transport	Scheduled and non-scheduled passenger and freight air transport, including charter services.
8. Services	Water; Construction; Trade; Accommodation, Food and service activities; Warehousing and support activities; Communication; Financial services; Insurance; Real estate activities; Business services; Recreational and other services; Public Administration and defense; Education, Human health and social work activities; Dwellings

9. Agriculture	Paddy rice; Wheat; Cereal grains; Vegetables, fruit, nuts; Oil seeds; Sugar cane & sugar beet; Plant-based fibers; Crops; Bovine cattle, sheep and goats, horses; Animal products; Raw milk; Wool, silk-worm cocoons; Forestry; Fishing

Below we outline the necessary definitions of the model that will govern our analysis and that our results focus on:

Sectoral output (QO): QO is defined in the standard GTAP model as the quantity of non-saving commodity output supplied in each region. In the present application, it represents a real quantity/index measure of sectoral production rather than the monetary value of production. Changes in QO capture the expansion or contraction of sectoral output following general-equilibrium adjustments in input use, relative prices, domestic demand and international trade.

Measurement in the figures: The maps show the difference between the NC and BAU scenarios in cumulative sectoral output growth from the common 2017 baseline to 2050. The indicator is expressed in percentage points. Negative values indicate weaker sectoral output growth under NC relative to BAU, while positive values indicate stronger growth. A negative value therefore does not necessarily imply that sectoral output falls below its 2017 level, but it indicates a weaker trajectory relative to BAU.

Sectoral employment (QFE): represents the quantity of a primary endowment (in this application, labour) demanded by firms in a particular sector and region. So QFE measures the quantity of labour input demanded by each sector. For this reason, *QFE* can be interpreted as an indicator of sectoral employment or sectoral labour demand, but it should not be interpreted as a direct count of jobs. It is a quantity/index measure of labour use within the GTAP production system.

An important qualification concerns the labour-market closure. Under the full-employment closure used in the simulations, aggregate labour supply is fixed and wages adjust to clear the labour market. Consequently, changes in labour demand across sectors primarily reflect the reallocation of labour between economic activities, rather than changes in economy-wide employment or unemployment. The QFE results should therefore be interpreted as changes in sectoral labour demand and labour allocation, rather than as net job creation or destruction at the national level. Alternative GTAP closures can allow employment to vary, but that is not the closure used here.

Measurement in the figures: The maps show the difference between the NC and BAU scenarios in cumulative sectoral labour-demand growth from the common 2017 baseline to 2050. The indicator is expressed in percentage points. Positive values indicate relatively higher labour demand in a sector under NC, while negative values indicate relatively lower labour demand. Under the full-employment closure, these differences should primarily be interpreted as labour reallocation across sectors.

Welfare effect – Equivalent Variation (EV): Welfare impacts are measured using Equivalent Variation (EV), the standard monetary welfare measure reported by GTAP. EV is reported in US$ million, with a positive value indicating an improvement in welfare and a negative value indicating a deterioration. Conceptually, EV translates a change in the utility of the representative regional household into a monetary equivalent. It represents the amount of income, evaluated at benchmark prices, that would have to be given to or taken from the household in the reference situation for it to attain the same level of welfare as under the counterfactual scenario. EV is therefore a money-metric measure of utility change, rather than a measure of GDP, output or household income itself. In GTAP, regional welfare reflects utility associated with private consumption, government consumption and savings. Consequently, changes in EV incorporate the general-equilibrium welfare consequences of changes in consumption possibilities, relative prices, the terms of trade and allocative efficiency, among other channels.

Measurement in the figure: Because the NC and BAU scenarios are evaluated relative to the same benchmark, the welfare map reports the difference in EV between NC and BAU. This difference is normalised by each country's projected BAU GDP in 2050 to facilitate comparison across economies of different sizes and is expressed as a percentage of BAU 2050 GDP. Positive values indicate higher welfare under NC relative to BAU, while negative values indicate lower welfare.

4.6 Consistency, validation and limitations

Consistency across the framework rests on four elements: a common scenario definition for all models, a harmonised mapping of countries and sectors, the exchange of relative growth indices that preserves each model's validated base year, and, in the NC scenario, the same emissions constraints in the economic and energy models. The socio-economic inputs of all models follow SSP2; where a component provides ensembles under other pathways, as the water supply projections do (Section 4.4.1), these are used as uncertainty bounds rather than as scenario inputs. Each component is validated in the way appropriate to its data: the land-use projections through hindcasting against the HILDA+ record and tests of robustness to measurement error (Section 4.2); the energy model against IEA and Eurostat energy balances for the current account (Section 4.3); the water withdrawals through base-year calibration to national water accounts and cross-checks with Aqueduct (Section 4.4); and the economic model through the consistency of the GTAP Data Base (Section 4.5).

The framework also has limitations that frame the interpretation of the results. It is a simulation of stated commitments rather than an optimisation, so it indicates the consequences of plans as written rather than the best way to meet their targets (which is the subject of our future work, as mentioned above). The models are soft-linked rather than solved simultaneously, and in this report the exchange runs from the economic model to the sectoral models without a return loop, so that water and land availability do not yet constrain the energy and economic results; two-way feedbacks belong to the optimisation set-up described in Section 7.3.2. The land and water analyses operate at national and sub-basin scales without spatially explicit land allocation within countries. Climate impacts enter through water supply, but they are not yet fed back to crop yields, hydropower or cooling within the same run. Finally, GTAP-E represents households through a representative agent per region, so distributional effects within countries are not captured (Chapter 2). Ongoing work extends the framework with optimisation modules, endogenous land–economy interactions and a beyond-GDP CGE model with ecosystem services valuation.

Countries not included in the current quantitative assessment were excluded where sufficient and consistent data could not be established for the required modelling inputs. Addressing these data gaps is part of ongoing work, and future versions of the assessment will seek to expand country coverage as additional reliable national and international data become available. Accordingly, in comparative visualisations where white is used to denote missing coverage, it should be interpreted as insufficient data rather than as a zero value or the absence of a policy commitment.

4.7 Online platform: a decision support explorer

The complete modelling suite is freely and publicly available online through the GCH Decision Support Navigator (https://gch-navigator-production.up.railway.app/#/hub). Open access is a deliberate choice that follows the principles of open science: when model structures, assumptions, data sources and results can be inspected by anyone, the analysis becomes transparent and reproducible, others can test, reuse and extend it, and the "black box" that often limits trust in model-based policy advice is opened [96]. The platform is maintained as a living tool rather than a static archive. Models, datasets and national inputs are updated as new commitments, statistics and methods become available, and feedback from users and stakeholders is incorporated into subsequent versions, consistent with the co-design approach of the Global Climate Hub [118]:

Box 1: The GCH online platform

Each bubble opens to a separate page, model-specific, allowing the user to explore global, country- and scenario-specific results.

The platform has two main sections. The Approach section introduces the vision of the GCH and its operational framework: continuous monitoring and assessment, co-designed transformation pathways, and aligned financing and governance. The Models section presents the modelling suite as an interactive map of coupled systems arranged around a core of stakeholder engagement through Living Labs. Selecting a system opens the corresponding model:

- **Land, agriculture and food (LandReqGCH):** land-use change and the land requirements of renewable energy expansion and agri-food systems;
- **Water systems (WaterReqGCH):** renewable water supply, sectoral withdrawals and water stress at global, national and sub-basin scale; the allocation of water between competing uses is under development (Section 7.3.3);
- **Energy and emissions (EnergyReqGCH, linked to LEAP):** fuel-by-fuel energy consumption by sector and the resulting greenhouse gas trajectories;
- **Economy (EconomyGCH, linked to GTAP): sectoral output, trade and welfare; the extension to beyond-GDP accounting, including the valuation of ecosystem services, is under development (Section 7.3.1);**
- **Scenarios and goals, and financing, governance and implementation:** modules under development that will host the library of climate scenarios and national plans, and the analysis of investment portfolios and blended finance.

Each model page summarises the scope of the model, such as its coverage, resolution and time horizon, and embeds the interactive application, which can be expanded or opened in a separate window. Within each application, an introductory page documents the data sources and methods, and a side menu leads to the results, for example global maps and country-level views. Links on every page allow users to move directly from one system to another, so that the connections between land, water, energy and the economy can be followed across models. Policy-makers, researchers and stakeholders can thus explore the results and trade-offs presented in this report without installing software or running the models themselves.

5. Scenarios: from national commitments to model-ready inputs

Chapter 4 described how the GCH models run together as one simulation. This chapter describes what they were fed. Two scenarios are simulated: a Business-as-Usual (BAU) scenario, which describes how the energy, land, water and economic systems would evolve without new commitments, and a National Commitments (NC) scenario, which describes the same systems if countries implement what they have pledged in their Nationally Determined Contributions (NDCs), long-term strategies and national energy and climate plans. The term NC is used rather than NDC because the scenario draws on all of these instruments, not only on the NDC document itself.

Neither scenario could be taken off the shelf. The BAU scenario required observed energy statistics for more than 150 countries in a consistent, machine-readable form. The NC scenario required every commitment, written in different units, with different base years, gases, sectors and horizons, to be read, coded and converted into the quantities that an energy system model, an economy-wide model, a land-use model and a water model can use. The chapter documents this translation and the rules that make it reproducible. Section 5.1 sets out the problem and the design principles; Section 5.2 defines the BAU scenario and the automated extraction of the observed data behind it; Section 5.3 derives the NC constraints; Section 5.4 converts them into inputs for each model; Section 5.5 summarises the resulting scenario inputs; Section 5.6 presents Hefaistos, a parallel development for extracting NDC information automatically; and Section 5.7 draws the lessons and leads into the results.

5.1 From pledges to model inputs

5.1.1 Why national commitments cannot be simulated as written

The Paris Agreement leaves the content and format of each contribution to the Party that submits it [3]. The resulting pledges are heterogeneous in almost every dimension that matters for quantification [176, 177]. Targets are expressed as reductions against a historical base year, as deviations from a self-declared business-as-usual projection, as reductions in emissions intensity, as absolute caps or peaking years, or only as lists of actions. Many combine an unconditional and a conditional component. Coverage differs in gases and sectors, and the treatment of land use, land-use change and forestry (LULUCF) is often ambiguous, although it can dominate the national inventory [178, 179]. Most NDCs end in 2030 or 2035, while long-term commitments, including carbon neutrality, are set out in separate strategies or laws.

Models, in contrast, need quantities. An energy system model such as LEAP needs final energy demand by sector and carrier, a supply mix and emission factors; a computable general equilibrium model such as GTAP-E needs macroeconomic drivers and emission constraints; a land-use model needs land-class areas; and a water model needs the activities that drive withdrawals (Chapter 4). Few NDCs state these quantities, and none states them in a form that can be entered directly.

Existing quantifications of the pledges answer a different question. Assessments of the emissions gap [38], the Climate Action Tracker [39], model-based studies of the aggregate effect of pledges on warming [180, 181] and the UNFCCC synthesis reports [177] translate targets into economy-wide greenhouse gas (GHG) levels, usually for large emitters or aggregated regions. They show that the interpretation of targets and the choice of baseline are the largest sources of uncertainty in such estimates [182], and that transparent, reproducible rules are needed to track how pledges change over successive rounds [183]. None provides, for well over a hundred countries, sector-by-fuel energy inputs, emission constraints and land-use trajectories that are consistent with one common baseline. A dataset of this kind did not exist, so it had to be built.

5.1.2 Design principles

The translation follows five principles, which also define what the NC scenario is and is not.

1. **Simulate commitments as stated.** The NC scenario reproduces the consequences of implementing what countries have pledged or legislated. It does not search for the least-cost way to reach a target; this is the purpose of the optimisation work described in Section 4.1.3.
2. **One decision procedure for all countries.** The same requirements, the same order of evidence and the same rules are applied to every country. Countries differ only in what they have pledged and legislated and in the evidence available, which determine which rule binds.
3. **An explicit hierarchy of evidence.** A country's own documentation is preferred to a reconstruction wherever the documentation is less ambiguous, and a reconstruction is preferred to imputation by the regional median (Section 5.3.4).
4. **No credit for abatement outside the energy system.** Mitigation pledged in forests or agriculture is not attributed to energy-related CO_2, and a target that requires no policy does not raise emissions above BAU.
5. **Traceability.** Every value is stored together with its source, the rule applied and any diagnostic flag, so that each number can be traced back to a document and re-examined.

The resulting workflow is summarised in Figure 5.1. It joins the observed data of the BAU scenario (Section 5.2) with the coded commitments of the NC scenario (Section 5.3) and ends in the inputs of the four models (Section 5.4).

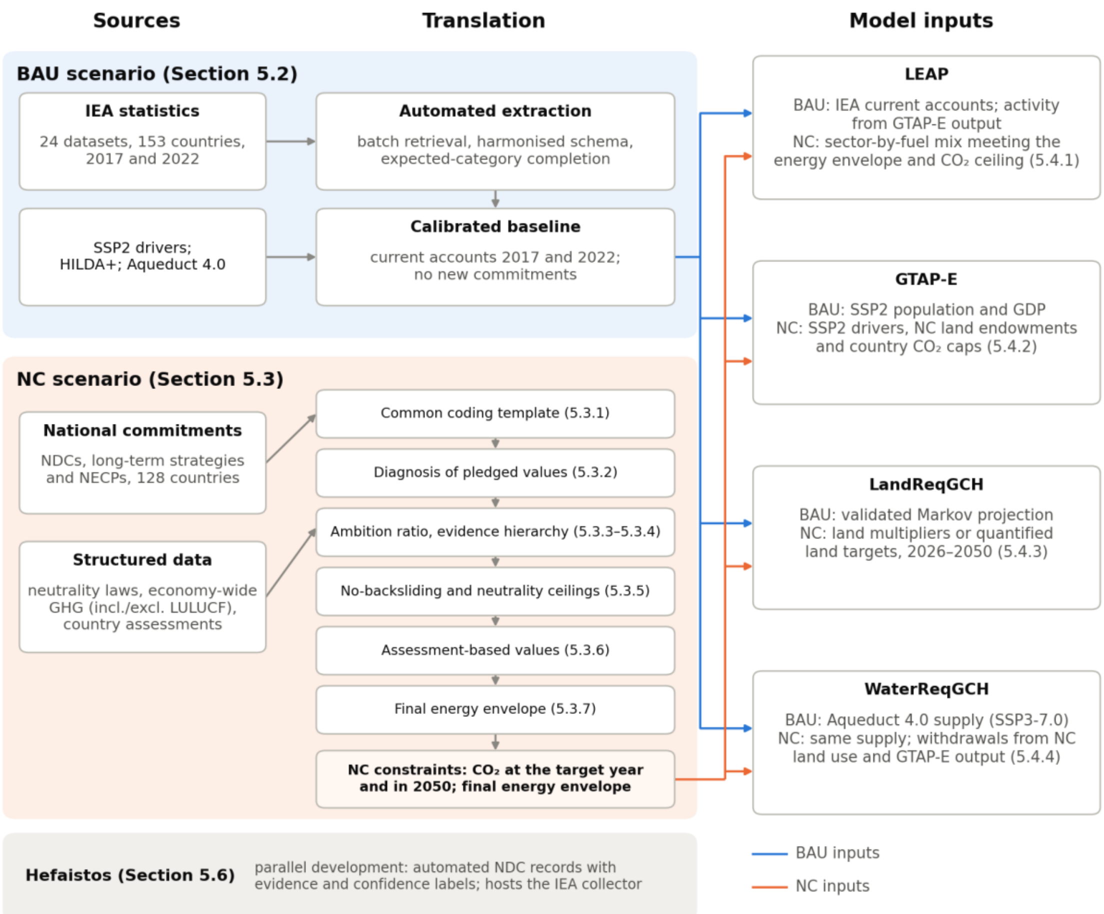


Figure 5.1. Workflow from source documents and observed data to the inputs of the GCH models under the BAU and NC scenarios. Hefaistos (Section 5.6) is shown as a parallel development that automates parts of the evidence base.

The global run covers 128 countries and territories, which together accounted for about 87% of global energy-related CO_2 emissions in 2017. The largest emitters not included are the Russian Federation (1,661 $MtCO_2$ in 2017), Australia (413 $MtCO_2$) and Ukraine (223 $MtCO_2$); international aviation and shipping bunkers are outside national inventories and are also excluded. The European countries of the run (32 of the 35 countries covered by the European layer: the EU-27, Albania, Norway, Serbia, Switzerland and the United Kingdom) are represented through that layer, which is based on the manual assessment of 35 National Energy and Climate Plans (NECPs) [32, 130]. Iran is included in the BAU scenario but carries no quantified NC constraint, since its contribution was not coded with a target year and Iran has not ratified the Paris Agreement; NC totals in this chapter therefore refer to 127 countries.

5.2 The BAU scenario

5.2.1 Definition and assumptions

The BAU scenario is the counterfactual against which the NC scenario is measured: a world in which socio-economic development continues along a middle-of-the-road path and no commitments beyond those already reflected in observed data are implemented. Socio-economic drivers follow the Shared

Socioeconomic Pathway 2 (SSP2), which extends historical patterns of population, economic growth and technological change without marked shifts towards or away from sustainability [43, 105]. SSP2 was preferred to policy-based projections such as the IEA Stated Policies Scenario, which by design reflects policies in place and under development [184] and would therefore already contain part of the commitments that the NC scenario is intended to isolate. SSP2 also provides population and GDP for every country on a consistent basis, which the economy-wide model requires.

Each model implements the same definition (Table 5.6 in Section 5.4). GTAP-E is calibrated to the GTAP Data Base version 11 for 2017 [175] and projected to 2050 with SSP2 population and GDP, without emission constraints. In LEAP, the historical years from 2017 are calibrated on observed energy balances (Section 5.2.2), and energy demand is carried forward with activity levels that follow the sectoral output of GTAP-E (Equation 4.1), without additional efficiency, fuel-switching or emission measures. LandReqGCH projects land use with the validated time-varying Markov chain of Section 4.2, so that the transition dynamics of recent decades continue. WaterReqGCH uses Aqueduct 4.0 renewable supply under SSP3-7.0 [124] and computes withdrawals from the BAU land areas, GTAP-E output and SSP2 population (Section 4.4).

For the 127 countries with an NC constraint, the BAU scenario implies that energy-related CO_2 emissions grow from 28,367 $MtCO_2$ in 2017 to 41,646 $MtCO_2$ in 2050 (+47%), and total final energy consumption from 8,205 Mtoe to 12,498 Mtoe (+52%). The carbon intensity of final energy therefore declines only slightly, from 3.46 to 3.33 tCO_2 per toe. The 2017 emissions of the baseline reproduce the IEA estimates of CO_2 from fuel combustion to within ±3% in sixteen spot checks covering the largest emitters, for example with ratios of 1.02 for the United States, 0.97 for China, 1.00 for India and Germany, and 0.99 for Japan and Türkiye, which confirms that the baseline is on an energy-related CO_2 basis. Regional values are given in Table 5.7.

5.2.2 Observed data made model-ready: automated extraction of IEA statistics

A baseline is only as good as its starting point. The current accounts of LEAP, the observed energy system from which all projections depart, require final consumption by sector and fuel, electricity generation by source, trade, refining and domestic production for every country, together with emissions by fuel and sector for validation. The International Energy Agency (IEA) publishes these statistics with harmonised definitions and broad coverage [160, 185], but through a web interface that returns one indicator at a time, with indicator-specific category labels and units and with categories omitted wherever values are missing. Collecting 24 indicators for 153 countries and two years manually would have required thousands of downloads and would have been slow and error-prone.

The data were therefore retrieved through an automated, configuration-driven pipeline that queries the IEA data services directly. Its design has four features.

- **A verified configuration.** A single configuration file defines, for each dataset, the service endpoint, the request parameters, the fields to keep and how to rename them, and the categories expected in a complete response. A maintained list of 153 ISO 3166 country codes defines the geographic scope.
- **Controlled retrieval.** Countries are queried in batches of 40, with a pause of 0.25 s between requests and a 60 s timeout; failed requests are logged in a separate file rather than silently dropped.

- **Harmonisation.** Responses are parsed into one schema (country code, category, value, year, unit), filtered to the study years, and completed with the expected categories, so that every country–year table has the same structure and a missing value is recorded as blank rather than as an absent row.
- **Reproducible outputs.** Each run produces a consolidated workbook, one CSV file per dataset and run metadata. New runs are written to separate, time-stamped folders, so the validated dataset used in this report is never overwritten. The pipeline is packaged with a local user interface in which countries, years and datasets can be selected and a run launched or simulated without retrieval (Section 5.6).

The delivered dataset contains 24 datasets for 153 countries and the years 2017 and 2022, a total of 20,981 records (Table 5.1, Figure 5.2).

Table 5.1. IEA datasets retrieved and harmonised by the automated extraction (years 2017 and 2022).

Block	Datasets	Units	Countries with data
Production and refining	Domestic energy production by source; domestic production of crude oil, natural gas and coal; domestic oil refining	TJ and native units	69–153
Final consumption	Total final consumption by fuel and by sector; consumption by fuel in the residential, transport, industry and services sectors	TJ	150–151
Electricity	Generation by source; imports and exports; emissions of electricity generation by fuel	GWh, TJ, $MtCO_2$	120–151
Emissions	CO_2 emissions from fuel combustion by fuel and by sector	$MtCO_2$	149
Trade	Imports and exports of crude oil, oil products, natural gas and coal	TJ	98–151
Efficiency indicators	Energy intensity of the residential (per floor area, temperature-corrected), transport, manufacturing and services sectors	Indicator units	37–55

The harmonised panels serve three purposes in the framework. First, they provide the 2017 and 2022 current accounts of LEAP for the countries of the global run. Second, they are the benchmark against which the calibration is checked: the 2017 reproduction reported above, and the validation of the 2022 current account against the IEA World Energy Balances and, for the European layer, Eurostat energy balances (Section 4.3.2) [160, 161]. Third, they anchor the NC scenario: the 2022 energy balance is the structural starting point of the NC fuel mix (Section 5.4.1), and observed 2022 emissions define where the no-backsliding rule applies (Section 5.3.5). The same observed baseline is thus shared by both scenarios and by all models.

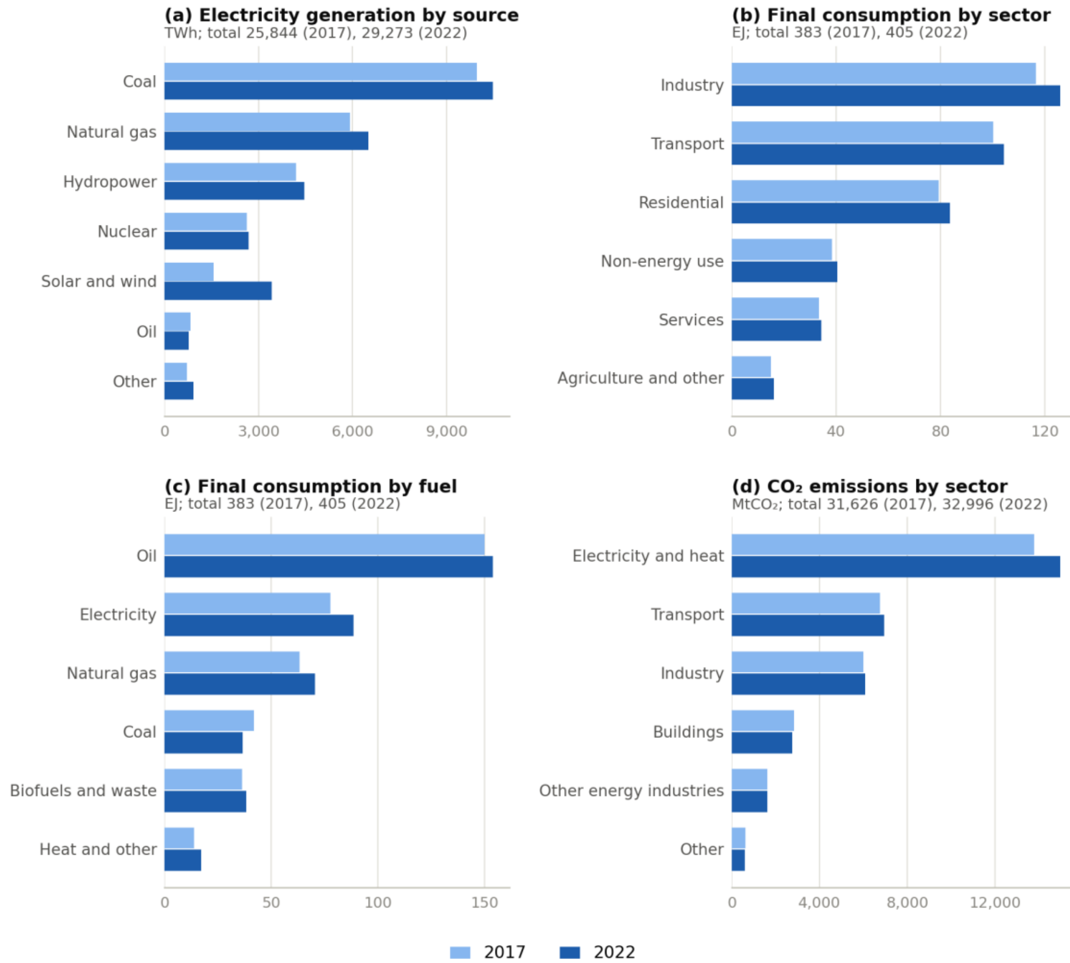


Figure 5.2. Examples of the harmonised IEA panels, aggregated over the countries covered: (a) electricity generation by source, (b) total final consumption by sector, (c) total final consumption by fuel and (d) CO_2 emissions from fuel combustion by sector, in 2017 and 2022.

5.3 The NC scenario: from commitments to constraints

5.3.1 Evidence base: systematic assessment of national commitments

Each country's official NDC was assessed, or the equivalent national plan where the operative document carries another name, most importantly the NECPs of the European Union and the Energy Community, in light of the 2050 climate-neutrality objective. Documents were obtained from the UNFCCC NDC Registry and long-term strategies portal [186] and from national sources. The published English version was used where one existed and an English translation of the national-language text otherwise, and the version used was recorded, since translation can affect the reading of target wording. Where a draft and a final plan existed, the final plan took precedence, and the status and publication date of the assessed document were recorded as indicators of how current and how binding the commitments are.

Every plan was coded against the same template, so that the records are comparable and form a single structured dataset (Table 5.2). The criteria capture the planning parameters that energy and climate models require, which also reveals where commitments are well specified and where they are absent, vague or inconsistent across countries. They fall into three groups: the framing and orientation of the plan, its quantitative targets, and its treatment of water.

Table 5.2. Coding template applied to every national commitment.

Group	Criterion	Recorded as
Framing	Assessed document, status (final or draft), publication date, language version	Text, date
	Planning horizon (target year)	Year
	Strategic orientation	Supply-focused, demand-focused or balanced
	Level of detail of the route to net zero	Quantified measures or descriptive
Quantitative targets	GHG emissions reduction in the target year, with reference (base year or BAU) and conditionality	%, reference
	GHG emissions level in the target year	$MtCO_2e$
	Renewable share in final energy consumption; renewable share in electricity generation	%
	Final energy consumption in the target year	Energy units
	Reliance on energy imports; energy export targets	Yes/no; quantity
	Afforestation or land-based sink target	%, ha or qualitative
	Other quantified sectoral or fuel-specific targets	Values and text
Water	Integration of water actions	Explicit, qualitative or absent

Two conventions govern missing information, because the distinction is analytically meaningful. A blank entry denotes that the plan says nothing on a criterion; a “not specified” entry denotes that the plan addresses the criterion in qualitative or comparative terms but gives no usable figure. The distinction separates silence from unquantified intent, which matters both for judging the specificity of a pledge and for deciding what a model can ingest. A subset of countries was independently re-coded by additional assessors and the readings reconciled, with disagreements resolved against the source text.

Water was coded although NDCs are not required to contain water-specific actions. NDCs are directed primarily at mitigation, and adaptation, under which water management usually falls, remains a voluntary component. Water is nevertheless the medium through which climate change is most directly experienced, through floods, droughts and changes in availability [187], and integrating it into climate plans connects them with Sustainable Development Goal 6 on clean water and sanitation [188]. Most plans mention water, but almost always in qualitative terms.

The template was complemented by structured datasets for the variables that national plans report inconsistently: the declared carbon-neutrality year and its legal status [186, 189], economy-wide GHG emissions in 2017 including and excluding LULUCF [190, 191], CO_2 emissions [192] and, where an NDC was ambiguous, published country assessments [39]. Country-level sources are recorded in the dataset.

Across the 128 countries of the global run, the target year is 2030 in 29 countries, 2035 in 61, 2040 in three and 2050 in 33 (the European countries, whose NECPs and the European Climate Law extend to 2050 [13], and Burkina Faso), while the target year was not coded for two contributions (Iran, and Tanzania, whose NDC target for 2030 is used in Section 5.3.6). A carbon-neutrality target is anchored in law or in binding national policy in 41 countries (27 through the European Climate Law and 14 through national legislation or an equivalent national framework), declared in a strategy or political pledge without such force in 36, and absent in 51. Eighteen countries had no usable quantified economy-wide target in the first coding round. The results of the detailed European assessment, including planning horizons, orientation and level of detail of the 35 NECPs, are summarised in Section 1.3.2 [32], while Figure 5.3 provides a visual overview of the main characteristics emerging from this assessment.

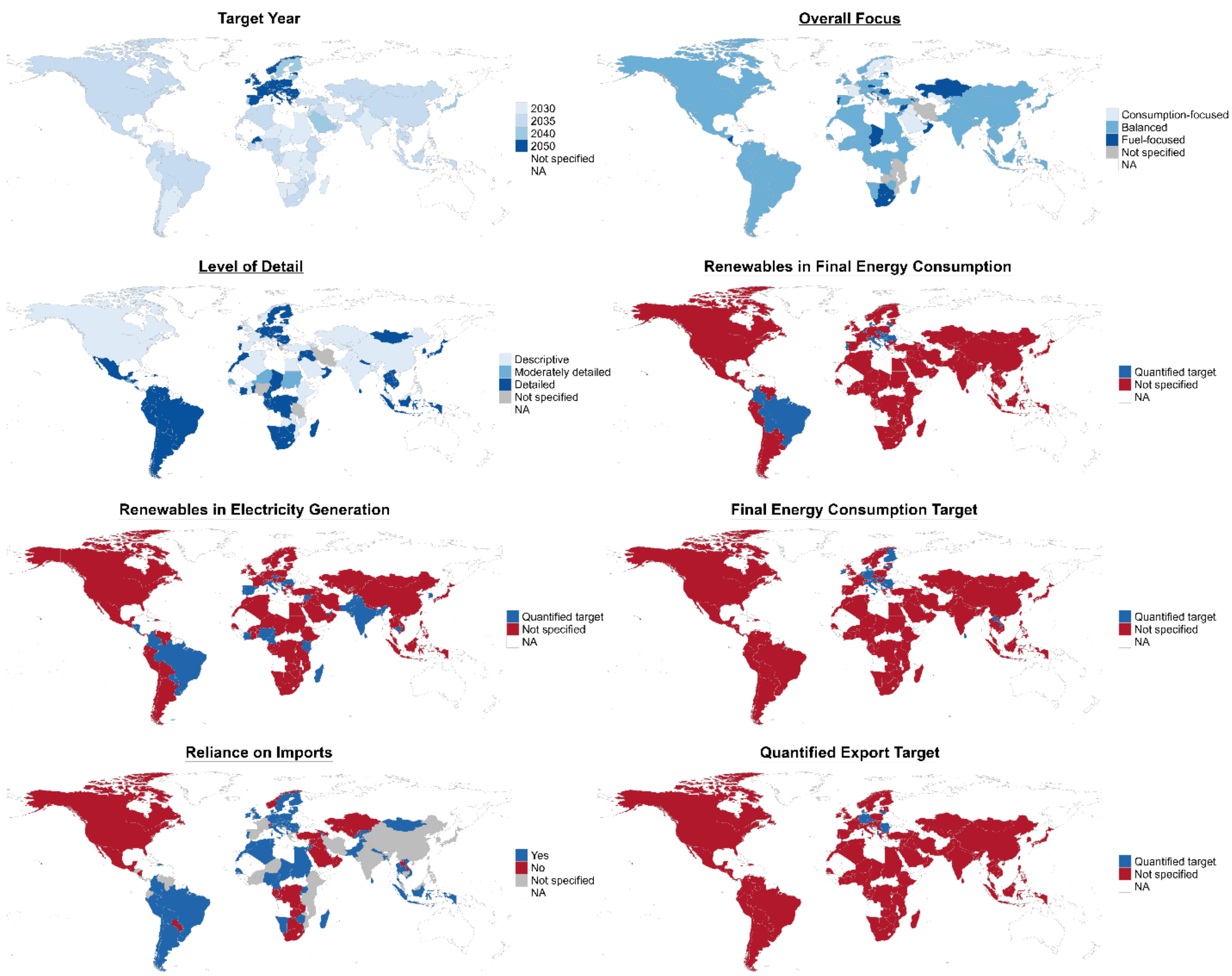


Figure 5.3. Cross-country comparison of key NDC assessment indicators.

5.3.2 Requirements for a consistent translation

Any translation of pledges into model inputs involves choices; what matters is whether the choices are explicit, principled and tested. The alternative to explicit rules is not a translation without rules, but one in which the rules remain implicit in how each target happens to be read. The NC constraints were therefore required to satisfy five requirements, which follow from the purpose of the scenario and from the Paris Agreement itself:

- **R1 Scope consistency.** A constraint refers to the same quantity as the model variable it constrains, so abatement pledged in land use, agriculture or non-CO_2 gases is not attributed to energy-related CO_2.
- **R2 Reference consistency.** Ambition is measured against a reference comparable to the one against which the pledge was made, and the resulting 2050 value lies between zero and the country's own BAU.
- **R3 Monotonicity.** Where a country has pledged to pass its emissions peak, its NC path does not rise again after the target year, consistent with the progression required by Article 4.3 of the Paris Agreement [3].
- **R4 Fidelity to the full commitment.** Commitments outside the NDC document or beyond its horizon, such as legislated carbon neutrality, and the form in which the operative target is expressed are represented rather than truncated or misread.
- **R5 Completeness and traceability.** Every country and every model input receives a value, and each value can be traced to a source and a rule.

Without harmonisation, the coded targets violate several of these requirements. Placing each target-year value on the energy-related CO_2 baseline and extending the path from 2017 through the target year linearly to 2050 gives target-year emissions above the country's own BAU emissions in 2050 in 43 of the 128 countries, and in 18 of these above five times the 2017 energy-related emissions. Linear extrapolation produces 2050 values above BAU in 49 countries and negative values in five, including −225 $MtCO_2$ for Gabon, about twice the national forest sink. Summed over all countries, the unharmonised 2050 values exceed the BAU with which they are meant to be compared by 2.7%.

These are not anomalies in the NDCs but consequences of comparing different quantities (R1). The baseline measures energy-related CO_2, while most NDCs report economy-wide, multi-gas emissions that include agriculture, forestry and other land use (AFOLU). Uganda illustrates the problem: its updated NDC reports a 2030 BAU of 148.8 $MtCO_2e$, of which 122.2 $MtCO_2e$ (82%) is AFOLU [193], against energy-related CO_2 of 5.2 $MtCO_2$ in 2017. Read against the energy baseline, the target appears to allow a twenty-fold increase in emissions; in fact it implies no constraint on the energy system at all. The inclusion of LULUCF is similarly decisive where land use dominates: emissions of Côte d'Ivoire in 2017 were 240.2 $MtCO_2e$ including land use and 21.7 $MtCO_2e$ excluding it. The remaining failures arise from the extrapolation rule itself, from targets stated net of forest sinks, and from missing or implausible values. Table 5.3 lists the issues, the requirement that each violates and the treatment developed for it in Sections 5.3.3–5.3.7.

Table 5.3. Issues found when entering coded commitments into an energy-system baseline, the requirement violated and the treatment applied.

Issue	Example	Effect if used directly	Requirement	Treatment	Section
Economy-wide, multi-gas target against an energy-CO_2 baseline	Uganda: 82% of 2030 BAU is AFOLU	Spurious growth or spurious cuts in energy CO_2	R1	Ambition ratio against an implied economy-wide BAU	5.3.3

Issue	Example	Effect if used directly	Requirement	Treatment	Section
Unclear inclusion of LULUCF	Côte d'Ivoire: 240.2 vs 21.7 $MtCO_2e$ in 2017	Forest abatement credited to the energy system, or no ambition at all	R1	Two-bound ratio (geometric mean)	5.3.3
Target above the country's own reference case	15 countries	Emissions raised above BAU	R2	Ratio capped at one	5.3.3
Self-declared baseline far above the reconstruction	Türkiye: 42% stated vs 6% reconstructed	Ambition understated	R2	Stated ratio used directly	5.3.4
Missing, net-of-sink or implausible target	18 missing; Gabon −121.5 $MtCO_2e$	Gaps, negative or unbounded values	R1, R5	Ratio sourced from the NDC; imputation by regional median	5.3.4
Linear extrapolation beyond the target year	Gabon −225 $MtCO_2$ in 2050	Overshoot or negative values	R2	Constant relative ambition	5.3.3
Emissions rebound after the target year	49 of 96 non-European paths U-shaped	Backsliding	R3	No-backsliding ceiling	5.3.5
Long-term commitment outside the NDC horizon	China: 2035 target ≈ 2024 emissions	Neutrality commitment ignored	R4	Legislated-neutrality ceiling	5.3.5
Headline target in a form the rules handle poorly	India (intensity target), United States	Reconstruction not representative	R4	Assessment-based value	5.3.6
No energy-demand target	Most NDCs	No input for final energy	R5	Calibrated energy response	5.3.7

5.3.3 The harmonised ambition ratio

Rather than converting each target level to an energy-CO_2 equivalent, which would require a sectoral decomposition that most NDCs do not report, each target is expressed as a dimensionless ambition ratio: the pledged economy-wide emissions divided by the economy-wide emissions the country would have without the pledge. The ratio is then applied to the energy-related CO_2 baseline. This assumes equal proportional effort across the economy, and it is self-consistent: a target equal to the country's own reference case returns exactly the BAU.

For country i, let C_i and G_i be energy-related CO_2 in 2017 and in the BAU in 2050, D_i the target year and E_i the target emissions level as published. The BAU is read at the target year by constant-growth interpolation, without modifying the baseline itself:

$$B_i(t) = C_i \left(\frac{G_i}{C_i}\right)^{\frac{t-2017}{2050-2017}} \qquad (5.1)$$

Non-energy emissions are held at their 2017 level, since AFOLU and non-CO_2 emissions do not scale with economic growth in the way energy demand does. The implied economy-wide BAU on accounting basis s, including or excluding LULUCF, is then:

$$\Lambda_i^s(t) = B_i(t) + N_i^s, \qquad N_i^s = \Gamma_i^s - C_i, \qquad s \in \{\text{incl}, \text{excl}\} \tag{5.2}$$

where Γ_i^{incl} and Γ_i^{excl} are economy-wide GHG emissions in 2017 including and excluding LULUCF [190, 191], both floored at 1.02 C_i to preclude inconsistent denominators.

Whether a target includes LULUCF is often unclear, and assuming either basis can be badly wrong. Assuming inclusion credits the energy system with abatement that occurs in forests: it implied a 66% reduction in Brazil's energy-related CO_2, although Brazil's NDC is dominated by deforestation commitments. Assuming exclusion implies no energy-sector ambition in the same countries. The ratio is therefore computed on both bases and the geometric mean is taken:

$$\rho_i^{\text{incl}} = \frac{E_i}{\Lambda_i^{\text{incl}}(D_i)}, \qquad \rho_i^{\text{excl}} = \min\left\{1, \frac{E_i}{\Lambda_i^{\text{excl}}(D_i)}\right\} \tag{5.3}$$

$$\rho_i = \min\left\{1, \sqrt{\rho_i^{\text{incl}}\,\rho_i^{\text{excl}}}\right\} \tag{5.4}$$

The rule is self-limiting, which is what justifies its general application. Where land use is a small part of the inventory the two bounds nearly coincide and the rule has almost no effect: the implied reduction for the United States changes from 68% to 66%, and those for Japan and the Republic of Korea do not change. Where land use dominates, the rule moderates the implied energy-sector ambition substantially, from 66% to 42% for Brazil and from 36% to 20% for Indonesia. This is consistent with assessments that exclude LULUCF from cross-country comparisons of targets because heterogeneous land-use accounting reduces comparability and can mask trends in energy and industrial emissions [39, 179, 180].

The cap at one in Equations (5.3)–(5.4) prevents a target above the country's own reference case, which requires no policy to meet, from raising modelled emissions above BAU [180]. Fifteen of the 65 countries harmonised in this way are capped: Armenia, Bangladesh, Brunei, Cameroon, China, Ecuador, Georgia, Honduras, Kenya, Nigeria, Pakistan, Rwanda, Togo, Uganda and Zimbabwe. This is a result rather than a failure of the method. For the AFOLU-dominated cases it is the correct reading, since Uganda's own NDC allocates most of its mitigation to AFOLU [193]; for China, the 2035 target of 13,700 $MtCO_2e$ is almost exactly its 2024 emissions on the same basis, so the NDC holds emissions flat and the binding commitment is carbon neutrality before 2060 [27], which enters through Section 5.3.5.

Applying the ratio to the BAU in 2050 carries the relative effort pledged for the target year forward to mid-century, $G_i\,\rho_i$. This replaces the linear extrapolation of the historical trend with constant relative ambition, the simplified form of the post-pledge extension used by the Climate Action Tracker [39]. It removes the guaranteed overshoot and all negative values by construction.

5.3.4 Evidence hierarchy for the ambition ratio

The ambition ratio, and with it the 2050 value, of each country is taken from the highest available tier of a fixed hierarchy of evidence: (1) quantified national readings in official plans, namely the NECP-based values of the European layer and the documentary readings admitted under the criteria of Section 5.3.6; (2) a ratio stated in the NDC or in a published country assessment, that is, a reduction against the country's own baseline; (3) the harmonised reconstruction of Section 5.3.3; and (4) imputation by the regional median. A lower tier is used only where the higher tiers provide no value that satisfies the requirements of Section 5.3.2. Documentary interpretation therefore enters through the choice of evidence, which is recorded for every country, rather than through adjustments to results. Tier-1 values already represent a national pathway to 2050, so the ceilings of Section 5.3.5 apply only to values from tiers 2–4. Table 5.5 reports the number of countries in each tier.

Stated ratios (tier 2). Where a country's self-reported inventory is much larger than the international dataset, the reconstructed baseline is too small and the NDC appears far weaker than it is. Where a submission states its target explicitly as a proportional reduction against its own baseline, that stated ratio is used directly, since a percentage does not depend on the scope of the inventory. This applies to four countries whose targets were coded as emissions levels and whose submissions also state the reduction against the national baseline: Türkiye (a 2035 target of 643 $MtCO_2e$ against a reference of 1,109 $MtCO_2e$, a 42% reduction, against 6% reconstructed) [194], Viet Nam (43.5% against 1%), Algeria (31% against 0.2%) and Botswana (18% against 10%). The principle is symmetric with the cap: in both directions a country's own statement of relative ambition is preferred wherever it is less ambiguous than the reconstruction.

Ratios sourced from the NDC (tier 2). For 14 of the 18 countries without a usable target in the first coding round, the target was retrieved from the submitted NDC or from a published country assessment. Most of these submissions express mitigation as a reduction against a self-declared BAU, so the percentage itself is the ambition ratio (for example 0.846 for Egypt, 0.683 for Saudi Arabia and 0.250 for the Philippines). Where a submission is disaggregated by sector, the energy-sector figure is used, as for Niger, because the constraint applies to an energy system model. Conditional targets are used wherever a submission distinguishes conditional from unconditional components.

Imputation by regional median (tier 4). Four countries lack a quantified economy-wide target (Bahrain, Bolivia, Syria and Uruguay) and are assigned the median ratio of their region. The same rule is applied to ten values rejected because they fail the requirements of Section 5.3.2: five targets stated net of forest sinks (Eswatini, Gabon, Namibia, Panama and the Republic of the Congo), two values that correspond to a baseline rather than a target (Chad and Paraguay), two values larger than the national inventory or likely cumulative (Equatorial Guinea and Nicaragua), and one 2050 value above the country's 2017 level despite a legal neutrality obligation (Malta, for which a documentary reading was subsequently adopted; Section 5.3.6). Regional medians are computed over all countries in the region that carry a usable ratio of their own, including sourced ratios; regions with fewer than three such countries fall back to a super-region and then to the global median. As a check, the independently sourced ratio of Saudi Arabia (0.683) lies within 2% of the regional median it replaced. The four countries without targets together account for less than 1% of 2050 emissions.

5.3.5 Ceilings on the 2050 value

Two further commitments cannot be expressed through a ratio fixed at the target year: the commitment not to backslide once a reduction has been pledged, and carbon-neutrality targets that fall after the NDC horizon. Both enter as ceilings. The rule-based 2050 value of each country with a tier 2–4 ratio (Section 5.3.4) is the lowest of three:

$$X_i = \min\{G_i\,\rho_i,\ V_i,\ P_i\} \qquad (5.5)$$

where $G_i\rho_i$ is the constant-relative-ambition value (Section 5.3.3), V_i the pledged target-year level and P_i the level consistent with a legislated neutrality target. Because the ceilings enter as a minimum, each can only lower a value: a country already below a ceiling is neither raised to it nor exempted from it, and countries differ only in which ceiling binds.

No backsliding. Constant relative ambition inherits the shape of the baseline, so where the baseline rises after the target year the NC path rises as well. Without this ceiling, 49 of the 96 non-European trajectories would be U-shaped, falling to the target year and rising afterwards, and 31 would end 2050 above their 2022 level. Such a path is inconsistent with the requirement that each successive NDC represent a progression beyond the previous one (Article 4.3) [3], and with observed national trajectories, in which a structural emissions peak is not later re-crossed. With $V_i = B_i(D_i)\,\rho_i$ the NC-consistent emissions at the target year and A_i observed emissions in 2022:

$$X_i \leq V_i \qquad \text{where } \rho_i < 1 \text{ and } V_i < A_i \tag{5.6}$$

The two conditions define where the ceiling applies. The rule concerns a country that has pledged to pass a peak: where a pledge still permits growth above current emissions ($V_i \geq A_i$) no peak is implied, and where the pledge is non-binding ($\rho_i = 1$) there is no pledged level to protect. The ceiling sets the 2050 value in 42 countries, 40 of which have a target year before 2050. A plateau at the target-year level does not freeze the energy system: across these 40 countries, final energy consumption in the executed run still grows by 18% between the target year and 2050 while emissions stay constant, which implies a further 15% reduction in the carbon intensity of final energy. The plateau is a lower bound on pledged ambition rather than a projection: it represents what has been pledged and nothing more, so any remaining gap that the NC scenario reveals is, if anything, understated.

Legislated carbon neutrality. With $R_i = w\,C_i$ the residual gross energy-related CO_2 at the neutrality year Y_i, where $w = 0.10$ represents the sinks and carbon capture that make net zero net rather than absolute:

$$P_i = \begin{cases} R_i, & Y_i \leq 2050 \\ R_i + (V_i - R_i)\dfrac{Y_i - 2050}{Y_i - D_i}, & Y_i > 2050 \\ G_i\,\rho_i, & \text{no legislated target} \end{cases} \tag{5.7}$$

so that gross emissions decline linearly from the target-year level to the residual at the neutrality year and the 2050 value is read from that line. A neutrality target is counted only where it is anchored in law or in binding national policy, that is, in legislation or in a national framework that commits the whole of government to the target, because such commitments carry materially higher credibility than targets announced in strategies or political declarations [195–197]. The carbon-neutrality goal of China for 2060, set through the national “dual carbon” framework and its sectoral action plans (Section 1.2.3), is counted on this basis. The restriction also preserves a consistency property of the scenario. Applied to every declared target, Equation (5.7) would invert the regional ordering of implied reductions, with Southeast Asia (94.1%), the Caucasus (93.7%) and South Asia (92.7%) decarbonising more deeply than Europe (91.9%). This happens because the residual is proportional to 2017 emissions: for a country whose baseline triples by 2050, the residual is a very small share of that baseline, so the rule would reward rapid baseline growth, and it would push the energy consumption of 18 developing countries below its 2017 level. Restricting the rule to targets anchored in law or binding national policy avoids both effects. The restriction is consequential: the neutrality ceiling of China alone accounts for about a quarter of the global reduction of the NC scenario relative to BAU, because its target for 2035 does not by itself constrain emissions below its own reference case (Section 5.3.3). The ceiling applies to the 11 non-European countries with such a commitment, among them China, Japan, the Republic of Korea, Canada and Türkiye; the United States is not among them, its federal commitments having been withdrawn in 2025 [23].

For the European countries, whose NECP-based values are tier-1 evidence (Section 5.3.4) and set out the national pathways for implementing the European Climate Law, the neutrality ceiling is not applied and the national 2050 values are retained [13, 32]. This follows from the hierarchy of evidence rather than creating an exception, and it is conservative with respect to mitigation: the median European reduction against BAU is about 83%, against about 92% had the ceiling been applied.

5.3.6 Assessment-based values

Quantified national readings rank first in the hierarchy of evidence (Section 5.3.4). For 18 countries, a different group from the 18 without a usable target in the first coding round (Section 5.3.1), the NDC was read together with the accompanying long-term strategy and national energy plans, and that reading was adopted (Table 5.4). A documentary reading replaces the rule-based value only where at least one of three criteria holds: (i) the headline target is not an economy-wide emissions level or reduction, as with the emissions-intensity target of India; (ii) the framework behind the target has been formally withdrawn or superseded, as with the federal climate commitments of the United States [23]; or (iii) a more recent official document quantifies energy-sector emissions or the energy pathway directly. For Malta, whose reported 2050 value was rejected (Section 5.3.4), the documentary reading also replaces the regional-median imputation. Fourteen adopted values are lower than the rule-based values and four are higher (Brazil, Indonesia, Malta and the United Arab Emirates), so the assessment does not move values systematically in one direction. The net effect on the 2050 total is −3,631 $MtCO_2$, dominated by India and the United States. Both the rule-based and the adopted value are retained for every country, so the effect of the documentary readings can be isolated. The United States shows how much uncertainty such a reading can carry. Its adopted 2050 value follows the trajectory of the 2021 long-term strategy, the only quantified national pathway to 2050 that has been published, whereas the 2035 NDC behind its rule-based value of 1,831 $MtCO_2$ and the federal framework behind that strategy have both since been withdrawn (Section 1.2.2). Current federal policy points to far shallower reductions [26]. The NC value for the United States therefore represents what its published plans imply, not a projection of the policy now in force, and it is the most uncertain single value in the dataset.

Table 5.4. Assessment-based 2050 values of energy-related CO_2 ($MtCO_2$) replacing the rule-based values.

Country	Region	Target year	Rule-based	Adopted	Change	Reduction vs BAU
India	South Asia	2035	5,034.2	2,402.0	−2,632.2	53%
United States	North America	2035	1,831.1	1,035.0	−796.1	83%
Indonesia	Southeast Asia	2035	605.8	846.0	+240.2	20%
Saudi Arabia	Middle East	2040	735.5	500.0	−235.5	54%
Mexico	North America	2035	271.3	99.4	−171.9	87%
Brazil	South America	2035	286.1	316.0	+29.9	42%
Pakistan	South Asia	2035	521.5	500.0	−21.5	4%
Tanzania	East Africa	2030	34.9	14.9	−20.0	71%
Japan	East Asia	2040	111.6	105.0	−6.6	91%
DR Congo	Central Africa	2030	10.8	5.7	−5.1	58%
Uganda	East Africa	2030	21.1	16.4	−4.7	22%

Country	Region	Target year	Rule-based	Adopted	Change	Reduction vs BAU
Ethiopia	East Africa	2035	29.5	26.7	−2.8	50%
Brunei	Southeast Asia	2035	11.1	9.0	−2.1	19%
Nepal	South Asia	2035	21.2	19.4	−1.8	21%
Kenya	East Africa	2035	41.7	40.7	−1.0	2%
Mozambique	East Africa	2035	23.8	22.9	−0.9	23%
United Arab Emirates	Middle East	2035	18.1	19.0	+0.9	94%
Malta	Europe	2050	0.1	0.5	+0.4	83%

5.3.7 Final energy consumption

NDCs constrain emissions, not energy demand, so NC-consistent final energy consumption in 2050 has to be inferred. The emissions reduction against the 2050 baseline, $e_i = 1 - X_i/G_i$, decomposes exactly into a reduction in final energy consumption, f_i, and a reduction in the carbon intensity of final energy, c_i:

$$(1 - e_i) = (1 - f_i)(1 - c_i) \qquad (5.8)$$

The problem reduces to dividing the abatement between the demand and intensity channels. Rather than imposing a split, it was calibrated on the 31 European countries for which both baseline and NC consumption were available from the NECP-based assessment, which provide 31 independent observations with emissions reductions between 30% and 97%. A regression of f on e returns a slope of 0.516 and an intercept of −0.055, statistically indistinguishable from zero, which supports a proportional relationship:

$$f_i = r\, e_i, \qquad r = \underset{j \in \mathrm{Europe}}{\mathrm{median}} \left(\frac{f_j}{e_j} \right) = 0.483 \qquad (5.9)$$

$$J_i = I_i(1 - f_i), \qquad c_i = 1 - \frac{1 - e_i}{1 - f_i} \qquad (5.10)$$

where I_i is BAU final energy consumption in 2050 and J_i the NC energy envelope. The fit has $R^2 = 0.35$, a mean absolute error of 12.1% in the implied consumption level and a maximum error of 28.0%; Malta is excluded from the calibration because its reported 2050 consumption exceeds its own baseline. A constant-elasticity alternative, $(1 - f) = (1 - e)^k$, gave a similar mean error but a clearly worse maximum error (44%).

Three properties support the use of Equation (5.9) beyond the calibration sample. It is bounded, since the implied reduction in consumption cannot exceed $r \approx 48\%$ however deep the emissions cut, so consumption cannot collapse. It satisfies Equation (5.8) exactly in every country. And it returns $f_i = 0$ wherever the commitment is non-binding, so capped countries retain their baseline consumption. The European values are used unchanged as calibration data. With this rule, the NC energy envelopes fall below 2017 consumption almost exclusively in high- and upper-middle-income economies with mature energy systems, while consumption continues to grow in developing economies; in 48 countries NC emissions in 2050 remain above their 2017 level, reflecting pledges that allow growth from a low base.

5.3.8 Summary of treatments

Table 5.5 summarises the tier of evidence from which the 2050 value of each country is taken, and how often each ceiling binds in the rule-based values.

Table 5.5. Source of the 2050 NC values by tier of evidence, and ceilings applied (128 countries).

Treatment	Countries
2050 value by tier of evidence (Section 5.3.4)	
Tier 1: quantified national readings: NECP-based values of the European layer (31) and assessment-based values (18; Section 5.3.6)	49
Tier 2: ratio stated in the NDC or a published country assessment, including 4 stated ratios replacing the reconstruction	14
Tier 3: scope-harmonised two-bound reconstruction (Section 5.3.3), of which 11 capped at one	52
Tier 4: imputation by regional median (4 countries without a target, 9 rejected values)	13
Ceilings in the rule-based values (Section 5.3.5)	
2050 value set by the no-backsliding ceiling	42
Neutrality target anchored in law or binding national policy: ceiling applied in 11 non-European countries; national values retained in 30 European countries	41

5.4 From constraints to model inputs

The constraints of Section 5.3 are aggregate: for each country, NC-consistent energy-related CO_2 at the target year and in 2050, and an NC energy envelope. This section describes how they were converted into the inputs of each model, so that all four models simulate the same commitments (Table 5.6).

5.4.1 LEAP: an NC-consistent sector-by-fuel energy system

The fuel-mix procedure does not reinterpret the commitments; it translates the aggregate constraints into a coherent set of sector-by-fuel inputs for LEAP [123]. For country i, sector s, fuel f and year t, let $F_{i,s,f,t}$ denote final energy consumption. The constructed energy system is built around two conditions:

$$\sum_{s} \sum_{f} F_{i,s,f,t} = T_{i,t} \qquad (5.11)$$

$$\mathrm{CO_2}_{i,t}^{\mathrm{LEAP}} \leq M_{i,t} \qquad (5.12)$$

where $T_{i,t}$ is the applicable final energy envelope and $M_{i,t}$ the NC-consistent energy-related CO_2 constraint. Equation (5.11) sets the scale of the provisional matrix, while Equation (5.12) is the binding condition for the accepted energy system. The emissions constraint is an upper bound: where the provisional energy system already emits less than the constraint, fossil fuel consumption is not increased to make the constraint bind.

The procedure has five steps.

1. **Historical anchor.** The 2022 energy balance, compiled from the IEA panels (Section 5.2.2), provides the observed distribution of final energy consumption across the LEAP demand branches (industry, residential, agriculture, transport, services, non-energy use and other non-specified

uses) and carriers (coal, oil, natural gas, renewables, biofuels, heat and electricity). Hydrogen is absent from the historical balance and is introduced only in future years where justified.

2. **Checkpoints.** The pathway passes through the country's own target year, 2022 → target year → 2050, rather than following a single straight line to 2050. This preserves the timing of each commitment, and it allows countries with fast-growing demand to increase total consumption while the carbon intensity of that consumption falls.
3. **Provisional matrix.** For each checkpoint, a provisional sector-by-fuel matrix is built from the 2022 structure and scaled to the applicable envelope. This retains country-specific features, such as the weight of transport fuels, gas use in buildings and industry, or existing renewable and bioenergy use, instead of imposing a common global fuel mix.
4. **Reconciliation with the emissions constraint.** The provisional matrix is evaluated with the LEAP emissions accounting, based on IPCC emission factors (Section 4.3). If emissions are at or below the constraint, no fuel switching is imposed. Otherwise, a single country- and checkpoint-specific parameter λ ($0 \leq \lambda \leq 1$), the share of combusted coal, oil and natural gas in the emitting branches that is displaced, is raised progressively until Equation (5.12) holds, so that λ is the smallest displacement that meets the constraint. The displaced energy is reassigned within the same sector to admissible low- or zero-carbon carriers (electricity, renewables, biofuels, heat and, where allowed, hydrogen), according to the sector and the existing energy structure of the country, so that the total final energy requirement of the sector is preserved. The degree of fuel switching is thus determined by the country's 2022 structure, its envelope and its emissions constraint, not by exogenous fuel shares. Non-energy use remains part of total final energy but is not combusted and is therefore not reduced to satisfy the constraint.
5. **Transformation-sector consistency.** Electricity demand resulting from fuel switching is reconciled with generation, imports, exports and transmission and distribution losses, and the resulting power-sector emissions are included in the check of Equation (5.12). Oil refining is kept consistent with the final demand pathway. Hydrogen is treated conservatively: green hydrogen is introduced only where a policy, strategy or industrial basis justifies it (in 18 of the 96 non-European countries by 2050, for example the United States, China, India and Chile), only as a final carrier in industry and transport, and never for electricity generation. It can be produced domestically by electrolysis or imported, and only domestic production adds to electricity demand. Where no country-specific value is available, a common electrolysis efficiency is assumed (67% up to the target year and 72% in 2050, within the range reported for current and future electrolysers [198]) with a capacity factor of 50%.

An energy system is accepted only when its identities hold: sector- and fuel-level consumption sums to the country total; modelled energy-related CO_2 does not exceed the constraint; no fossil demand is added to make a non-binding constraint bind; electricity consumption, generation, trade and losses reconcile; hydrogen demand is consistent with domestic production, imports and electrolysis electricity; and transformation quantities remain consistent with final demand. For each country an audit record documents the constraints and the resulting inputs at 2022, the target year and 2050: demand by sector and fuel, electricity generation, capacity and availability by technology, fossil feedstock shares in power generation, network losses, oil refining and the hydrogen pathway. The procedure was applied to the 96 non-European countries; the 32 European countries use the NECP-based inputs of the European layer [32].

The resulting fuel mix is an NC-consistent allocation of the energy system, not a forecast of the technologies each country will choose. Its purpose is to turn aggregate commitments into coherent model inputs while preserving the structure of each national energy system.

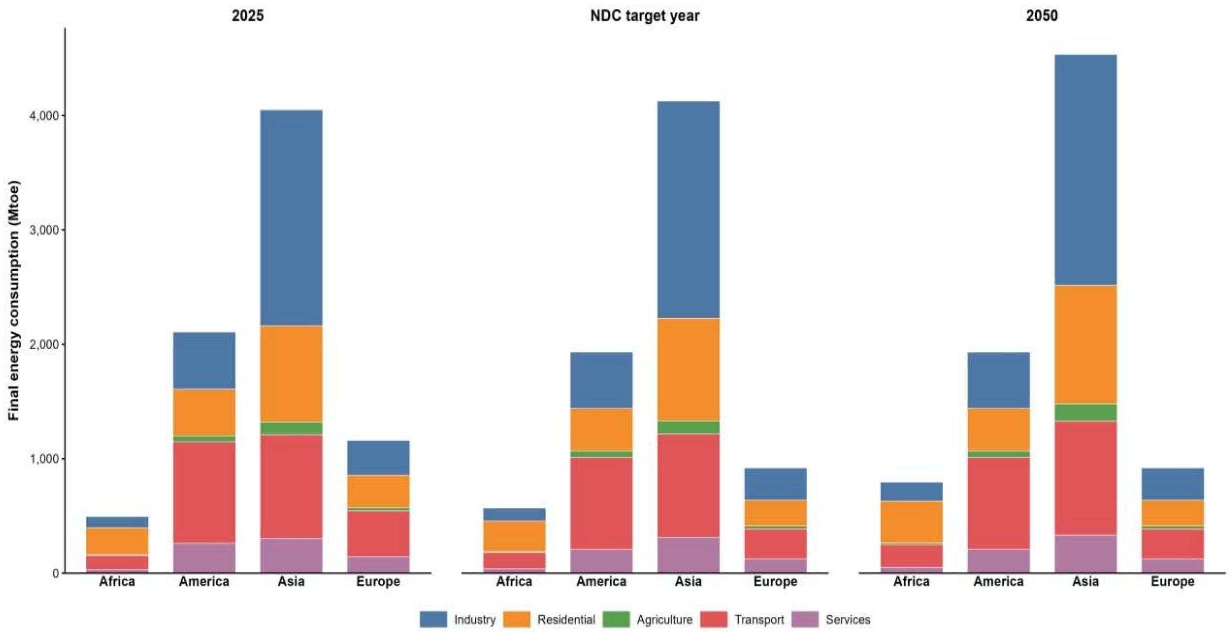


Figure 5.4. Final energy inputs of the NC scenario by carrier in 2022, at the NDC target year and in 2050, aggregated over the studied regions.

5.4.2 GTAP-E: macroeconomic drivers, land and emission caps

In the NC scenario GTAP-E [122, 199] receives three sets of shocks. Population and GDP follow SSP2, as in the BAU scenario, so that differences between the scenarios are not caused by different socio-economic assumptions. Land endowments follow the NC land-use trajectories of LandReqGCH (Section 5.4.3). The emissions caps of Section 5.3, the NC-consistent energy-related CO_2 of each country in 2050, are imposed as quantity constraints on CO_2 emissions; under this closure the carbon price that makes the caps bind is determined endogenously by the model [199]. The resulting sectoral output of agriculture, industry, transport and services provides the activity drivers used by LEAP and WaterReqGCH (Section 4.1.2), and because GTAP-E and LEAP are constrained by the same emissions values, the economic and energy representations of the NC scenario refer to the same commitment.

5.4.3 LandReqGCH: land-related commitments

Land-related commitments enter through the class-specific multipliers of Section 4.2.6 (Table 4.3), which express the 2050 NC area of each land class relative to BAU. Where a country's NDC or national plan quantifies a land-related target, such as an afforestation area or a land-based carbon sink, recorded in the assessment (Table 5.2), that target is applied directly; otherwise country-specific multipliers are selected within the ranges of Table 4.3 according to national context and the caps of Section 4.2.6. The adjustment is phased in linearly between 2026 and 2050 (Equations 4.11–4.12).

5.4.4 WaterReqGCH: no water-use targets to simulate

The assessed commitments do not set quantified, enforceable water-use targets at national scale that could be simulated, which is consistent with the European findings in Section 1.3.2. No water-specific target was therefore imposed. Water use in the NC scenario differs from BAU through its drivers: irrigation and livestock withdrawals follow the NC land-use areas, and industrial and energy-sector withdrawals follow NC sectoral output from GTAP-E (Section 4.4.2). Renewable supply is the same in both scenarios (Aqueduct 4.0 under SSP3-7.0), so that differences in water stress arise from the commitments rather than from climate assumptions. The absence of water targets is itself a finding of the assessment: the water consequences of national commitments are determined by energy and land decisions that are planned without reference to water.

Table 5.6. Definition of the BAU and NC scenarios in each model.

Model	BAU	NC
GTAP-E	GTAP Data Base v11 (2017); SSP2 population and GDP; land endowments from BAU land use; no emission constraint	SSP2 population and GDP; land endowments from NC land use; country caps on energy-related CO_2 in 2050 from Section 5.3, with an endogenous carbon price
LEAP	2017 and 2022 current accounts from IEA panels; activity levels following GTAP-E sectoral output; no additional measures	Same current accounts; sector-by-fuel inputs satisfying the NC energy envelope and CO_2 constraint at the target year and in 2050 (Section 5.4.1); European countries from NECP-based inputs
LandReqGCH	Validated time-varying Markov projection (Sections 4.2.3–4.2.4)	BAU dynamics to 2025; NC multipliers or quantified land targets phased in 2026–2050 (Section 4.2.6)
WaterReqGCH	Aqueduct 4.0 supply under SSP3-7.0; withdrawals from BAU land areas, GTAP-E output and SSP2 population	Same supply; withdrawals from NC land areas and NC GTAP-E output; no water-use targets

5.5 The scenario inputs in numbers

Table 5.7 summarises the constraints that define the NC scenario, by region, together with the BAU values against which they are measured. For the 127 countries with a constraint, NC-consistent energy-related CO_2 in 2050 is 15,195 $MtCO_2$, 63.5% below BAU and 46% below 2017. The NC energy envelope is 8,629 Mtoe, 31% below BAU but 5% above 2017, so that mitigation is expressed mainly as decarbonisation of a still-growing energy system rather than as a contraction of demand: the carbon intensity of final energy implied by the constraints falls from 3.33 tCO_2 per toe in the BAU to 1.76 in 2050. The envelope sets the scale of the provisional energy system, whereas the emissions constraint is the binding condition (Section 5.4.1). In the executed LEAP run, total final energy consumption in 2050 is therefore not identical to the envelopes but amounts to 9,058 Mtoe, 5% above their sum. Most countries remain close to their envelope, but simulated demand is higher in some, most notably Brazil (410 against 247 Mtoe) and Japan (208 against 170 Mtoe), where the emissions constraints are nevertheless met. The results in Chapter 6 refer to the simulated values.

Table 5.7. BAU and NC values of energy-related CO_2 and final energy consumption in 2050, by region (127 countries).

Region	n	CO_2 2017 ($MtCO_2$)	CO_2 BAU 2050	CO_2 NC 2050	Change vs BAU	FEC BAU 2050 (Mtoe)	FEC NC 2050	Change vs BAU
North America	3	5,852	7,465	1,189	−84%	2,526	1,500	−41%
Central America & Caribbean	10	103	204	136	−34%	91	77	−16%
South America	10	1,025	1,399	768	−45%	625	489	−22%
Europe	32	3,342	4,088	927	−77%	1,512	914	−40%
North Africa	4	435	922	659	−29%	266	229	−14%
West Africa	9	145	415	191	−54%	242	179	−26%
Central Africa	5	12	44	24	−45%	71	52	−26%
East Africa	11	96	299	169	−43%	319	251	−21%
Southern Africa	4	440	669	290	−57%	118	86	−27%
Middle East	12	1,624	3,052	1,099	−64%	839	576	−31%
Caucasus	3	45	74	61	−18%	27	25	−8%
Central Asia	4	323	609	303	−50%	142	113	−20%
South Asia	5	2,463	5,938	3,185	−46%	1,656	1,308	−21%
East Asia	6	11,100	13,754	4,896	−64%	3,340	2,291	−31%
Southeast Asia	9	1,360	2,712	1,298	−52%	725	539	−26%
Total	**127**	**28,367**	**41,646**	**15,195**	**−63.5%**	**12,498**	**8,629**	**−31.0%**

FEC: total final energy consumption. NC values of final energy are the envelopes of Section 5.3.7; simulated values are discussed in the text. Iran is excluded (no NC constraint).

The contribution of each step of the construction is shown in Table 5.8. The rule-based values of Sections 5.3.3–5.3.5 alone reduce 2050 emissions by 56% relative to BAU. The assessment-based values of Section 5.3.6 lower the total by a further 3,631 $MtCO_2$, partly offset by the European national values retained in place of the neutrality ceiling. The executed LEAP run reproduces the resulting constraint total almost exactly; its total is reported in CO_2-equivalent and therefore also includes the small non-CO_2 share of combustion emissions.

Table 5.8. Energy-related CO_2 in 2050 at each stage of the construction of the NC scenario (127 countries).

Stage	2050 energy-related CO_2 ($MtCO_2$)	Change vs BAU
BAU	41,646	–
Rule-based values: ambition ratio and ceilings (Sections 5.3.3–5.3.5)	18,214	−56.3%
NC constraints: with assessment-based and European national values (Sections 5.3.5–5.3.6)	15,195	−63.5%
NC scenario as simulated in LEAP	15,190	−63.5%

The constraints were checked against six criteria before and after simulation.

- **Compliance.** Modelled 2050 emissions are within ±1% of the constraint in 85 of the 127 countries, within ±2% in 103 and within ±5% in 120. Eight countries exceed their constraint by 2–8% (largest:

Togo, Chile and Gabon), and four fall more than 5% below it (Haiti, Chad, Niger and Colombia), where the provisional fuel mix already satisfied the ceiling and, as intended, no additional fossil fuel was added. The only large relative deviation is Malta, where the simulation used its originally reported value (6.7 $MtCO_2$), which was rejected in Section 5.3.4, instead of the adopted constraint of 0.5 $MtCO_2$ (Section 5.3.6), a difference equal to 0.04% of the total.

- **Monotonicity.** Of the 49 trajectories that would be U-shaped without the no-backsliding ceiling, three remain in the LEAP output (Armenia, Senegal and Togo), which together account for 0.2% of 2050 emissions. A further 30 countries rise between the target year and 2050 without a U-shape, because their pledges permit growth above 2022 emissions and no peak is implied.
- **Regional ordering.** The implied reductions preserve the broad gradient from industrialised to low-income regions (Table 5.7). The lowest value, in the Caucasus (−18%), reflects the pledges rather than the method: the contributions of Armenia and Georgia lie above their own reference case on an energy-CO_2 basis and are therefore capped at BAU (Section 5.3.3).
- **Development consistency.** In the simulated energy systems, no low-income country consumes less energy in 2050 than in 2017, and final energy in developing regions remains well above 2017 levels.
- **Robustness.** Introducing the two-bound LULUCF treatment and the stated-ratio rule changed the rule-based global total by only 0.3 percentage points while changing individual country values substantially, which shows that the aggregate result is insensitive to the principal methodological choices. The assessment-based values (Section 5.3.6) are reported separately for the same reason.
- **External benchmarks.** The NC constraints were also tested against external, pledge-based assessments: the projections for full implementation of NDCs in the UNEP Emissions Gap Report [38], the country assessments of the Climate Action Tracker [39] and the Announced Pledges Scenario of the IEA World Energy Outlook [200]. The agreement was satisfactory, taking into account the differences in gas, sector and country coverage between these assessments and the energy-related CO_2 constraints of this study.

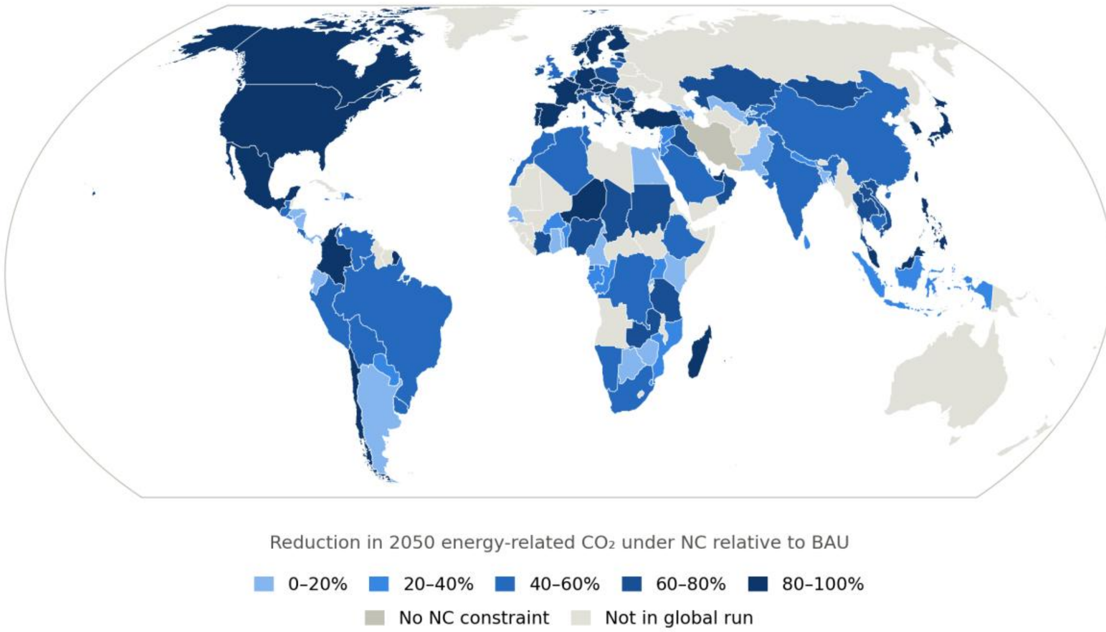


Figure 5.5. Reduction in energy-related CO_2 in 2050 under the NC constraints relative to BAU, by country. Iran is included in the BAU scenario but carries no NC constraint. Small countries and territories (for example Hong Kong, Malta, Mauritius and Singapore) are not visible at this scale.

5.6 Hefaistos: an automated route to NDC-ready information

The assessment of Section 5.3 was carried out by a team of trained coders. Repeating it for every country, and keeping it current as the third round of NDCs is submitted, exceeds what manual coding can sustain. In parallel with the scenario work, and independently of the NC scenario simulated in this report, Hefaistos was developed to extract the same variables automatically while preserving the evidence behind each one [201]. It is presented here as a complementary achievement, because it addresses the same bottleneck that the manual assessment exposed.

Automated reading of climate policy texts is an active field. Machine-learning and language-model methods can identify targets, net-zero pledges and themes in large policy corpora more exhaustively than manual review [202, 203], but they still require human intervention at several stages [204], and they have generally stopped at detecting and classifying targets rather than producing variables that models can use [183]. Hefaistos was designed to take this further step.

Hefaistos is an integration and analysis framework rather than a stand-alone text parser. Its NDC component stores one structured record per country, in JSON format, that contains the target statement, target type, planning horizon and reference or base year needed for comparative modelling. Three design choices make the records auditable:

- **Evidence fields.** Each key variable, for example a reduction percentage, an absolute emissions cap or a base year, is stored with the text snippet from which it was extracted, so every downstream value can be traced to a sentence in the source document.

- **Confidence labels.** Where the source wording allows more than one interpretation, the confidence of the record is lowered and the record is flagged for review, instead of forcing a numerical value.
- **Quality-first curation.** Records are checked against the official NDC text and revised by maintainers when the phrasing is ambiguous; the JSON records remain the operational source for corrections, provenance and reuse, and compact cross-country tables are generated from them.

A first automated extraction following the template of Table 5.2 returned records for the latest submissions of 197 Parties, most of them submitted in 2025. For users, launching an analysis in the Hefaistos interface takes three steps: selecting a country, naming the analysis and launching it. A completed run returns downloadable outputs, including a compute bundle, summaries and quality-assurance reports, which researchers can compare side by side with the official NDC and the corresponding IEA statistics to detect anomalies. The same application hosts the IEA data collector described in Section 5.2.2.

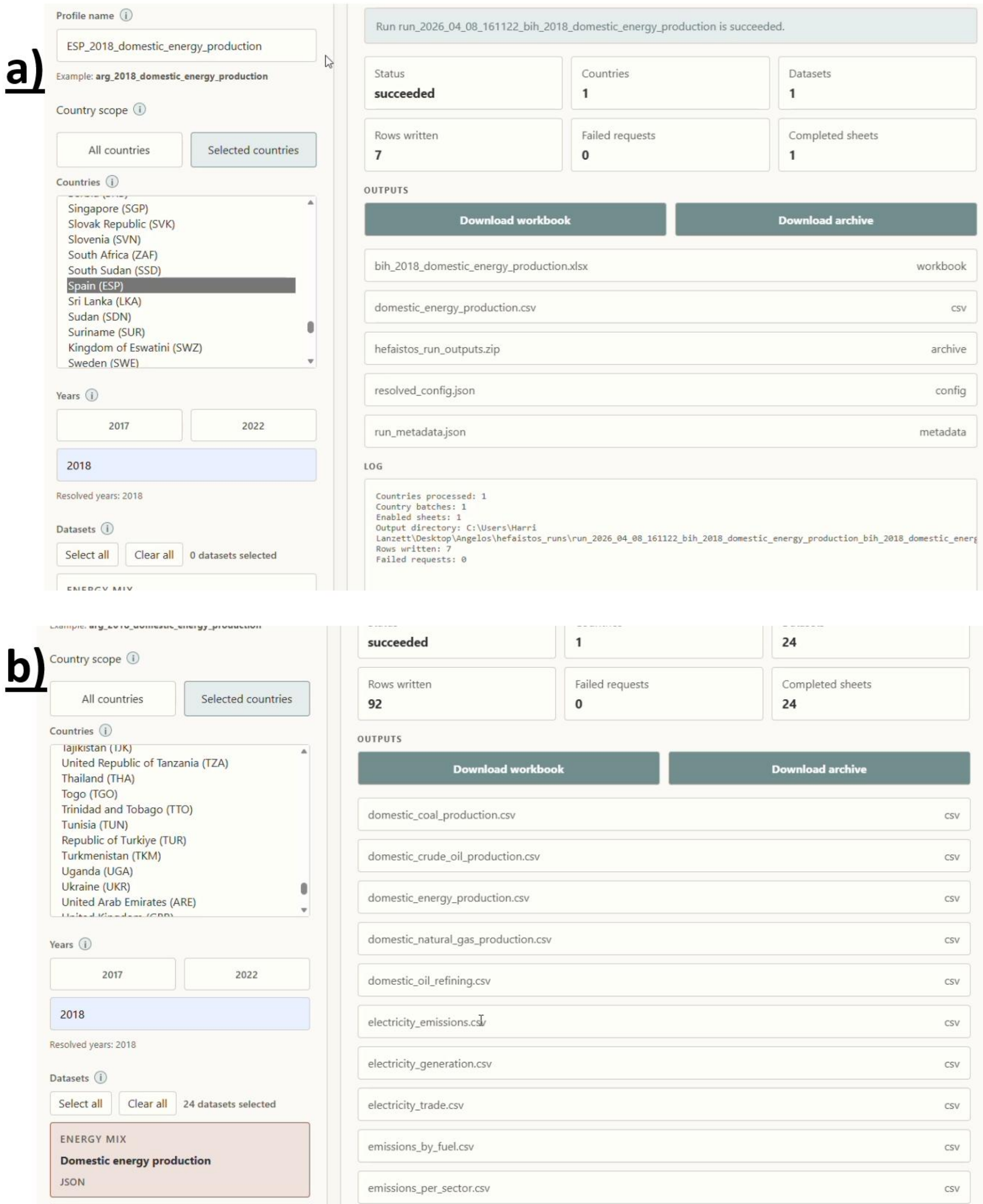


Figure 5.6. The Hefaistos interface: a) selection of a country and analysis, b) the outputs of a completed run, with the whole series of those cvs files being saved in the user's computer. These include all the information one can find in the IEA website and NDC, which are retrieved automatically on demand.

The current Hefaistos records demonstrate that the workflow functions and that evidence is handled traceably, but they are development-phase outputs and should not yet be treated as a complete global benchmark. Their value for the framework lies in the next iterations: keeping the evidence base of Section 5.3 current as new NDCs are submitted, extending it to countries not covered by the global run, and reducing the manual effort that the present scenario required.

5.7 What it took, and why it was necessary

The NC scenario could not have been built by entering national pledges into models. Assembling it required:

- coding the NDCs, long-term strategies and national plans of 128 countries against a common template, and complementing them with structured data on neutrality laws and economy-wide inventories;
- retrieving and harmonising 24 IEA datasets for 153 countries and two years, about 21,000 records, to calibrate the energy system and anchor both scenarios;
- defining the requirements that a consistent translation must satisfy, and a single decision procedure (a hierarchy of evidence, a harmonised ambition ratio and two ceilings) applied to every country;
- reading the full documentation of 18 countries whose headline commitments met the criteria for a documentary reading, and recording the effect of each reading;
- inferring energy envelopes that the commitments do not state, calibrated on European plans; and
- converting the aggregate constraints into sector-by-fuel energy systems for 96 countries, emissions caps for the economy-wide model, land-use trajectories and the drivers of water use, each checked against accounting identities.

No existing source provides these inputs. International assessments quantify pledges as aggregate emissions [38, 39, 180], national plans are not written in model units, and the global models that underpin international scenario databases do not represent the commitments of individual countries at the resolution required (Chapter 3). The resulting dataset is therefore a contribution in its own right: a transparent, reproducible translation of national commitments into model-ready inputs at global scale, in which every value can be traced to a document and every rule can be changed and re-run.

Each element of the procedure has precedent: the exclusion of LULUCF from cross-country comparisons of targets and the capping of targets that require no policy [180], constant relative ambition beyond the pledge horizon [39], and the use of conditional targets as the upper range of ambition [181]. The contribution here is their joint, documented application at country level and their translation into sector-by-fuel model inputs.

The translation also has limits that bear on the interpretation of the results. The ambition ratio is measured against a baseline reconstructed from the energy scenario and constant non-energy emissions rather than against each country's own baseline, except where a stated ratio exists. The energy-response coefficient r is calibrated on European economies with mature energy systems, and its transfer to countries whose demand doubles or triples by 2050 is an assumption. The residual share w and the post-target plateau are modelling choices, and the restriction of neutrality targets to those anchored in law or binding national policy follows the evidence on their credibility; the plateau and the restriction both lean towards understating, rather than overstating, the ambition of the NC scenario. Conditional targets are used where submissions distinguish them, which assumes that the international support on which they depend is provided. Each of these choices is exposed as a single parameter or switch that can be varied in sensitivity analysis.

With these inputs, the four models were run together under the BAU and NC scenarios as described in Chapter 4. Chapter 6 presents what the simulations show: the land, energy, emissions, water and economic consequences of implementing national commitments as they stand.

6. Results: land, energy, water and economic outcomes of national commitments

This chapter presents the results of the simulations described in Chapters 4 and 5. The four models were run as one system under the BAU and NC scenarios, and the results are presented in the order of Chapter 4: land use (Section 6.1), energy and emissions (Section 6.2), water (Section 6.3) and the economy (Section 6.4). Section 6.5 summarises the main findings across models, and Section 6.6 describes how these and further results can be explored on the GCH online platform. The figures use two kinds of comparison. Land-use, energy and water results are shown for each scenario, so the BAU and NC panels are read side by side, whereas the economic results are shown directly as differences between the NC and BAU scenarios in 2050. Some figure panels label the NC scenario “NDC”.

6.1 Land use: LandReqGCH

6.1.1 Historical land use and validation

The pre-processing of HILDA+ produced country-level datasets of annual land-use states, transition matrices in areas and in percentages, and pooled matrices for the three temporal windows of Section 4.2.2 [119, 120]. Global maps of the historical land-use states and of the main transition hotspots (Figure 6.1) provide a visual check of the input data and support the comparative analysis and validation of the projections.

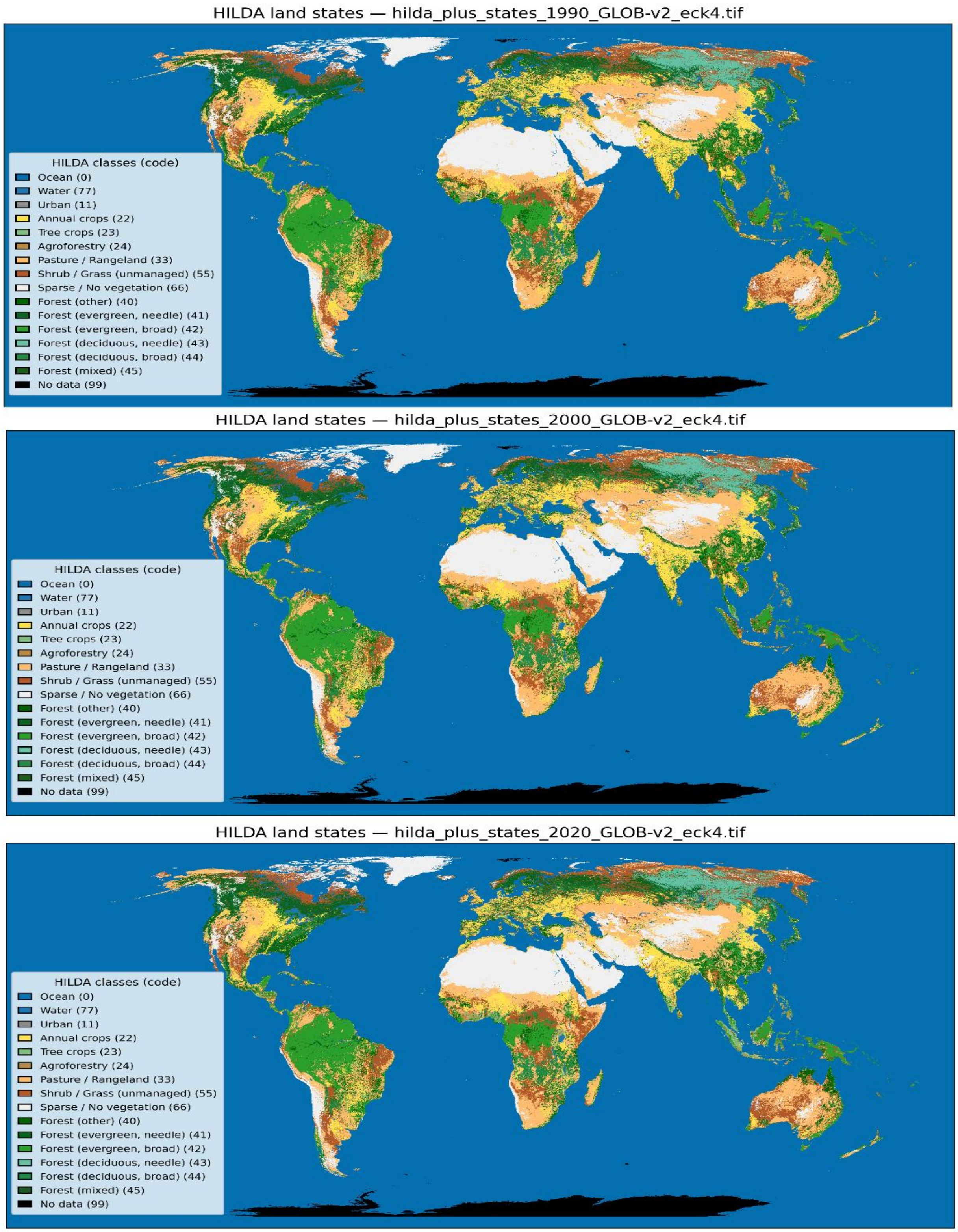


Figure 6.1. Global land-use states in 1990, 2000 and 2020 from HILDA+ version 2.0, by HILDA+ class [119, 120].

The time-varying Markov model generated projections to 2050 for 229 of the 234 states of the HILDA+ record (98%). The five states for which projections failed lack sufficient HILDA+ coverage and are mainly uninhabited islands, such as South Georgia and the South Sandwich Islands and the British Indian Ocean Territory. For a fully automated global analysis, this is a high success rate. The windows selected by the hindcast validation of Section 4.2.4 (Figure 6.2) reflect the adaptive behaviour of the algorithm:

- **Recent window (2010–2020):** 105 states (46%), predominantly stable, high-income countries with consistent land-use trends;
- **Medium window (2000–2020):** 7 states (3%), intermediate cases with recent volatility but stable longer-term trends;
- **Long window (1990–2020):** 116 states (51%), typically developing countries with long-term structural transitions, such as forest transitions and urbanisation, or large developed countries whose land-use policies have changed recently.

This distribution is consistent with the expectation that recent trends predict the future best in stable settings, while longer averages smooth out volatility where land use is changing rapidly. For the states using the recent window, hindcast errors were generally low, with median errors of 6.8% for cropland, 3.2% for forests and 4.1% for urban land. States that fell back to the medium or long window showed higher but still acceptable errors (median about 14%).

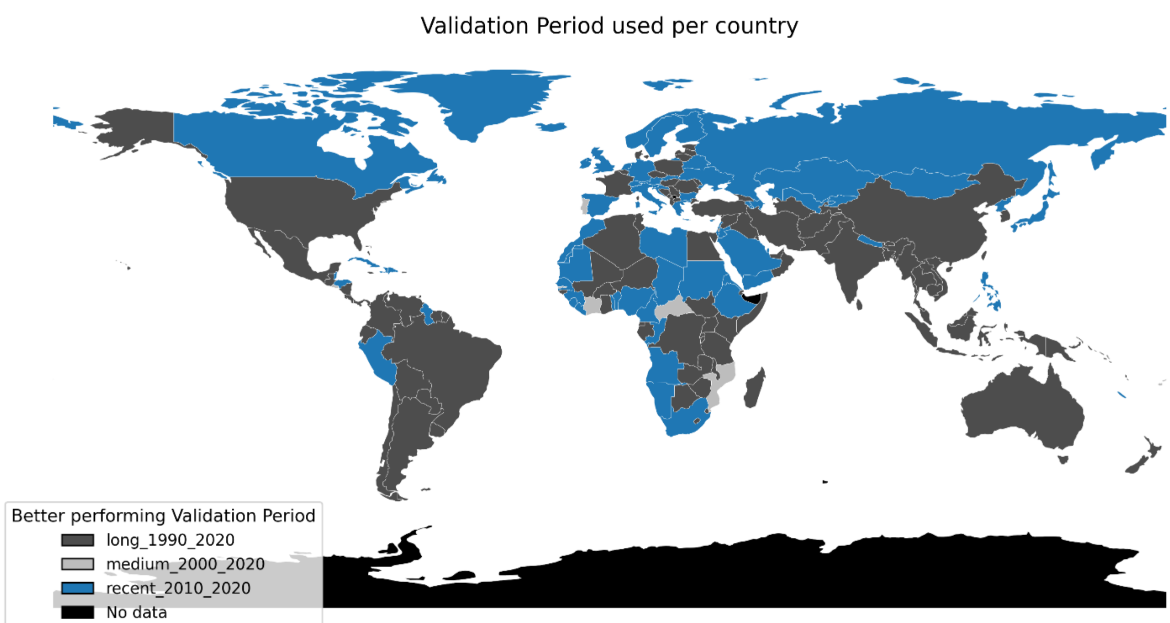


Figure 6.2. Validation window selected for each state by the hindcast test of Section 4.2.4 (recent: 2010–2020; medium: 2000–2020; long: 1990–2020).

6.1.2 Land use under BAU

Aggregated over all states, the BAU projections (Figure 6.3) are consistent with independent assessments. Between 2020 and 2050, cropland expands slightly (+0.7%, about 111,000 km²), in line with FAO projections in which agricultural intensification offsets most of the growth in demand driven by population [205], while tree crops grow rapidly (+32.3%, about 554,000 km²), reflecting documented trends in oil palm (Indonesia, Malaysia and West Africa), coffee, cocoa and fruit plantations. Forest area continues to decline (−2.2%, about 897,000 km²), consistent with baseline scenarios in which persistent tropical deforestation is only partly offset by reforestation in temperate regions [64, 109]. Urban land expands by 16.6%, consistent with the projected increase in the urban share of the world population from 55% in 2018 to 68% in 2050 [206].

Figure 6.3. Global land use in the BAU scenario, 2020–2050: absolute (km²) and relative (%) change in area by class, global areas in 2020 and 2050, and land-use composition in both years.

The projections also reproduce trends already observed in major regions. In the United States, cropland consolidation (−9%) is paired with forest expansion (+1.9%), reflecting agricultural intensification and natural reforestation on abandoned farmland, while cropland and forest in Canada change little (−0.4% and −0.3%). In China, a large expansion of tree crops (+65.5%) and a modest forest increase (+5.3%) capture the ongoing Grain for Green Program, which converts marginal cropland to orchards and timber plantations. In India, cropland contraction (−6.5%) alongside forest growth (+13.1%) reflects reforestation policies and urban expansion onto agricultural land, although cropland may persist under intensification. In Brazil, cropland (+11.9%) and grassland (+3.9%) expand while forest declines (−3.9%), the pattern of the "arc of deforestation" in the Amazon and the Cerrado, driven by soy and beef production for global markets. Sub-Saharan Africa shows heterogeneous patterns, with rapid cropland expansion in the Sahel (Niger +29.5%, Mali +16.9%) and continued forest loss in the Congo Basin (−14.3% in the Democratic Republic of the Congo).

The uncertainty analysis of Section 4.2.7 provides, for each state, land-use class and year, the 10th percentile (P10, lower bound), the median (P50), the mean and the 90th percentile (P90, upper bound) of the projections.

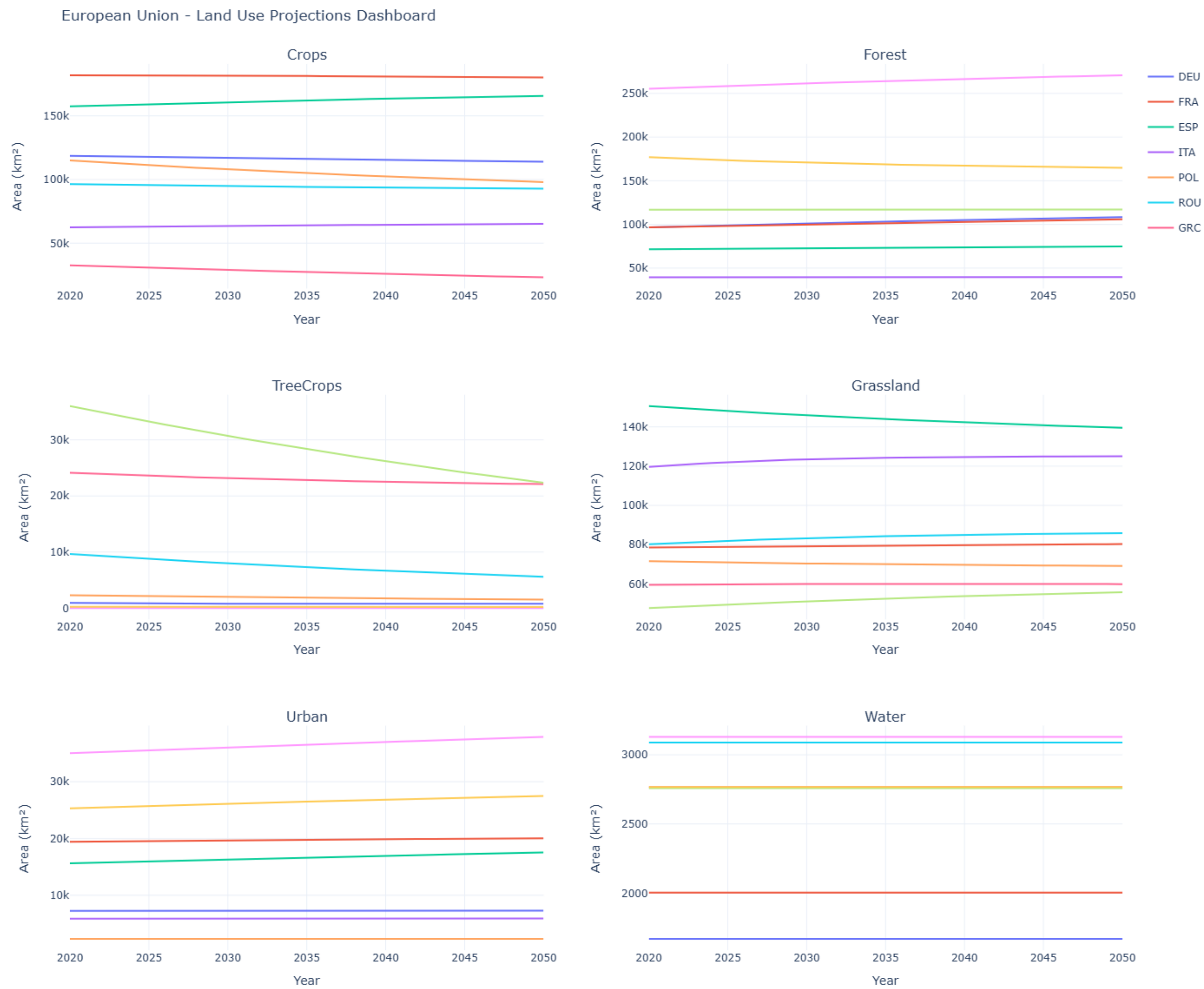


Figure 6.4. BAU land-use projections to 2050 for a subset of European Union countries, by class (indicative extract).

As Figure 6.4 shows for a subset of European countries, forest area is broadly stable or growing in most countries, with small declines in a few. Cropland changes only slightly, with a modest increase in Spain and small declines in several others, such as Poland, Romania and Greece. Tree crops decline in most countries, whereas urban area expands steadily everywhere. Inland water remains essentially constant, and grassland shows mixed changes, with small declines in some countries and slight increases in others.

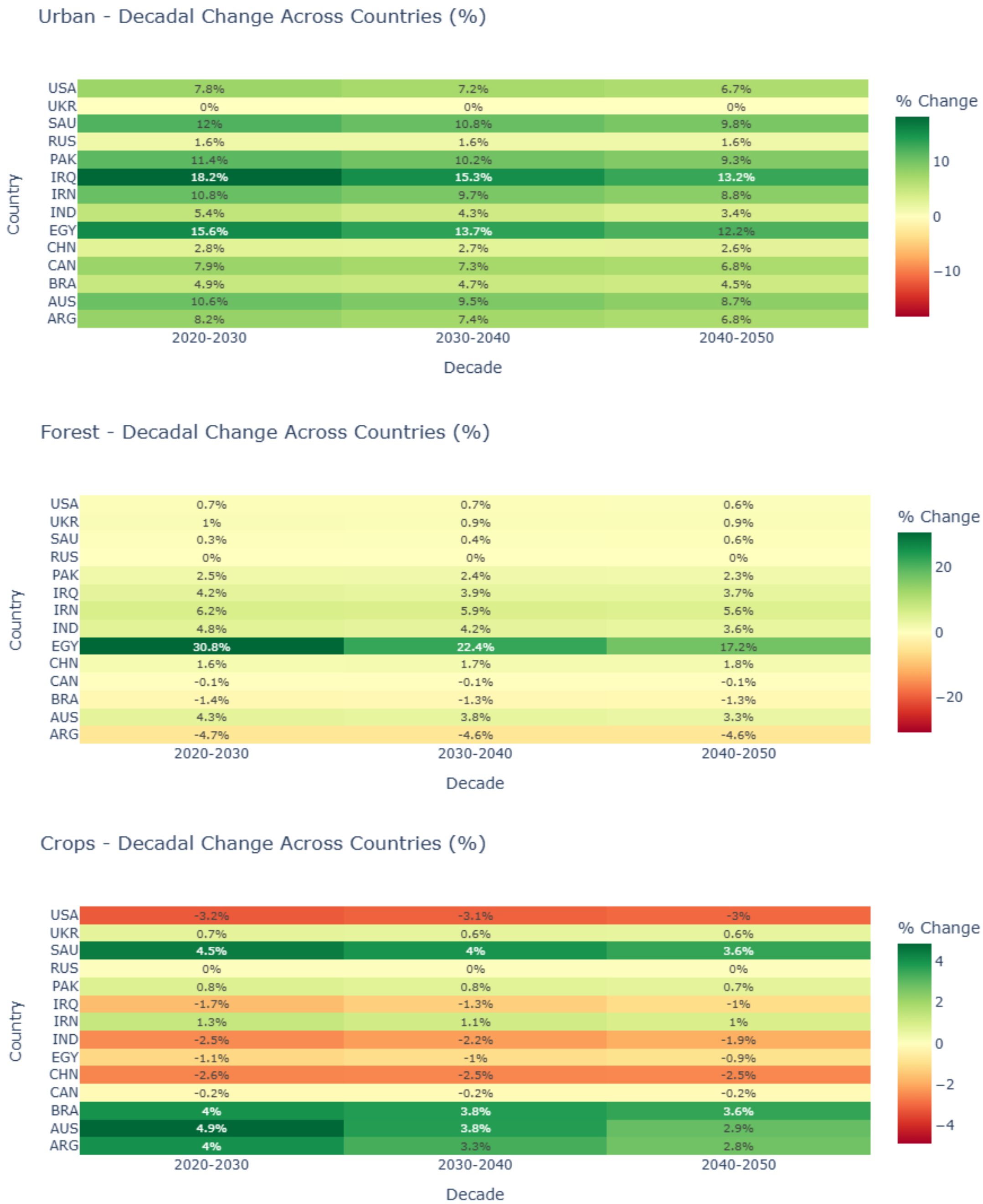


Figure 6.5. Decadal change (%) in urban, forest and cropland area, 2020–2050, in countries with strong variations (BAU).

Urban land expands or remains stable in all of the countries of Figure 6.5, with the fastest growth in Iraq and Egypt, followed by Saudi Arabia, Pakistan and Iran. This widespread increase points to continued urbanisation and population growth, with implications for infrastructure planning, resource use and environmental management. Forest cover increases in most of these countries, most strongly in relative terms in Egypt, where it starts from a very small area, whereas it declines in Argentina, Brazil and, marginally, Canada, raising concerns about deforestation and the loss of ecosystem services in forest-rich countries. These projections reflect the balance between reforestation and the pressure of agricultural expansion. Cropland shows mixed trends: the largest decreases occur in the United States, China and India, and the largest gains in Australia, Saudi Arabia, Brazil and Argentina, reflecting shifts in agricultural productivity and land management.

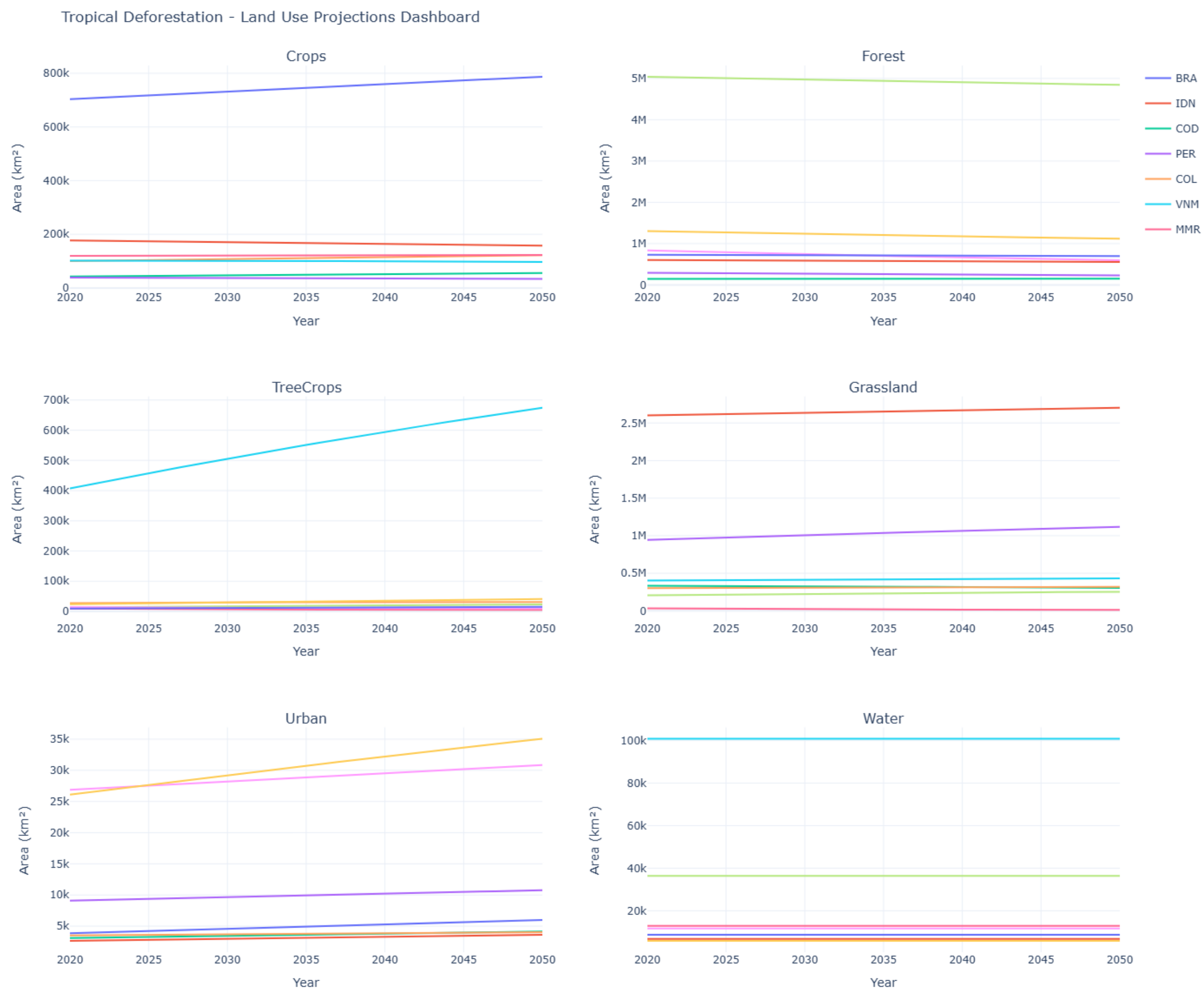


Figure 6.6. BAU land-use projections to 2050 for major tropical deforestation areas, by class (indicative extract).

In the main tropical forest countries (Figure 6.6), forest area continues to decline to 2050. Cropland and tree-crop plantations expand markedly, with a clear increase in cropland in Brazil, while grassland and urban areas generally grow as well, which indicates the conversion of natural land to agriculture and settlements. Inland water remains broadly stable compared with the large shifts in forest and agricultural land.

6.1.3 Land use under NC

The NC scenario behaves like an afforestation pathway with mixed policy effects, in which reforestation commitments are combined with demand for crops that can be used for bioenergy (Section 4.2.6).

Between 2026, when the commitments are phased in, and 2050, forest area increases by about 1.5 million km² (+3.7%), reversing the loss projected under BAU, while cropland (+2.8%) and tree crops (+29.5%) also expand. The land is released mainly by grassland (−1.7%) and other land (−7.1%), and urban growth continues (+11.9%). In 2050, the global areas reach about 15.50 million km² of cropland, 2.36 million km² of tree crops, 41.80 million km² of forest and 47.66 million km² of grassland and pastures (Figure 6.7). The outcome is intermediate: cropland and tree crops remain moderately above those of a diet-shift pathway of the EAT–Lancet type, in which lower consumption of animal products frees land for a larger expansion of forests [147].

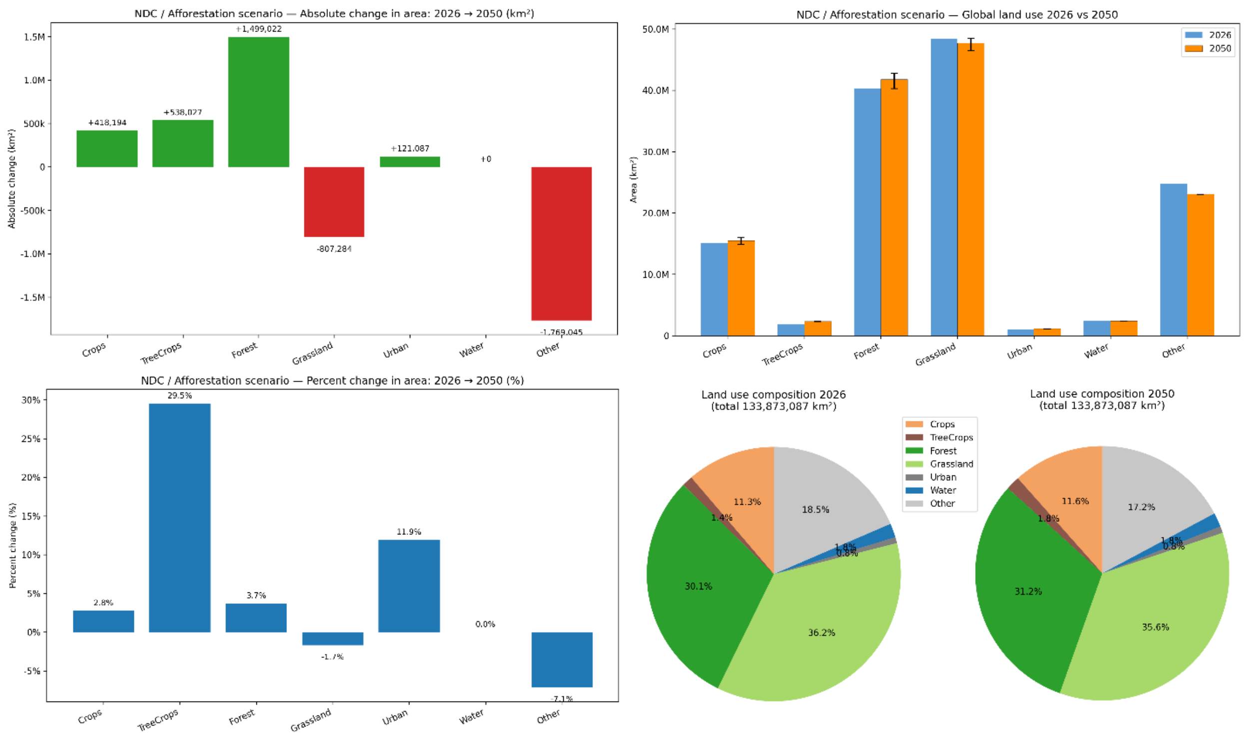


Figure 6.7. Global land use in the NC scenario, 2026–2050: absolute (km²) and relative (%) change in area by class, global areas in 2026 and 2050 (with uncertainty ranges), and land-use composition in both years.

6.2 Energy and emissions: LEAP

6.2.1 Final energy consumption and emissions

The LEAP maps show, for each country, the growth of a quantity between 2025 and 2050 within each scenario, computed as 100 × (value in 2050 / value in 2025 − 1). They do not show differences between the scenarios: the BAU and NC maps share a colour scale and are read side by side. Red denotes a decline and blue an increase; values beyond the ends of the scale are shown with the end colour, while the underlying data remain uncapped. Emissions are the total GHG emissions of the energy system, in CO_2-equivalent.

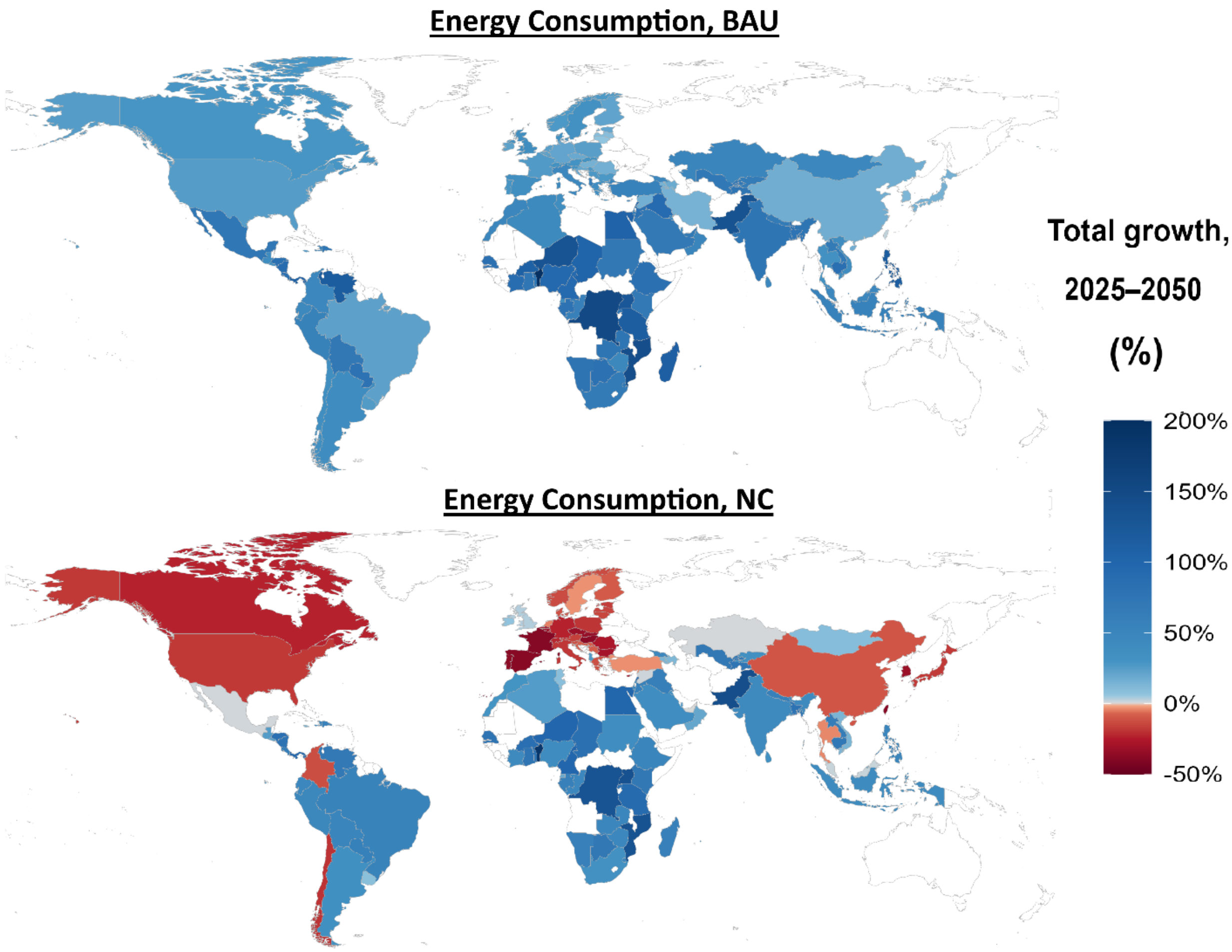


Figure 6.8. Growth of total final energy consumption between 2025 and 2050 under the BAU (top) and NC (bottom) scenarios (%).

Under BAU, final energy consumption grows in almost every country between 2025 and 2050 (Figure 6.8). Growth is moderate in the mature energy systems of North America, Europe and China, and fastest in sub-Saharan Africa, Pakistan and parts of South and Southeast Asia, where it exceeds 100% in many countries. Under NC, the picture divides. Consumption falls in 40 of the 127 countries with a constraint: in the United States and Canada (−18% for North America), in most of Europe (−21% overall, and close to −40% in France and Spain), in China, Japan, the Republic of Korea and Taiwan, and in Chile and Colombia. It continues to grow in the other 87 countries, mostly developing economies in Africa, South Asia, the Middle East, Southeast Asia and Latin America, in most cases by less than under BAU. In total, NC final energy consumption in 2050 is 9,058 Mtoe, 4% above 2025 and about 28% below BAU. The commitments therefore bend demand downwards in the industrialised economies while developing economies continue to expand their energy use, as intended by the construction of the energy envelopes (Section 5.3.7).

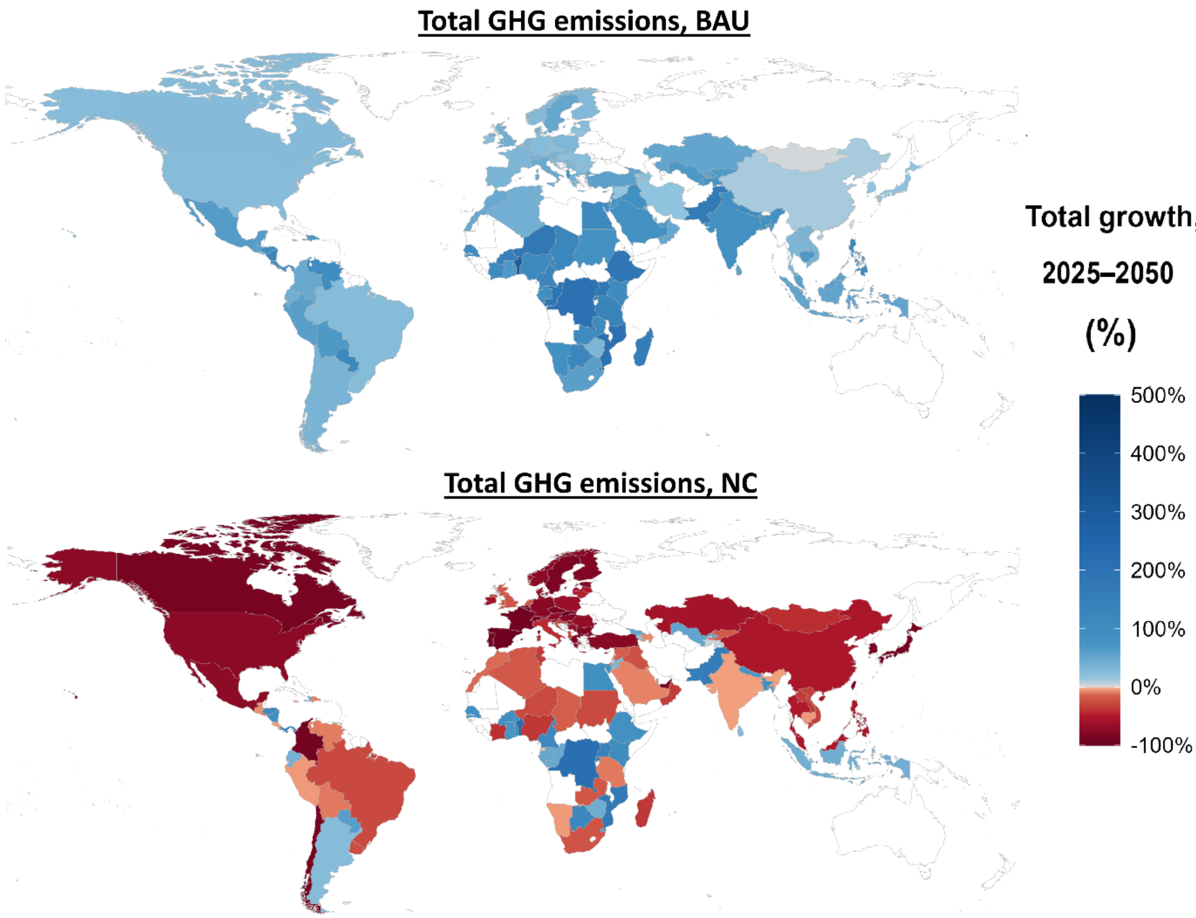


Figure 6.9. Growth of total GHG emissions of the energy system between 2025 and 2050 under the BAU (top) and NC (bottom) scenarios (%).

Under BAU, energy-system emissions rise between 2025 and 2050 in almost all countries, most steeply in sub-Saharan Africa and South Asia (Figure 6.9). Under NC, they decline in 89 of the 127 countries with a constraint, and total emissions fall from 27,983 $MtCO_2e$ in 2025 to 15,190 $MtCO_2e$ in 2050 (−46%), 64% below BAU. Emissions in Europe fall by 65% overall. The deepest reductions, of 80–95% relative to 2025, occur in 13 European countries, including France, Spain and Sweden, and in Canada, Japan, the Republic of Korea, Taiwan, Chile, Colombia and the United Arab Emirates; emissions fall by about three quarters in the United States, Mexico and Germany and by more than half in China. Emissions still grow in the remaining countries, mostly developing economies in sub-Saharan Africa, South Asia and Central America, together with countries such as Indonesia, Egypt and Argentina, whose commitments allow growth from a low base.

6.2.2 Energy transformation

Figures 6.10–6.13 show, by continent, the growth between 2025 and 2050 of four transformation activities: oil refining, fossil electricity generation, renewable electricity generation (solar, onshore and offshore wind, hydropower, geothermal energy, and biomass and waste; nuclear power and pumped storage are excluded) and green hydrogen production. All heatmaps share a scale from −100% to +500%. White denotes a calculated growth of zero, grey denotes that no growth rate can be calculated because there is no activity, no data or the category does not apply, and “NEW” marks an activity that is absent in 2025 but present in 2050.

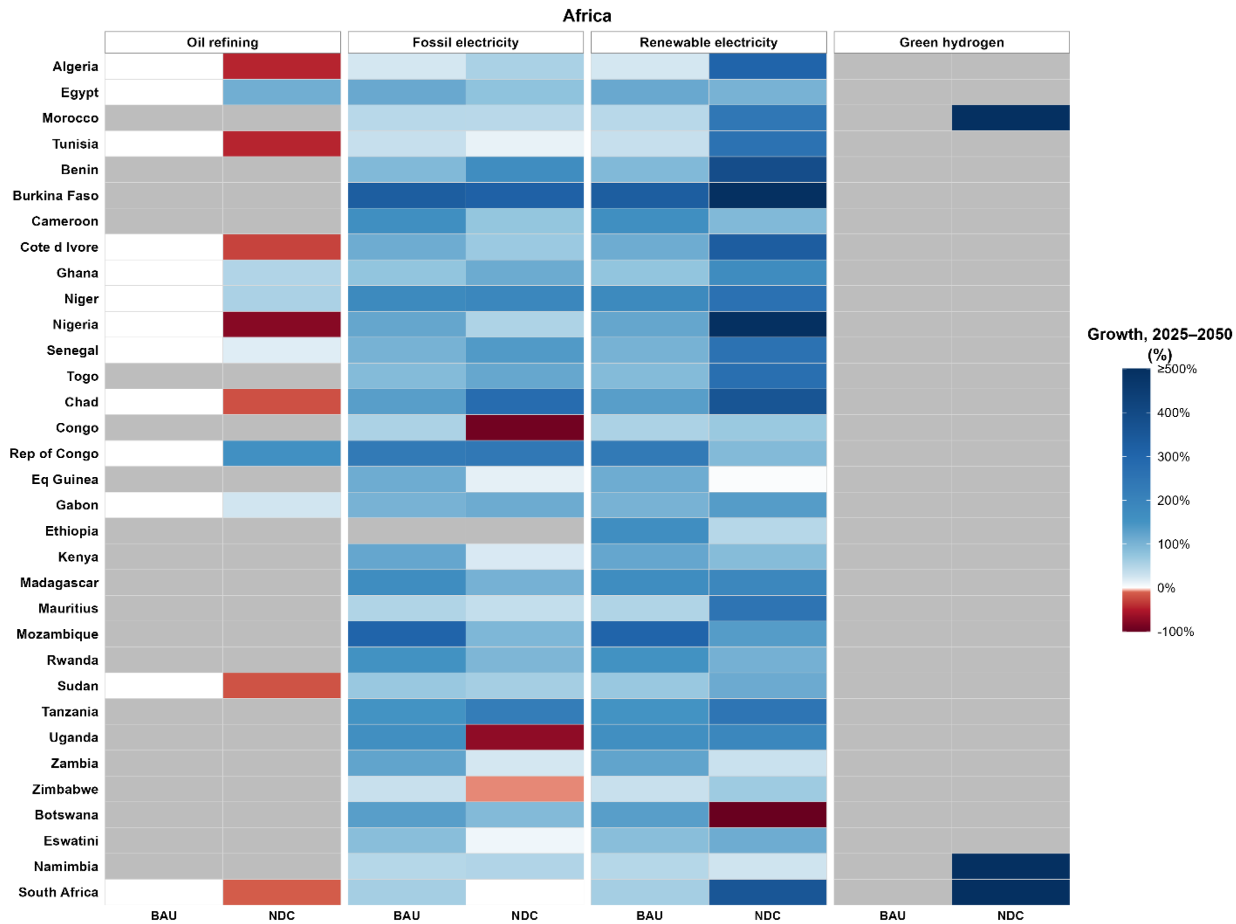


Figure 6.10. Growth (%) of oil refining, fossil and renewable electricity generation and green hydrogen production between 2025 and 2050 under the BAU and NC (labelled NDC) scenarios: Africa.

The BAU columns show little structural change. Refining activity remains at its 2025 level, and fossil and renewable electricity generation grow at the same rate in each country, so the generation mix of 2025 is carried forward. The NC columns show the transformation implied by the commitments. Oil refining declines in 63 of the 86 countries with refining activity in 2025, falling close to zero in much of Europe, in North America, Japan and the Republic of Korea, and in Kazakhstan, Türkiye and the United Arab Emirates; it grows in 22 countries, mostly in Africa, South Asia and Latin America, where final demand for oil products continues to grow.

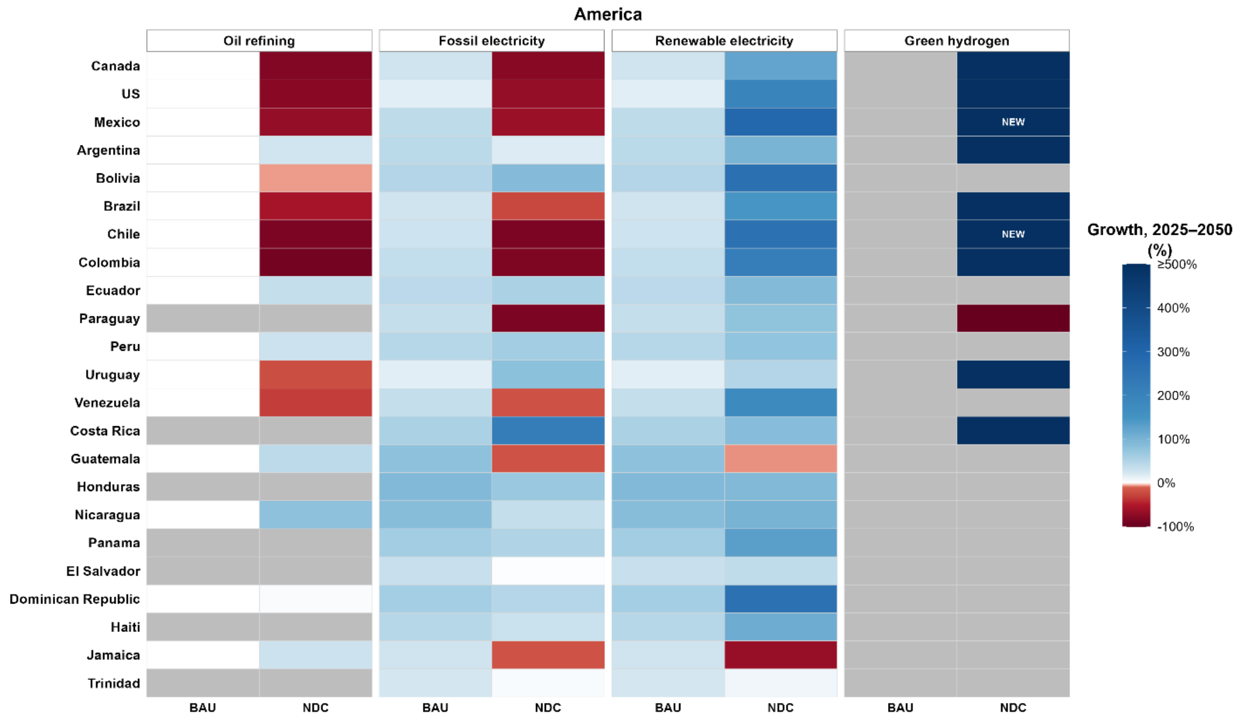


Figure 6.11. Growth (%) of oil refining, fossil and renewable electricity generation and green hydrogen production between 2025 and 2050 under the BAU and NC (labelled NDC) scenarios: America.

Fossil electricity generation falls steeply in Europe, North America, East Asia and parts of Latin America and the Middle East, while it still grows in many developing countries. Renewable electricity expands in almost every country, often by more than 200% and in several countries by 500% or more.

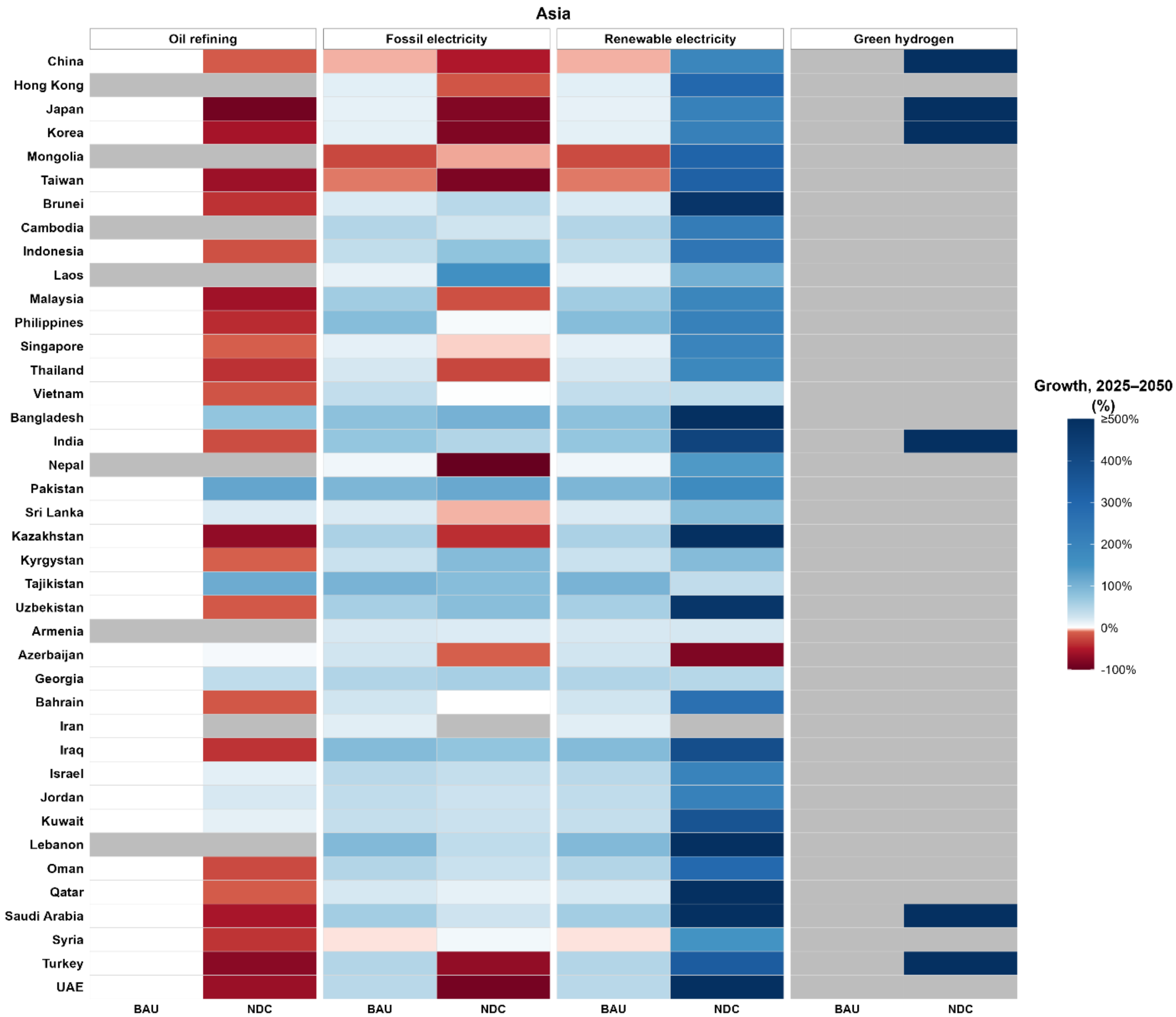


Figure 6.12. Growth (%) of oil refining, fossil and renewable electricity generation and green hydrogen production between 2025 and 2050 under the BAU and NC (labelled NDC) scenarios: Asia.

Green hydrogen is produced in 2050 in 44 countries: in 26 European countries, in most of which it is new, and in 18 countries elsewhere with a hydrogen policy, strategy or industrial basis, including the United States, Canada, Mexico, Brazil, Chile, China, Japan, the Republic of Korea, India, Saudi Arabia, Türkiye, Morocco, Namibia and South Africa (Section 5.4.1).

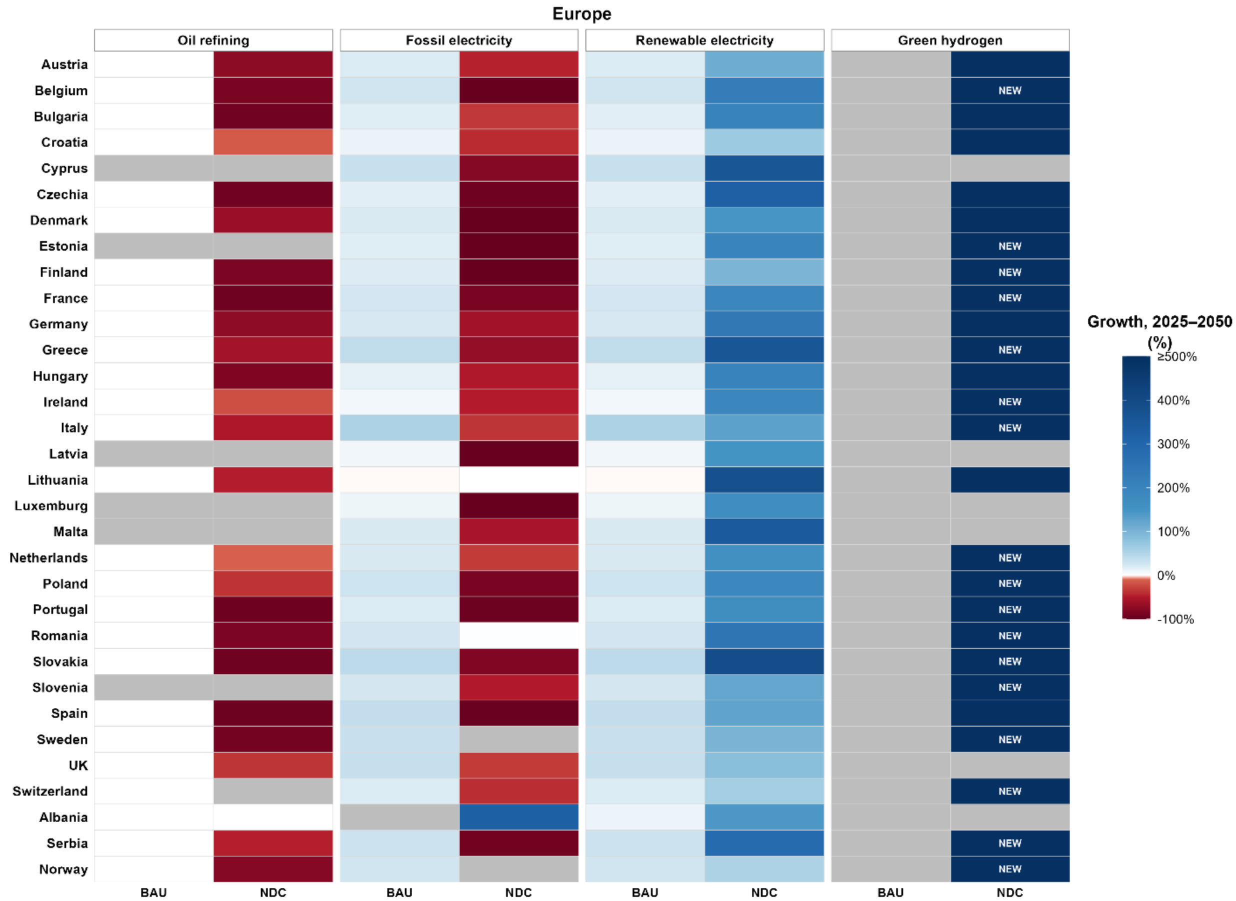


Figure 6.13. Growth (%) of oil refining, fossil and renewable electricity generation and green hydrogen production between 2025 and 2050 under the BAU and NC (labelled NDC) scenarios: Europe.

6.3 Water: WaterReqGCH

6.3.1 Water under BAU

Under BAU in 2050, renewable blue water availability (Figure 6.14a), shown on a logarithmic scale that spans deserts and rainforests, follows the climatic gradient. It is lowest across the dry belt that extends from North Africa and the Middle East to Central Asia, and in southern Africa, the Atacama and interior Australia, and highest in the humid tropics, including the Amazon and Congo basins and Southeast Asia. Withdrawals (Figure 6.14b) follow a different pattern. They are concentrated where population, irrigated agriculture and industry are concentrated, with hotspots in India, China, the United States, Europe, the Middle East and North Africa, and they are low across most of South America and Central Africa.

Water stress (Figure 6.14c) combines the two. It is high to extremely high in the Middle East (including Saudi Arabia, Iraq and Iran), in North Africa (the Nile valley and the Mediterranean coast), in Pakistan, Afghanistan and parts of India, in the south-western United States and northern Mexico, in northern China, in Spain and other parts of the Mediterranean, in South Africa and in the agricultural regions of south-eastern Australia. Stress is low where abundant water meets low demand, as in the Amazon and Congo basins, northern Canada and Alaska, Scandinavia, Siberia and the high-rainfall parts of Southeast

Asia, and medium in transition zones such as eastern China, parts of Europe and the agricultural regions of the United States.

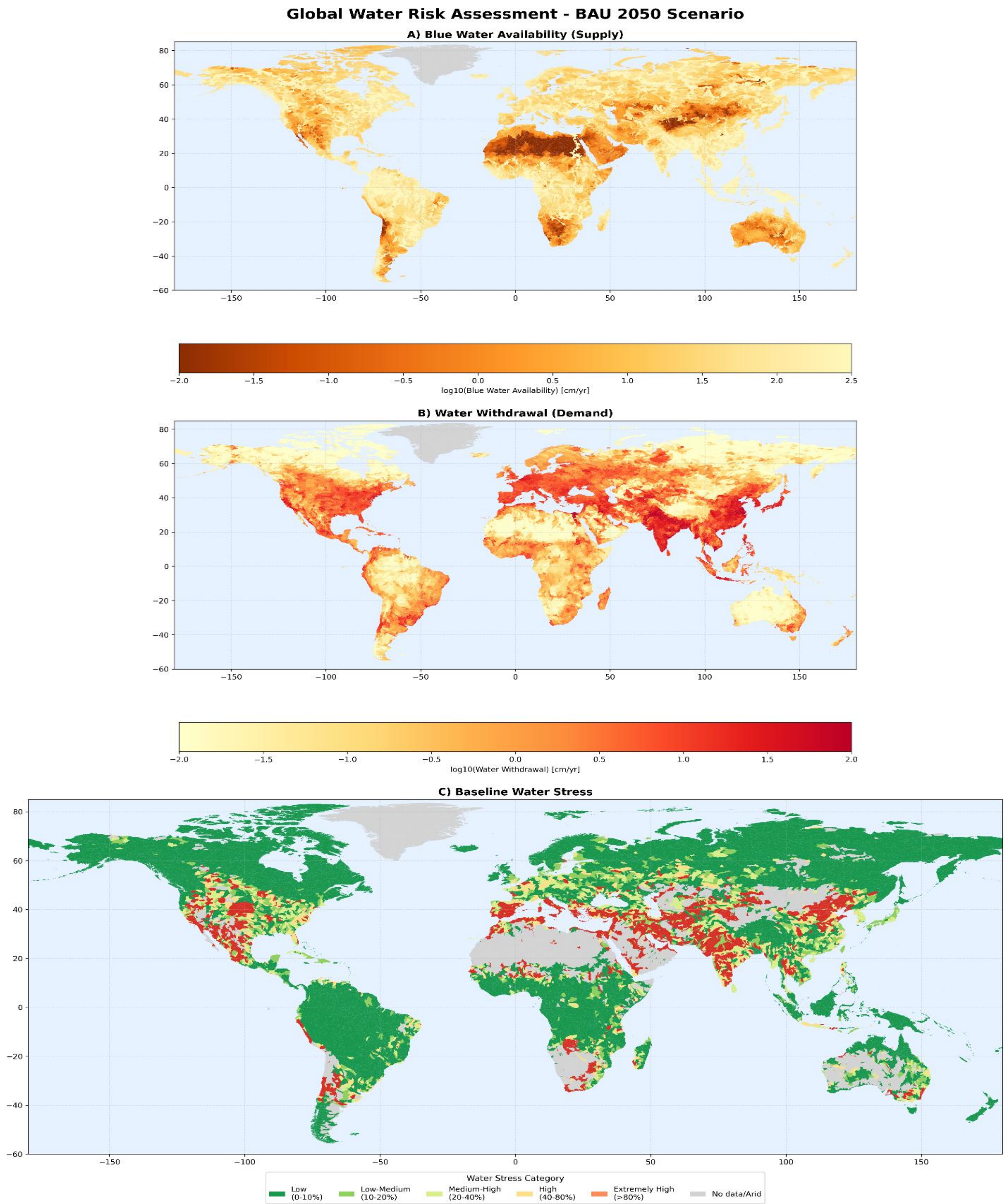


Figure 6.14. Water risk under the BAU scenario in 2050, by sub-basin: (a) blue water availability, (b) water withdrawals and (c) baseline water stress.

6.3.2 Water under NC

No national commitment sets quantified water-use targets (Section 5.4.4), so water use in the NC scenario differs from BAU only through its drivers. Dietary choices and land-use policies determine the area of land needed, or allowed, for food, feed, fibre and forest, and every land-use class carries a different water demand: a hectare of irrigated cropland draws far more from rivers and aquifers than a hectare of pasture, forest or restored land, so replacing one with another changes withdrawals even when the total land area is unchanged (Section 4.4.2). The NC land-use trajectories of Section 6.1.3 and the NC sectoral output of GTAP-E (Section 6.4) were therefore translated into annual withdrawals, combining the HILDA+ land-cover dynamics with country-calibrated water-use intensities derived from Aqueduct 4.0, FAO AQUASTAT and water-footprint data [124, 171, 172].

Renewable supply is the same in both scenarios, so the differences between Figures 6.14 and 6.15 arise from withdrawals. In 2050, withdrawals under NC are lower than under BAU in most demand hotspots, including India, eastern China and the United States, and broadly unchanged in Europe. Two effects pull in opposite directions: the expansion of cropland and tree crops adds irrigation demand, while the contraction of grassland reduces livestock withdrawals and the lower output growth of fossil energy industries and electricity (Section 6.4) reduces industrial and energy-sector withdrawals. The reductions are modest relative to the gap between demand and supply in the most stressed basins, so the hotspots of Figure 6.14 remain highly or extremely stressed. The water consequences of national commitments are thus side effects of energy and land decisions that are planned without reference to water.

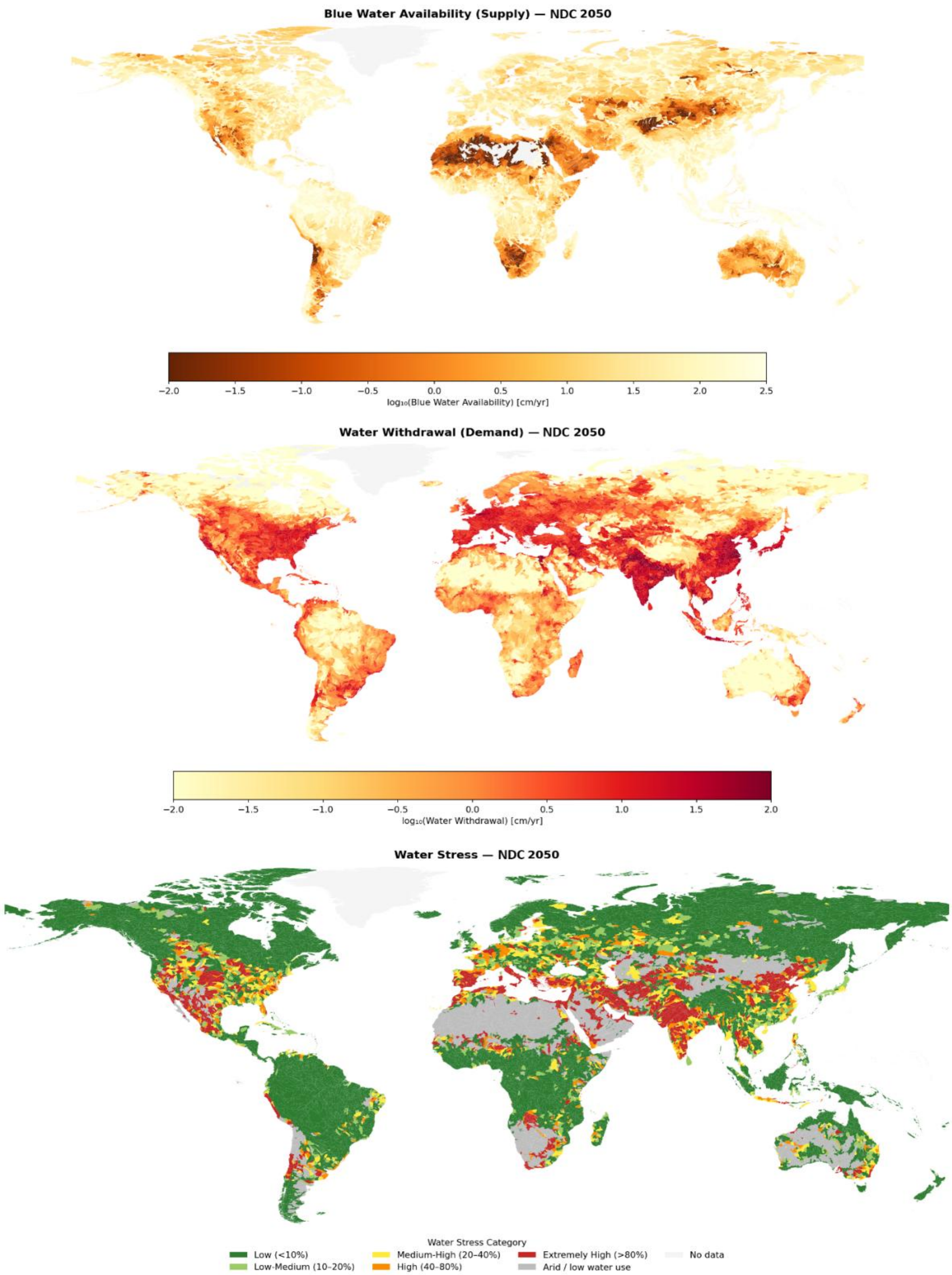


Figure 6.15. Blue water availability, water withdrawals and water stress in 2050 under the NC scenario (labelled NDC), by sub-basin. Supply is identical to Figure 6.14; the colour ramp of the withdrawal map extends to darker shades than in Figure 6.14, so values should be compared using the colour bars.

6.4 Economy: GTAP-E

The economic results are shown as differences between the NC and BAU scenarios in 2050, which share the same SSP2 socio-economic drivers. Sectoral output (QO), sectoral labour demand (QFE) and welfare, measured by the equivalent variation (EV), are defined in Section 4.5. For QO and QFE, the maps show the difference between the two scenarios in cumulative growth from the common 2017 base year to 2050, in percentage points, for the eight non-agricultural sectors of Table 4.7. A negative value means weaker growth under NC than under BAU, not necessarily a fall below the 2017 level. Each variable uses one colour scale for all sectors, capped at about ±150 percentage points for QO and ±200 percentage points for QFE (the 95th percentile of absolute values); values beyond the cap keep their true magnitude in the data. The welfare map expresses the difference in EV as a percentage of each country's BAU GDP in 2050. In all maps, red denotes a lower and blue a higher outcome under NC, and white denotes countries without GTAP data.

6.4.1 Sectoral output

Output growth of fossil energy industries is lower under NC than under BAU in almost every country (Figure 6.16), the direct effect of the emissions caps and of the carbon price that enforces them (Section 5.4.2). Electricity output growth is also lower in most large economies, including the United States, China, India and much of Europe, but higher in some countries, such as Canada and several African economies. The results for energy-intensive industries are mixed: output growth is lower in several large economies, such as Brazil and India, and higher in others, including Canada and some economies of the Middle East, Central Asia and Africa, a pattern consistent with a partial relocation of energy-intensive production towards countries where the caps bind less. Terrestrial transport grows less in most countries, whereas water and air transport show mixed patterns, and the output growth of other industries and services differs little between the scenarios.

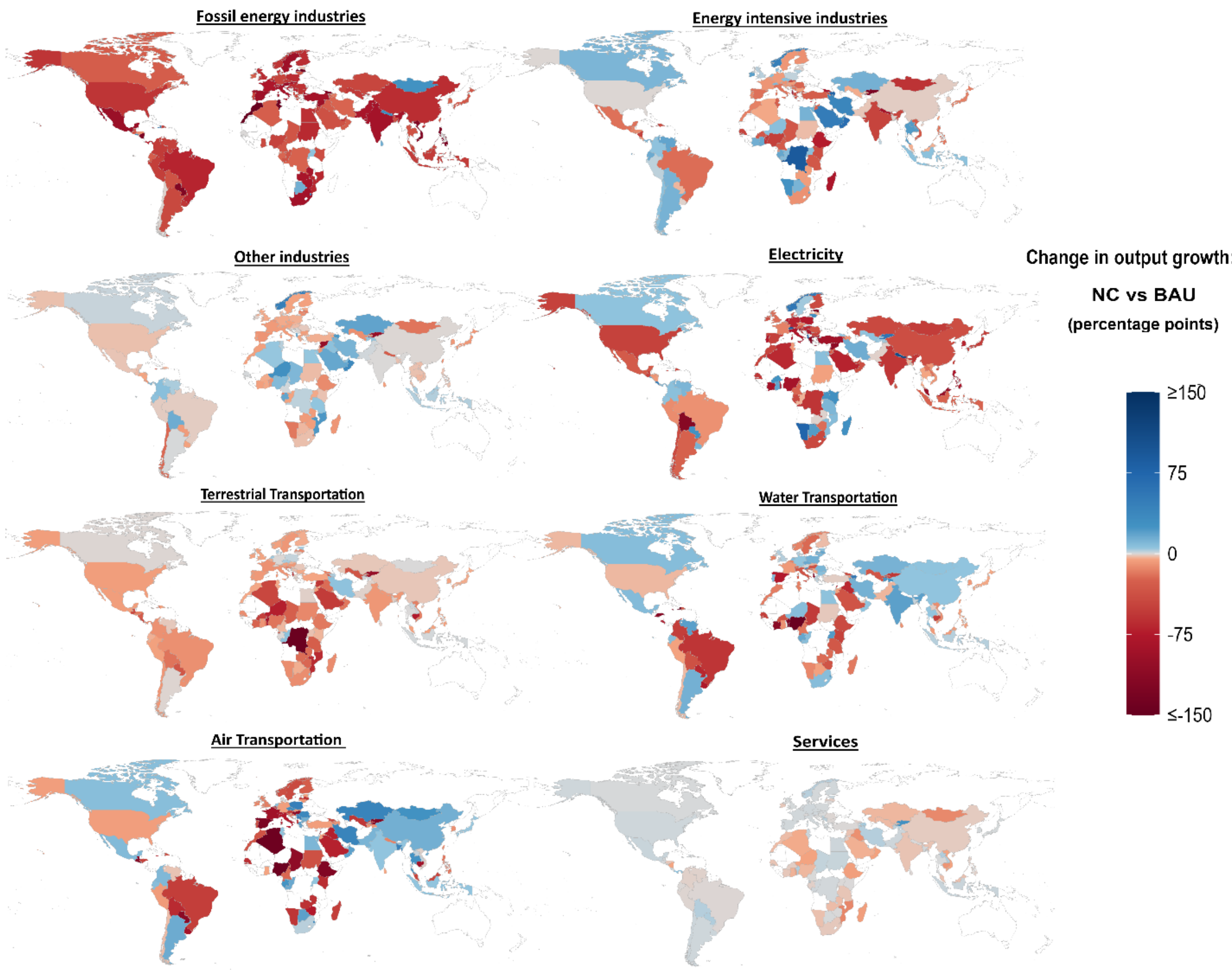


Figure 6.16. Difference in sectoral output growth (QO) between the NC and BAU scenarios, 2017–2050, by sector (percentage points).

6.4.2 Sectoral labour demand

Labour demand shows a clear reallocation (Figure 6.17). Labour demand in fossil energy industries grows less under NC in almost every country, in line with their lower output, whereas it grows more in electricity, energy-intensive industries and the three transport sectors in most countries, and slightly less in services. In several sectors, such as electricity and transport, labour demand rises under NC even where output grows less, which is consistent with the substitution of primary factors for energy inputs that the carbon price makes more expensive. Because the simulations use a full-employment closure, these differences describe the reallocation of a fixed labour force across sectors rather than net job creation or loss (Section 4.5).

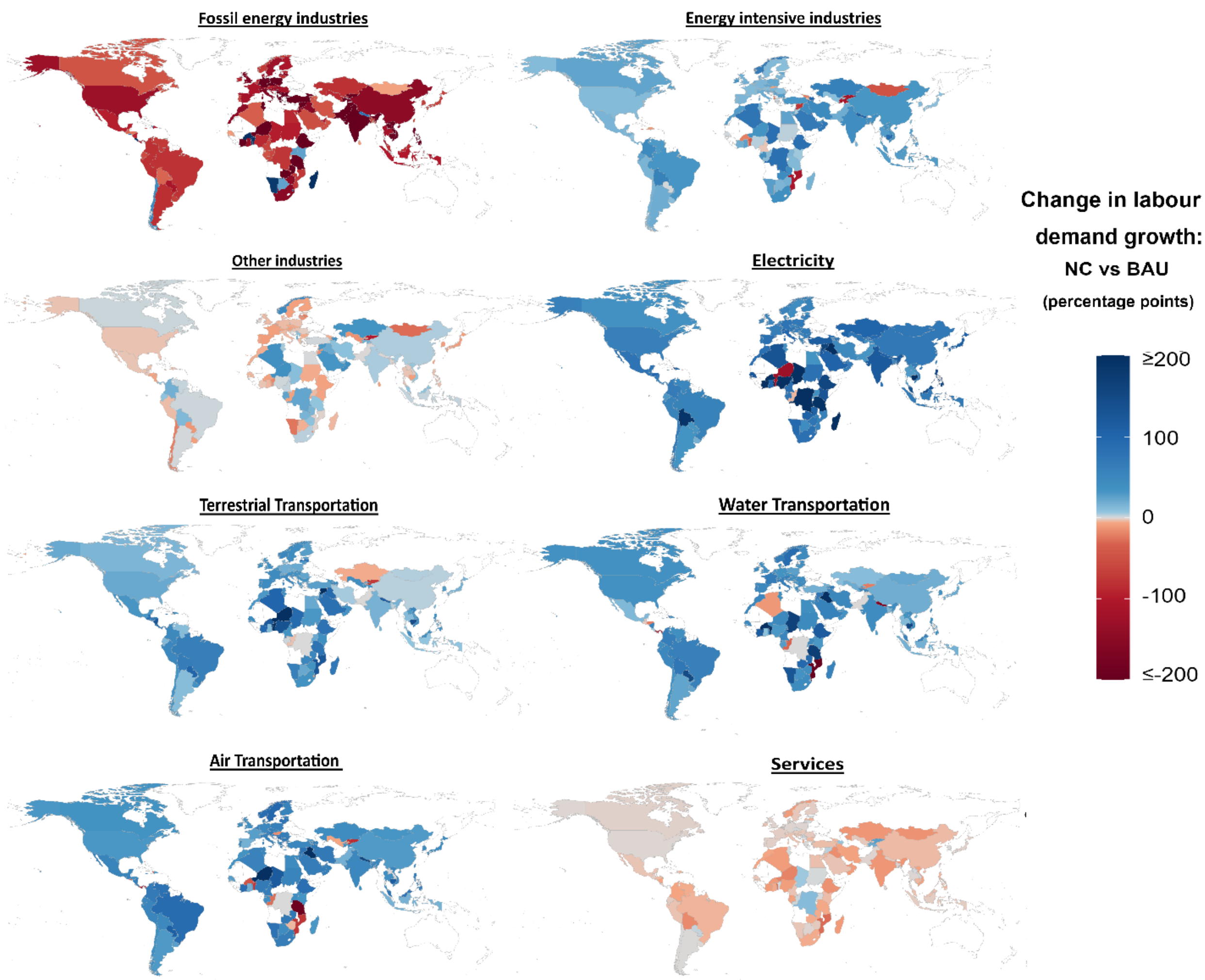


Figure 6.17. Difference in sectoral labour-demand growth (QFE) between the NC and BAU scenarios, 2017–2050, by sector (percentage points).

6.4.3 Welfare

Welfare effects range from losses to gains of several percent of BAU GDP and differ in sign across countries (Figure 6.18). The largest losses occur in fossil fuel exporters, including Saudi Arabia, Iraq, Iran, Oman, Algeria, Kazakhstan, Norway, Canada, Venezuela, Colombia, Bolivia, Nigeria and Gabon, and smaller losses in Indonesia and Malaysia, consistent with lower international demand and prices for fossil fuels, which reduce export revenues and worsen the terms of trade of producers. Most fossil fuel importers gain, including most European countries, Japan, the Republic of Korea, China and the United States, as well as Morocco, South Africa and much of East Africa, while the differences for India, Brazil and Mexico are close to zero. EV captures only the economic adjustment to the emissions caps. It does not include the avoided damages of climate change or co-benefits such as cleaner air, so it is not a measure of the net benefits of the commitments.

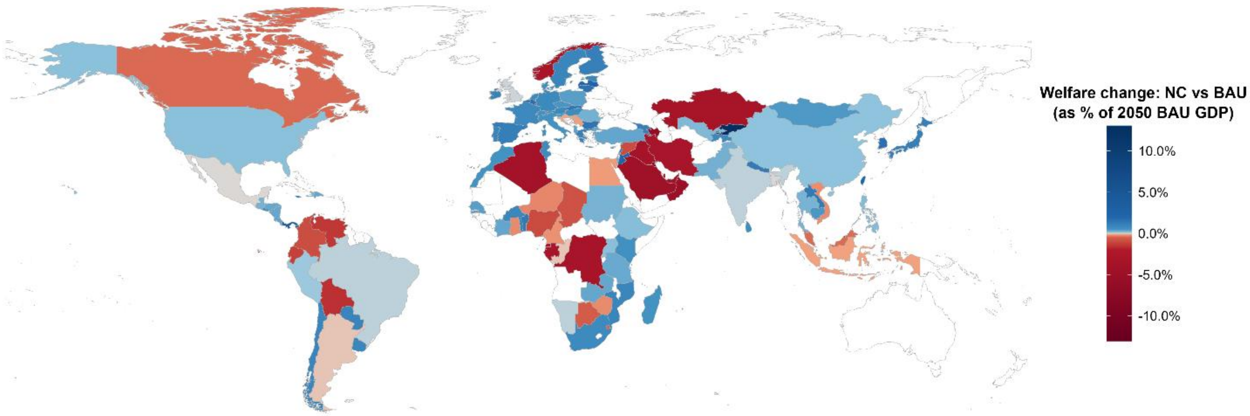


Figure 6.18. Welfare effect of the NC scenario relative to BAU in 2050: difference in equivalent variation as a percentage of BAU GDP in 2050.

6.5 Summary of results

Implementing national commitments as they stand changes the four systems in different ways. In the energy system, the commitments reduce emissions in 2050 by almost two thirds relative to BAU, mainly by decarbonising an energy system that still grows slightly: demand falls in industrialised economies but continues to grow in developing ones, renewable electricity expands almost everywhere, and fossil electricity and oil refining contract where the commitments bind. On land, the commitments turn the forest loss projected under BAU into a forest gain, while cropland and tree crops still expand. No commitment targets water, and water use changes only as a side effect of the land and economic changes, with lower withdrawals in most hotspots and a largely unchanged pattern of water stress. In the economy, the caps shift output and labour away from fossil energy towards electricity, energy-intensive industries and transport, and welfare losses are concentrated in fossil fuel exporters. These interactions across systems, and what they imply for policy, are discussed in Chapter 7.

6.6 Exploring the results on the GCH online platform

The results of this chapter, and many more that could not be shown here, can be explored interactively on the GCH Decision Support Navigator (Section 4.7). Each model has its own application, opened from the Models section of the platform, with pages or tabs that lead from an introduction to the data and methods, through global maps and country views, to tools with which users can test their own assumptions. This section summarises the main features of each application. The land and water applications also include scenarios beyond the BAU and NC scenarios of this report.

6.6.1 Land use: LandReqGCH

The land-use application (https://web-production-29d01.up.railway.app/) is organised in five tabs (Figures 6.19 and 6.20):

- **Introduction:** a summary of the approach (HILDA+ data, time-varying Markov chain, hierarchical validation and Monte Carlo uncertainty analysis with bias correction), the seven land-use classes, the timeline (historical data for 1960–2020, projections for 2021–2050 and scenarios applied from 2026) and key statistics.

- **Global Results:** the validation window selected for each state, the global change in land use between 2020 and 2050 in absolute and relative terms, and indicative results for Europe, for countries with strong decadal changes and for tropical deforestation areas, as presented in Section 6.1.
- **Country Explorer:** land-use projections to 2050 for any state, selected by its ISO3 code, shown as lines or stacked areas for the chosen land-use classes, together with the underlying data. Scenarios can be compared directly: in addition to BAU and NC, the explorer includes six land-use policy and dietary scenarios, listed in the table of the tab (Table 6.1).
- **Scenario Comparison:** the trajectory of a chosen land-use class across several countries and scenarios at once, optionally normalised to 2020 = 100 so that countries of different size can be compared.
- **Custom Model:** a model builder in which users run the land-use model with their own data and assumptions. In the first stage, users select a country and its 2020 baseline, keep the seven default land-use classes or add land uses of their own, and either use the validated transition matrix of that country, which is displayed with its uncertainty ranges, or enter their own matrix describing how land uses have evolved; the model then projects land use to 2050. In the second stage, users apply their own multipliers to the 2050 results, and can thus test scenarios of their own design, such as a national afforestation plan or a change in diets. A reference chart compares global land use in 2050 under the high-meat diet, EAT–Lancet diet and NC scenarios.

Table 6.1. Land-use scenarios available in the Country Explorer of the land-use application.

Code	Scenario	Description
BAU	Business as usual	Baseline projections to 2050 (Section 6.1.2)
NDC	National commitments (NC in this report)	Forest gain targets and bioenergy crops (Section 6.1.3)
Fat	High-meat diet	More area for pasture and feed crops
EAT	EAT–Lancet diet	More vegetables and legumes, less pasture
Afforest	Afforestation and reforestation	Forest protection policies
Bioen	Bioenergy expansion	Biofuel mandates increase crop area
Yieldint	Yield intensification	Higher yields reduce the land needed
Landretir	Land retirement	Marginal cropland converted to forest

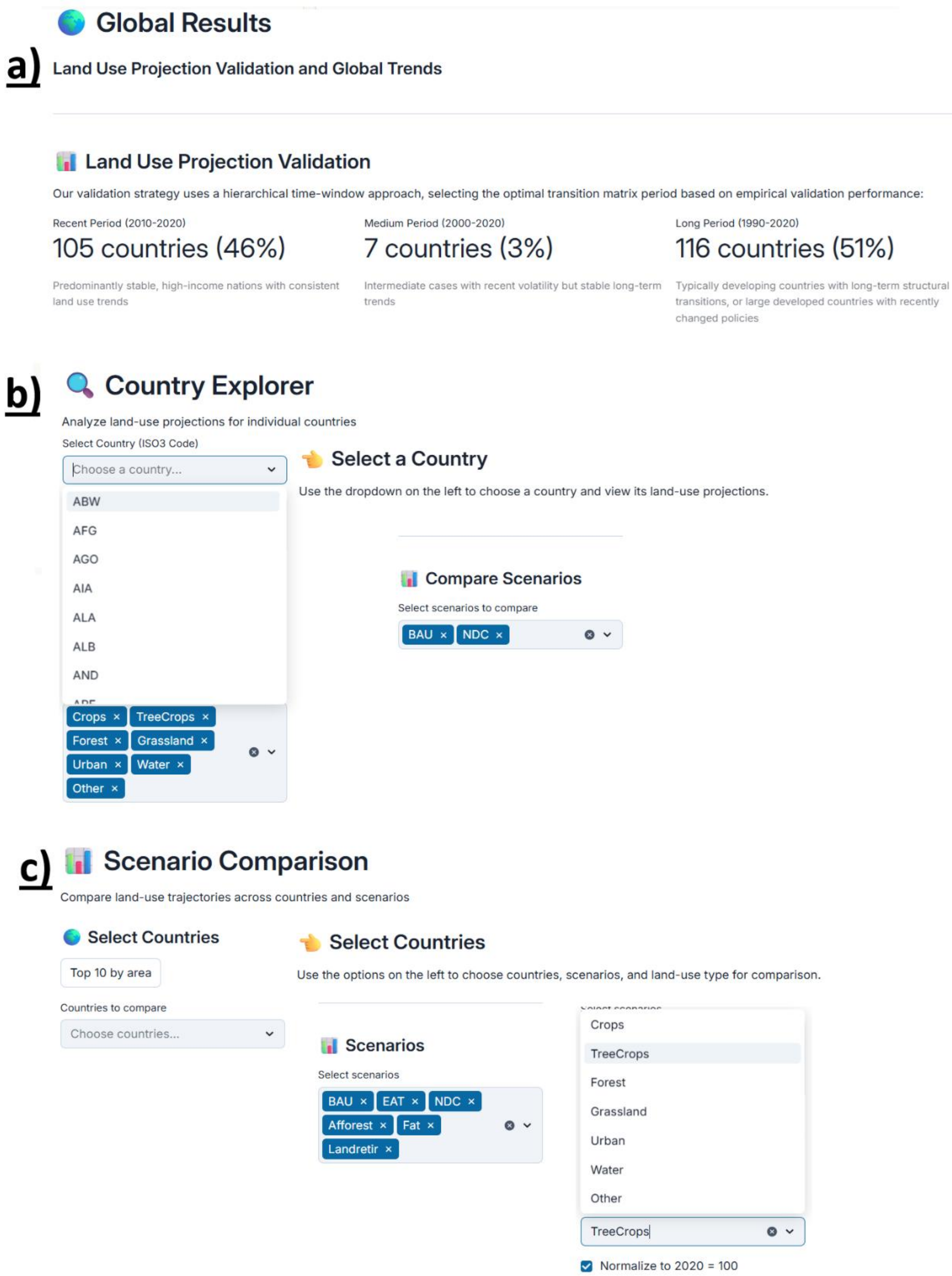


Figure 6.19. The Global Results (a) and Country Explorer tabs (b) and scenario comparison (c) of the land-use application.

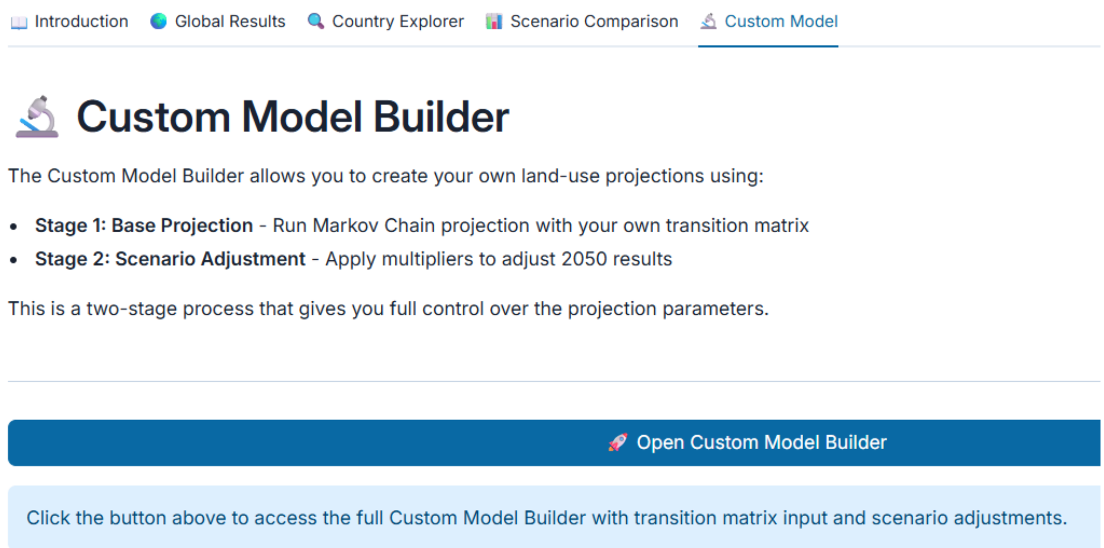


Figure 6.20. The Custom Model builder of the land-use application: baseline, transition matrix input and scenario adjustment menu.

6.6.2 Energy and emissions: LEAP

The energy application (https://gch-energygch-production.up.railway.app/) has three pages. The **Introduction** describes the energy system and the LEAP methodology, the fuels and transformation processes represented and the seven sector groups, and defines the scenarios used on the platform: BAU, a reference scenario with climate-change impacts, and NC. The **Global maps** page shows, for each of the 128 countries, the percentage change between 2017 and 2050 in GHG emissions or in energy consumption, with the global mean and median change, the number of countries in which the indicator increases and the ten largest increases and decreases; hovering over a country shows its exact values. The **Country explorer** presents, for a selected country, energy consumption and emissions by sector and energy generation by technology at five-year intervals from 2017 to 2050, with the 2050 totals and their change since 2017 (Figure 6.21). The pages currently display the BAU projections.

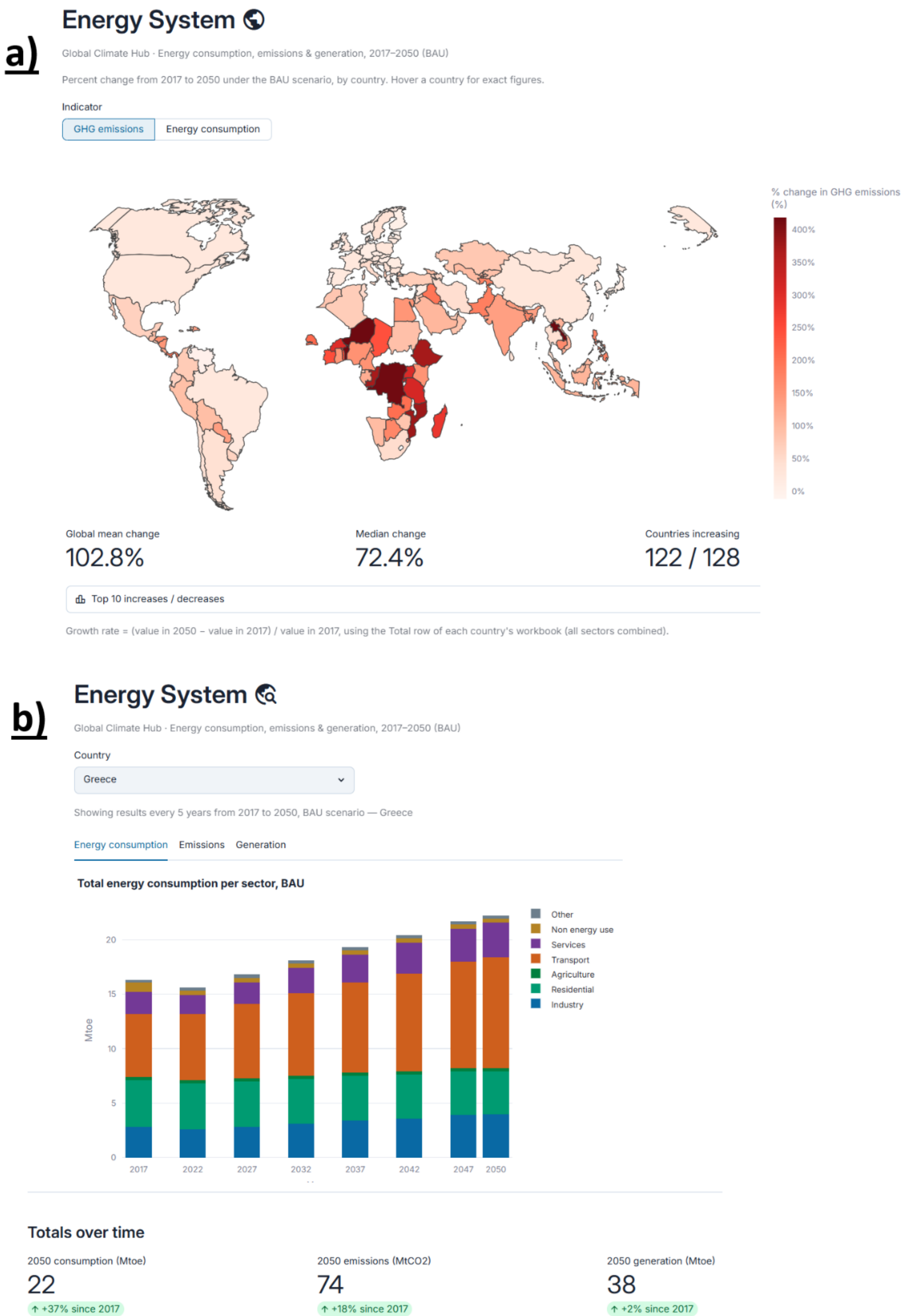


Figure 6.21. The Global maps and Country explorer pages of the energy application.

6.6.3 Water: WaterReqGCH

The water application (https://gch-watergch-production.up.railway.app/) covers the globe at the scale of about 16,400 HydroBASINS level-6 sub-basins [124, 170] and has four pages:

- **Introduction:** the data sources and the construction of the sub-basin dataset from Aqueduct 4.0 and HydroBASINS.
- **Global model:** maps of blue water availability, water withdrawals and water stress for three scenarios (BAU under SSP3-7.0, an optimistic SSP1-2.6 and a pessimistic SSP5-8.5 scenario) and three time horizons (2030, 2050 and 2080), with an explanation of each indicator and downloadable maps.
- **Country deep-dive:** the same indicators for a selected country, and monthly patterns of baseline water stress, baseline water depletion and interannual variability over 1979–2019, as raw values or Aqueduct scores, which show in which months each basin is most stressed.
- **Land & water:** the connection between land use and water, a distinctive feature of the platform. The page translates the land-use scenarios of Table 6.1 into annual water withdrawals and shows the global withdrawals from 2020 to 2050 under each scenario, their percentage change between 2026 and 2050 and their decomposition by land-use class in 2050 (Figure 6.22).

The Land & water page shows how strongly diets and land policies move water use. Between 2026 and 2050, the global withdrawals computed from the land-use trajectories fall by about 22% under the EAT–Lancet diet, 19% under land retirement, 14% under yield intensification, 9% under the NC land pathway and 3% under afforestation, whereas they rise by about 4% under the high-meat diet and under bioenergy expansion. Dietary change, which national commitments rarely address, is therefore a stronger water lever than the land-related commitments themselves.

Land & water

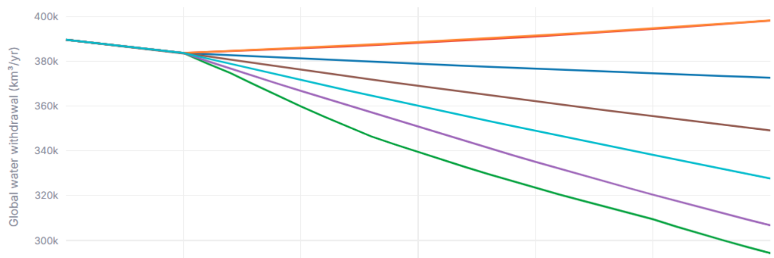
Dietary choices and land-use policies strongly affect the area of land needed — or allowed — for food, feed, fibre and forest. Because every type of land carries a different water demand, those land-use shifts also reshape how much water humanity withdraws each year. A hectare of irrigated cropland draws far more from rivers and aquifers than a hectare of pasture, forest, or restored land; replacing one with another therefore moves the global water needle, even when total land area stays the same.

The figures below trace this connection through a set of contrasting **LandGHC scenarios**. Each scenario describes a different plausible trajectory for global land use between 2020 and 2050, driven by changes in diet, climate policy, energy demand, agricultural productivity, or land-management ambition. We translate those land-use trajectories into annual water withdrawals by combining HILDA+ land-cover dynamics with country-calibrated water-use intensities derived from WRI Aqueduct 4.0, FAO/AQUASTAT and peer-reviewed water-footprint datasets.

› ⊞ Scenario descriptions

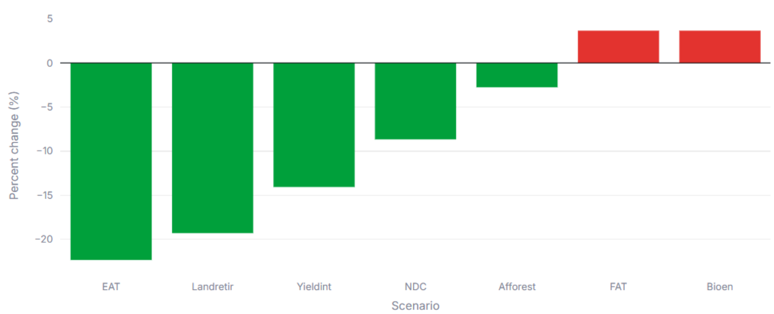
Global total water withdrawals, 2020–2050

The first figure tracks global annual water withdrawals from 2020 to 2050 under each scenario. The trajectories diverge after the mid-2020s as land-use signals accumulate: high-meat and bioenergy pathways push withdrawals up, while plant-shifted diets and land retirement bend the curve down.



Change in global water withdrawals, 2026→2050

The second figure summarises the percent change in global withdrawals between 2026 and 2050. The Lancet EAT diet delivers the largest reduction; high-meat (FAT) diets and large-scale bioenergy expansion produce the largest increases. Yield intensification and land retirement are roughly water-neutral overall — but for very different reasons, since one frees land through productivity gains and the other through deliberate withdrawal of marginal cropland.



Global water withdrawals by land class, 2050

The third figure decomposes the 2050 withdrawal totals by land class so the mechanism is visible. Cropland and urban water use dominate every scenario, but their proportions change: under EAT, croplands account for roughly half of total withdrawals rather than the ~60% share they hold in the high-meat scenario, with the difference largely absorbed by reduced pasture-feed demand.

Figure 6.22. The Land & water page of the water application: global water withdrawals under the land-use and dietary scenarios, 2020–2050.

6.6.4 Economy: GTAP-E

The economic application (https://gch-economy-production.up.railway.app/) has three pages. The **home page** introduces the economic system and CGE modelling, the GTAP-E model and its data, the typical inputs and outputs of the model, and the three scenarios (BAU under SSP2, a reference scenario with climate impacts, and NC). The **Methodology** page explains how a scenario works, from the introduction of a shock through the responses of firms, households and governments to a new equilibrium, and describes the four broad sector groups. The **Explore results** page maps, for the selected scenario, the percentage change in sectoral output for all four sector groups (agriculture, industry, transport and services) across all of the approximately 128 countries, with the global mean and median change and the number of countries with increases and decreases in each sector. Users can choose the sectors to display and highlight a country of interest (Figure 6.23).

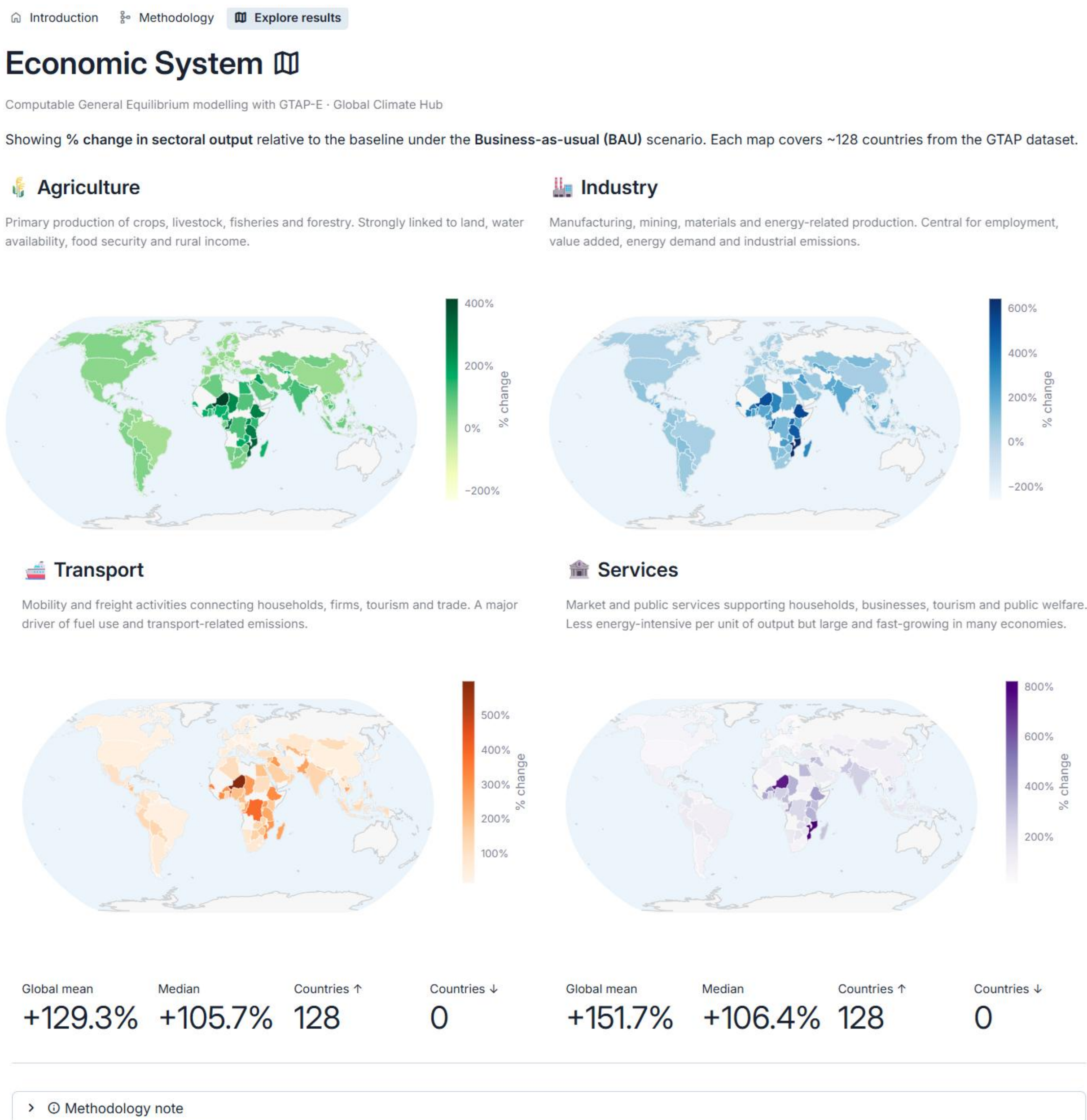


Figure 6.23. The Explore results page of the economic application: change in sectoral output by country and sector group.

7. Discussion, next steps and policy recommendations

This report set out to answer a practical question: do national commitments, implemented as written, add up, what do they imply for land, energy, water and the economy, and who bears the costs? This chapter draws together the evidence of Chapters 1–6. Section 7.1 discusses the main findings and Section 7.2 their limits. Section 7.3 sets out the next steps in the development of the GCH framework, Section 7.4 translates the findings into policy recommendations, and Section 7.5 concludes.

7.1 What the results show

7.1.1 Commitments bend the curve, but unevenly and not to net zero

Implemented as stated, the commitments of the 127 countries with a quantified constraint reduce energy-related emissions in 2050 by 63.5% relative to BAU and by 46% relative to 2017, whereas under BAU emissions would grow by 47% (Section 5.5). This is a decisive change of direction. It is achieved mainly by decarbonising an energy system that keeps growing, rather than by shrinking it: final energy consumption in 2050 is about 28% below BAU but slightly above its 2025 level, renewable electricity expands in almost every country, and fossil electricity generation and oil refining contract where the commitments bind (Section 6.2). Demand falls in the industrialised economies and continues to grow in developing ones, which is consistent with the development needs of the latter.

Yet about 15 $GtCO_2e$ of energy-system emissions remain in 2050, so even full implementation leaves the world far from net zero. Almost half of this residual is emitted in China and India, and emissions still grow between 2025 and 2050 in 38 of the 127 countries, mostly developing economies whose commitments allow growth from a low base or do not constrain emissions below their own reference case (Sections 5.3.3 and 6.2.1); one of the 38, Malta, reflects the source value noted in Section 5.5. The gap between what has been pledged and what the Paris goals require is therefore not a gap of a few laggards, but a structural feature of the current round of commitments.

7.1.2 Commitments are energy plans; land and water change as side effects

The commitments are written primarily for the energy system. Land enters mainly through forest-gain targets and bioenergy. Under NC, the forest loss projected under BAU turns into a gain of about 1.5 million km^2 between 2026 and 2050, while cropland and tree crops still expand (Section 6.1.3); the land for new forests comes mainly from grassland and other land, with implications for pastoral livelihoods and biodiversity that the plans do not address. No commitment sets quantified water targets (Section 5.4.4), and water use changes only as a side effect of land and economic changes: withdrawals are lower under NC in most demand hotspots, but the reduction is modest and the pattern of water stress is largely unchanged (Section 6.3). Levers outside the energy system, such as diets, yield intensification and land retirement, would reduce the water withdrawals associated with land use by more than the NC land pathway does (Section 6.6.3). The finding of Chapter 1 for 35 European plans, that plans ignore the resources they consume, therefore holds at global scale.

7.1.3 The economic adjustment is a reallocation with winners and losers

The emissions caps shift output and labour from fossil energy industries towards electricity, energy-intensive industries and transport, and they reduce welfare mainly in fossil fuel exporters, while most importers gain (Section 6.4). The just transition challenge is therefore international as well as national.

Countries whose export revenues depend on fossil fuels bear welfare losses of several percent of GDP, and within countries the reallocation of labour between sectors has regional and skills dimensions that a model with a representative household and full employment cannot resolve (Sections 2.2 and 4.5). Welfare as measured here also omits the avoided damages of climate change and co-benefits such as cleaner air, so it understates the benefits of implementation.

7.1.4 Pledges are not model-ready, and this is itself a finding

Translating the commitments into model inputs required a systematic assessment of 128 countries, the automated extraction of 24 IEA datasets and an explicit decision procedure with five requirements and four tiers of evidence (Chapter 5). Targets expressed against self-declared baselines, multi-gas targets that cannot be read against energy baselines, unclear treatment of land use, horizons ending in 2030 or 2035 and long-term commitments kept outside the NDC make the pledges difficult to compare and impossible to simulate as written. As long as submissions remain this heterogeneous, every assessment of the collective effect of the Paris Agreement will depend on the interpretive choices of its authors. The procedure of Chapter 5 makes these choices explicit and testable, but the underlying problem can only be solved at the source.

7.2 Interpreting the results

The results describe the consequences of commitments as stated, not the best way to meet them. They rest on conditional targets, which assume that international support is provided; on a single socio-economic pathway (SSP2) and a single climate projection for water supply (SSP3-7.0); on an energy-response relationship calibrated on European plans; and on one representative household per country, so that distributional effects within countries are not resolved (Sections 4.6 and 5.7). The water analysis is annual, and the soft-linked models do not yet feed climate impacts back to crop yields, hydropower or cooling. The value adopted for the United States is the most uncertain of all, because the plans it rests on have been withdrawn (Section 5.3.6). These limits define the next steps.

7.3 Next steps: towards optimised, financed and co-designed pathways

The framework applied in this report is the first stage of a larger system. Five extensions are under way, each closing a gap identified in Chapters 2–6.

7.3.1 Beyond-GDP economic assessment

GTAP-E measures welfare through the equivalent variation and represents nature only through land endowments. The next version extends the CGE model with environmental valuation, following the routes set out in Section 2.1.3: ecosystem services such as water regulation, pollination, soil fertility and carbon storage enter as inputs to production, so that their degradation reduces output, and natural capital and non-market values are added to the measure of welfare [44–47]. The land and water models already provide the physical accounts that such valuation needs, in square kilometres by land-use class and cubic metres by sub-basin. Disaggregating households by income group will allow the welfare effects of commitments to be reported by who gains and who loses, rather than as national averages (Section 2.3). Pathways can then be compared not only by their cost, but by their effect on the natural capital and wellbeing on which long-term prosperity depends.

7.3.2 Optimised pathways: LEAP–NEMO with cross-system constraints

The second extension moves the framework from simulation to optimisation. NEMO, the optimisation module of LEAP [134], identifies the least-cost combination of technologies and fuels that meets a given energy demand and emissions constraint, and it has already been used by the GCH to derive economically optimal electricity generation for the European energy system [135]. Applied to the NC constraints of Chapter 5, it will show, for each country and each sector, how the commitments can be achieved better, faster and more cheaply, with less money and fewer resources, and with more jobs.

The decisive step is to bring the other systems into the optimisation as constraints rather than as afterthoughts: the land available for solar, wind and bioenergy from LandReqGCH, the water available for cooling, hydrogen production and irrigation at basin level from WaterReqGCH, and the macroeconomic, employment and welfare implications from the CGE model. This adds a further link stage to the framework of Figure 4.1, in which the least-cost pathway is also feasible within the land, water and economic limits of each country. The resource accounts that national plans omit (Section 1.3.2) are then produced by construction, and each country obtains a pathway that is optimal across all sectors rather than within the energy system alone.

7.3.3 Water allocation, decarbonisation pressures and hotspots at basin level

The third extension answers the water questions that the commitments leave open. WaterReqGCH will allocate the available water among competing uses in each basin, and will thereby show where decarbonisation adds pressure, for example through cooling water for thermal power plants, electrolysis for green hydrogen, irrigated bioenergy crops or hydropower reservoirs, and where these demands would push already stressed basins into further stress. The analysis will extend the annual indicators of this report to the monthly patterns and interannual variability that the platform already displays for the baseline (Section 6.6.3), and it will cover all basins globally, identifying the hotspots where energy and land plans must be reconciled with water availability. Climate impacts on supply will be fed back to hydropower, cooling and crop yields, closing a gap shared by most global models (Section 3.3.6).

In the same logic, the models are expected to be expanded in the future with the inclusion of critical minerals accounts, as they are already a scarce set of resources, albeit critical for decarbonization infrastructure development.

7.3.4 Financing portfolios for implementation

Commitments are implemented only when they are financed. The fourth extension links each measure of an optimised pathway to the money that can pay for it, in line with the third stage of the GCH approach. For every country, the financing module will list the available funding opportunities, including grants, concessional loans, climate funds, just transition instruments and private and blended finance, match them with the measures for which they can be used and the amounts they can mobilise, and assemble them into investment portfolios. Existing catalogues of funding sources and financial instruments, such as the Pathways2Resilience catalogue for adaptation finance, provide a starting point. Such portfolios turn a modelled pathway into a bankable programme, show where public finance is needed to attract private investment and help to secure and accelerate implementation, which is the stage at which many existing plans and partnerships stall (Sections 1.1.4 and 1.5).

7.3.5 Co-development with stakeholders through Living Labs

Models and pathways are only as useful as their uptake. Following its co-design approach [118], the GCH operates Living Labs in more than 70 countries, in which policy-makers, researchers, businesses and communities define objectives, constraints and narratives, contribute local data and knowledge, and review model results. Through this network, the models of this report and their extensions will be tailored and validated country by country, and pathways will be co-developed with those who have to implement them, so that they are technically feasible, economically realistic and socially acceptable. Combined with the open platform (Sections 4.7 and 6.6), this creates a uniquely holistic process, in which the same integrated evidence base supports national planning, stakeholder dialogue, financing and implementation.

The core of this process, with the co-development of models, measures and their implementation, will be the Just and Equitable Transition (JET), addressing current issues of systemically vulnerable populations and inequalities. This will lead to a simultaneous process of better linked models, AI supported processes and data, and solutions' co-design through Living Labs and funding through the selected funding portfolios.

7.4 Policy recommendations

The findings translate into recommendations on five grounds, from the design of policy instruments to the distribution of their effects. They are addressed to national governments, the UNFCCC process, international organisations and financial institutions, and the modelling community.

7.4.1 Designing policy instruments

- **Anchor targets and incentives in law, and keep them stable.** Policy volatility is priced by investors and raises the cost of capital for long-lived assets (Section 1.2.2). Targets set in law, with predictable review procedures, reduce this risk premium and, as shown in Section 5.3.5, are also more credible.
- **Align horizons, baselines and planning cycles.** NDCs, long-term strategies, energy and climate plans, agricultural plans and river basin plans should share a common 2050 horizon, base year and accounting, so that they describe one physical system (Sections 1.3 and 1.5.3).
- **Publish a physical resource account with every target.** Each capacity or emissions target should state the land, water, materials and investment it requires, which the reviewed European plans do not do for land and water (Section 1.3.2).
- **Give the intersections an owner.** A standing cross-ministerial body with a shared model and shared data should reconcile energy, land, water and fiscal plans, and cross-border assumptions should be reconciled with neighbouring countries (Section 1.5.3).
- **Prefer absolute metrics.** Intensity targets can be met while emissions still rise (Sections 1.2.3 and 5.3.6); targets should be expressed as absolute emissions levels, or at least accompanied by the absolute trajectory they imply.

7.4.2 Tools for assessing commitments

- **Match the tool to the decision.** Global IAMs are suited to scenario screening, whereas country-level nexus and just transition questions require modular, country-level frameworks that can take a national plan as input (Sections 3.5 and 3.6).

- **Close the structural blind spots.** Water at basin level, critical minerals, climate-impact feedbacks, distribution within countries and beyond-GDP welfare should become standard features of assessment models, because what a model does not represent it implicitly values at zero (Sections 2.4 and 3.3.6).
- **Validate against observations.** Model components should be tested against historical data, as the land-use projections are tested by hindcasting and the energy model against observed energy balances (Sections 4.2.4 and 5.2.2), and their validation should be reported.
- **Make models open and use them with stakeholders.** Open, documented and publicly accessible models allow results to be scrutinised, reused and improved, and they gain credibility when they are developed together with the people who use them (Sections 4.7, 6.6 and 7.3.5).
- **Adopt integrated, country-level frameworks such as the GCH approach for national planning.** A chain of validated land, energy, water and economic models that share one scenario definition and consistent base years provides evidence on synergies, trade-offs and distribution that single-domain tools and global IAMs do not provide at national level (Chapters 3 and 4).

7.4.3 NDCs and national plans

- **Make NDCs quantifiable and comparable.** Submissions should state target emissions as absolute levels, together with the baseline, gases, sectors, treatment of land use and the conditional and unconditional components, in a common tabular format alongside the narrative (Sections 5.1.1 and 5.3.2).
- **Report energy trajectories and energy demand.** Economy-wide targets should be accompanied by the energy-related CO_2 trajectory and the final energy consumption they imply, by sector and to 2050, because these are what energy and economic planning require and what most NDCs omit (Sections 5.3.2 and 5.3.7).
- **Separate land-based removals from fossil abatement.** Targets and accounts for land use, land-use change and forestry should be reported separately, so that forest pledges do not mask weak ambition in the energy system (Section 5.3.3).
- **Bring long-term commitments into the NDC.** Carbon-neutrality targets should be legislated and linked to the NDC through an explicit trajectory beyond 2035 that does not rebound after the target year (Section 5.3.5).
- **Include land and water.** NDCs and national plans should quantify the land and water implications of their measures, and set explicit targets or safeguards where these resources are scarce (Sections 5.4.4 and 6.3).
- **Invest in machine-readable and verified pledge data.** Automated tools such as Hefaistos and statistical pipelines such as the IEA extraction of Section 5.2.2 should be scaled up and linked to the UNFCCC registry, so that the collective effect of pledges can be tracked transparently at each round (Section 5.6).

7.4.4 Sectoral synergies and trade-offs

- **Plan electrification, renewables and grids together.** The NC pathways rest on the transformation of electricity generation and on fuel switching to electricity (Section 6.2.2); renewable expansion, grids, storage and end-use electrification should be planned as one programme.

- **Manage the decline of fossil industries and refining in advance.** Output and labour demand in fossil energy industries and oil refining contract in almost every country (Sections 6.2.2 and 6.4); phase-down plans, the reuse of sites and infrastructure and retraining programmes should precede the decline rather than follow it.
- **Treat hydrogen and bioenergy as land and water decisions.** Green hydrogen emerges in 44 countries and cropland expands partly for bioenergy (Sections 6.1.3 and 6.2.2); their siting should be screened for water stress and land competition, especially in stressed basins.
- **Use diets and agricultural productivity as climate and water levers.** Dietary shifts, yield intensification and land retirement reduce land-related water withdrawals by more than the NC land pathway and free land for forests (Section 6.6.3), yet they are largely absent from national commitments and should be integrated into NDCs and agricultural policy.
- **Safeguard forests, grasslands and livelihoods together.** Deforestation continues in major tropical forest countries under BAU, while the NC forest gain comes largely from grassland and other land (Section 6.1); forest targets should be combined with safeguards for biodiversity and pastoral livelihoods.
- **Address water stress directly.** Because the commitments reduce withdrawals only modestly in the hotspots (Section 6.3), water-stressed countries need enforceable abstraction limits and allocation rules alongside their climate plans (Section 1.4.4).

7.4.5 Welfare, equity and a just transition

- **Support fossil fuel exporters in diversifying their economies.** Welfare losses are concentrated in fossil fuel exporters (Section 6.4.3); international cooperation, finance and trade arrangements should support their diversification, which also reduces their incentive to delay.
- **Protect vulnerable households.** The distributional effects of carbon pricing depend on design, and returning revenues to households can more than compensate the poorest [57]; every measure should carry a distributional annex stating who gains, who loses and who is compensated (Sections 1.5.3 and 2.3).
- **Plan for workers and regions, not only for net jobs.** The reallocation of labour towards electricity, industry and transport requires skills, mobility and regional development policies targeted at the people and places exposed (Sections 2.2 and 6.4.2).
- **Finance the transition in developing countries on fair terms.** Conditional targets depend on international support, and developing countries must continue to expand energy use; grants and concessional finance, rather than debt-creating loans, are needed to implement their commitments (Sections 1.1.4, 5.7 and 6.2.1).
- **Measure progress beyond GDP.** Welfare, natural capital and distribution should be reported alongside GDP in the appraisal of commitments, in line with the call of the Pact for the Future for measures of progress that complement GDP [47] (Sections 2.1.3 and 7.3.1).
- **Put people at the centre of implementation.** Co-design with communities through Living Labs and other participatory processes improves acceptance and reduces the risk of delay, litigation and reversal (Sections 1.5.1 and 7.3.5).

7.5 Concluding remarks

Every country has a plan. This report shows what the plans add up to when they are implemented together. They bend the global emissions curve decisively, but not to net zero; they transform the energy system while leaving land and water largely to chance; and they create economic winners and losers that no plan accounts for. None of this can be seen by reading the plans one at a time, or with a model that represents only part of the system.

The approach of this report makes these findings practical. A transparent translation of commitments into model inputs, a linked set of validated land, energy, water and economic models, and an open platform allow any country to see the consequences of its commitments across systems and to test alternatives. With the next extensions, optimised pathways under land and water constraints, beyond-GDP valuation, basin-level water allocation, financing portfolios and co-design through Living Labs, the same framework will show how commitments can be delivered better, faster, more cheaply and more fairly. The implications are tangible, and the tools to act on them are available.

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Appendix 3.A

Table 3.A.1. Detailed Model Comparison Table

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularity	Data scarcity
MESSAGEix–GLOBIOM (IIASA stack)	MESSAGEix energy demands, technology & resource data + GLOBIOM land/agriculture/forestry data + GAINS air pollution coefficients + MACRO economic feedback + MAGICC climate parameters. Nexus module adds basin-level water availability (from GHMs) and climate-impact data.	Least-cost energy system + land-use allocations + bioenergy/BECCS supply curves + multi-gas emissions + air pollution (GAINS) + climate outcomes (MAGICC). Nexus module adds: water withdrawals/stress by basin, water-constrained energy & land pathways, SDG indicators.	Full integrated assessment: energy–land–water–climate–economy. SSP marker scenarios (SSP2). Nexus module [107] endogenizes water allocation decisions across 210 basins.	MESSAGEix framework open-source (Apache 2.0); GLOBIOM code available via IIASA; relies on GAMS + CPLEX/GUROBI (commercial solvers).	MESSAGEix: dynamic linear optimization, perfect foresight. GLOBIOM: PE optimization (10-yr steps). Iterative coupling; nexus module extends to basin-level water constraints.	Complex multi-model stack; coupling requires consistent region/commodity mapping and versioned data pipelines. Water nexus module is recent — limited validation so far. Computational overhead high; "black box" risk from multiple interacting components. No minerals.	MESSAGEix: 11 macro-regions (R11). GLOBIOM: up to 37 economic regions, grid-based supply side. Nexus water module: 210 basins mapped to R11. Country flexibility via sub-models.	Very data-intensive (union of all component models). Strong reliance on global datasets (GTAP, FAO, ISIMIP). Country applications require dedicated calibration effort.
GCAM	Socioeconomics (population, GDP); sectoral technology & resource data; land productivity & demand parameters; water representations; policy constraints. Multi-market equilibrium closure.	Energy supply/demand & prices; emissions (multi-gas); land-use allocations & production; water demands/supply metrics; policy costs; long-run scenario pathways.	Cross-sector interactions via market equilibrium; energy–land–water tradeoffs; mitigation policy analysis.	Open-source (GCAM-Core publicly released); no commercial solver dependence.	Recursive-dynamic (period-by-period market equilibrium; myopic).	Recursive dynamics miss intertemporal foresight effects. Regional aggregation may mask distributional impacts. Coupling to gridded impact models requires downscaling (e.g. DEMETER). Land classification mismatches and base-year calibration	Global multi-region (32 regions). Country-level use possible but non-trivial — requires defining the country as its own region with calibration and trade assumptions.	Requires broad datasets; users often rely on global defaults. Credible national calibration is the main barrier in data-scarce settings.

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularity	Data scarcity
						differences are frequent friction points.		
IMAGE	Exogenous drivers: population, GDP, lifestyles, technology, policy assumptions. Sectors: energy (TIMER), agro-economy (MAGNET), land management, vegetation & hydrology (LPJmL), emissions, climate (MAGICC-style). 26 regions + gridded inputs (5/30 arc-min).	Regional energy & land-use trajectories; gridded land cover; GHG & air-pollutant emissions and concentrations; temperature (pattern-scaled); environmental indicators (water stress, biodiversity).	Broad sustainability assessments integrating climate, land, and environmental impacts; pathway narratives with rich spatial outputs.	Not packaged as a fully open standalone model; some components public (e.g. TIMER residential modules).	Simulation (recursive state updates). LPJmL coupling can be annual; other links are iterative soft-links.	Large modular system with coupling/integration overhead. Soft links can create reproducibility issues across component versions. Water and biodiversity indicators are outputs, not decision variables. Regional aggregation obscures national policy detail unless explicitly represented.	26 regions with gridded outputs; policy levers remain regional. Country studies require dedicated modules or downscaling.	High data requirements across all sector modules. In sparse-data settings, substantial assumptions/proxies needed; uncertainty management is central.
REMIND–MAgPIE	REMIND energy–economy drivers & policy constraints + MAgPIE food/bioenergy/material demands + LPJmL biophysics. Combined input sets of both component models.	Internally consistent energy mix + land-use patterns; land & energy emissions; bioenergy/BECCS tradeoffs; mitigation costs.	Energy–land coupling for deep mitigation pathways; avoids treating land as exogenous to energy policy.	Follows components: REMIND open-source, MAgPIE open framework; both commonly rely on GAMS + commercial solvers.	Mixed: REMIND intertemporal optimization + MAgPIE recursive dynamics; coupling must reconcile timing and feedbacks iteratively.	Key risk is interface consistency: bioenergy commodity definitions, land-CO_2 accounting, regional aggregation differences, iterative convergence. Higher computational overhead and "double calibration" risk. No water or mineral sectors.	Global multi-region; country-level work requires redefining regions and recalibrating both models.	Data demands are the union of both models; not data-scarcity friendly without strong priors/proxies.

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularity	Data scarcity
REMIND	Exogenous drivers: population, GDP paths, techno-economic parameters, policy constraints. Sectors: energy supply & conversion, end-use demand, macroeconomic core, emissions/carbon pricing. No endogenous land, water, or mineral modules (land via coupling to MAgPIE).	Energy investments & capacity mix; emissions by species; carbon prices & mitigation costs; technology deployment trajectories; regional welfare indicators.	Energy–economy transformation under climate targets; technology portfolios & innovation; policy cost/feasibility.	Code open-source; solved as nonlinear program with CONOPT (commercial solver required for full-scale runs).	Intertemporal optimization, perfect foresight. Default 5-yr steps to 2060, coarser thereafter; horizon 2005–2100.	Perfect foresight may understate transition frictions. Nonlinear solver finds local optima only. No water, land, or mineral sectors natively. Coupling to land models requires consistent commodity definitions and iterative convergence (bioenergy, land-CO_2 accounting).	Default 12 regions; supports flexible re-aggregation and higher resolution, with caveats for small countries.	High data needs (technology costs, energy balances, macro calibration). Country runs require full national calibration; less tolerant of data gaps than lightweight frameworks.
GLOBIOM (IIASA)	Exogenous population/GDP (for demand); grid-cell biophysical data (EPIC crop yields, G4M forestry); livestock production systems [127]; land cover/suitability; trade costs; bioenergy demand (from MESSAGEix or exogenous). 37 economic regions; supply side at simulation-unit resolution	Land-use allocations (cropland, grassland, forest, bioenergy); crop/livestock/forestry production & prices; bilateral trade flows; land-use-change emissions (CO_2, CH_4, N_2O); deforestation/afforestation; bioenergy supply curves.	Global land-use competition (agriculture–forestry–bioenergy); food security vs. climate mitigation; AFOLU emissions & abatement. Core land module of the IIASA IAM stack.	GAMS codebase; documentation public (IIASA). Not fully open-source for external standalone use; solver requires CPLEX.	Partial-equilibrium optimization (surplus maximization via LP); recursive over 10-yr steps (2000–2100). Prices endogenous at regional level.	No energy system or macroeconomic module natively (requires coupling to MESSAGEix/MACRO). Water use can be post-processed but is not a decision variable (no endogenous water constraints). No minerals. Trade modelled as homogeneous goods — misses	37 economic regions; supply side at grid/simulation-unit level. Regional versions available with finer detail. Bilateral trade explicitly modelled.	High: requires EPIC/G4M yield data, FAO production statistics, livestock systems, land cover maps. Global defaults available but national calibration increases accuracy.

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularity	Data scarcity
	(5–30 arc-min).					quality/variety differentiation.		
MESSAGEix (MESSAGE)	Demands by commodity/service; technology & resource data; policy constraints; discounting; optional macro feedback (MACRO module). Sectors: energy system core; macroeconomy and land/water when coupled (e.g. MESSAGEix–GLOBIOM stack).	Technology capacities & dispatch; resource extraction; system costs & shadow prices; emissions & policy costs. With MACRO: demand feedbacks. In IAM stacks: extends to land, water, emissions, climate.	Least-cost energy/commodity system transformation; scenario analysis; full integrated assessment when linked to GLOBIOM/MAGICC.	Open-source (Apache 2.0); implemented in GAMS, commonly relies on CPLEX or GUROBI (commercial solvers).	Dynamic linear optimization; perfect foresight by default, rolling-horizon possible.	Central-planner optimization; sensitive to perfect-foresight and technology assumptions. No water, land, or climate modules natively (requires coupling). Coupling to GLOBIOM/MAGICC needs consistent region and commodity mappings; versioned data pipelines are crucial.	Very flexible: configurable for national models, but global IAM datasets are multi-region. Country-only analysis requires explicit trade/boundary assumptions.	Data-hungry (technology inventories, demands, resources). As a framework, reduced-form national prototypes can be built with less data — at the cost of realism.
OSeMOSYS / CLEWs	Energy: technology costs, capacities, efficiencies, resource potentials, service demands. CLEWs extension adds: land-use data (GAEZ), water supply/demand (basin-level), climate inputs (GCMs). All represented as commodity flows in a single	Least-cost energy supply/demand; electricity generation mix; GHG emissions. CLEWs: land allocation for crops/bioenergy, water withdrawals, cross-sector resource conflicts & synergies.	Explicit Climate–Land–Energy–Water nexus analysis in one framework. Designed for capacity development in developing countries; transparent, reproducible, educational.	Fully open-source (GNU GPL); no commercial solver needed (open solvers: GLPK, CBC). Active community (KTH, IAEA, UNDESA). Free self-learning courses available.	Linear optimization (LP); configurable time-steps (annual typical); horizon flexible (often 2020–2070). Perfect foresight.	Sectoral representations are simpler than dedicated models (e.g. less technology detail than TIMES, simpler land than GLOBIOM). Most applications are national/regional — global CLEWs model exists but is less mature. No macroeconomic feedback.	Flexible: applied from single-country to global. Global CLEWs model exists but most applications are national/basin-level.	Designed for data-scarce contexts. Relies on global open datasets (GAEZ, OSeMOSYS Global). Lowest barrier to entry among reviewed models.

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularity	Data scarcity
	optimization framework.					No minerals. Limited validation at global scale.		
EPPA (MIT)	GTAP-based SAMs; exogenous population & labour productivity growth; energy resource endowments; technology parameters (including advanced energy: wind, solar, CCS, hydrogen, biofuels); emission factors (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, air pollutants). Land-use via coupled modules.	Regional GDP, consumption, trade; sectoral output & prices; emissions (multi-gas + air pollutants); energy supply/demand by fuel; carbon prices; welfare. Via IGSM-WRS coupling: water demands, availability, stress.	Economy-wide climate policy assessment within the MIT IGSM framework. Unique IGSM-WRS coupling adds water resource system (via IMPACT-WATER model). Multi-gas, multi-sector, multi-region CGE.	EPPA6 base version publicly downloadable (GAMS). Full IGSM framework requires MIT collaboration.	Recursive-dynamic CGE; 5-yr steps from 2015 to 2100. Forward-looking version also available.	CGE equilibrium assumptions (full employment, market clearing) may miss transition frictions. Water module (IGSM-WRS) is loosely coupled — water demand driven by GDP/population, not endogenous technology choice. Land-use included but aggregated. No minerals.	18 regions, 32 sectors. Expandable for specific projects. IGSM-WRS adds basin-level water.	Relies on GTAP database; reasonable for regions covered by GTAP. Country-level disaggregation requires additional SAM data.
MAgPIE	Demand drivers: diets, population, bioenergy/material demand, trade parameters. Land: crops, livestock, forestry, land conversion, irrigation, land-based GHGs. Biophysics from LPJmL at 0.5° (clustered). No energy-	Land-use areas by type; crop/livestock production; prices & land rents; trade flows; irrigation water use; land-use-change emissions & mitigation (afforestation, BECCS supply); nitrogen budgets, CH_4.	Land competition (food–feed–bioenergy–nature); land-based mitigation; water constraints on agriculture; agricultural technology change.	Open-source framework with public documentation; GAMS codebase (commercial GAMS + solver typically needed).	Recursive-dynamic partial equilibrium (myopic, period-by-period).	Heavy dependence on LPJmL/FAO/HYDE datasets; spatial clustering can hide local heterogeneity. No energy system or macroeconomic feedback. Coupling issues: aligning regional definitions, bioenergy	Global; fine underlying grid but economic decisions at regional/cluster level. Single-country runs require redesigning regionalization and trade closure.	Data intensive (crop/livestock systems, land cover, yields, water, trade elasticities). Data-scarce contexts rely on global defaults/proxies; calibration is the main bottleneck.

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularity	Data scarcity
	system or macroeconomic module.					commodity mapping, land-CO_2 conventions, iteration stability.		
E3ME	Historical econometric data (national accounts, energy balances, emissions inventories, material flows). Exogenous assumptions for projections (population, policy instruments). FTT technology diffusion sub-models (power, vehicles, steel, heating). No land or water modules.	GDP & components (consumption, investment, trade); sectoral output, GVA, prices; employment, unemployment, wages (by income quintile); energy demand by sector & fuel; CO_2 & 13 other airborne emissions; material demands.	Macro-econometric (non-equilibrium) assessment of energy/climate policy. Captures involuntary unemployment, path-dependence, innovation dynamics. Methodological contrast to CGE and optimization-based IAMs.	Proprietary (Cambridge Econometrics). Access via consultancy or research collaboration. Extensive peer-reviewed publication record.	Econometric simulation; annual steps to 2050. Post-Keynesian dynamics; no equilibrium assumption.	No land-use, water, or agricultural module — energy & economy only. No minerals. Econometric parameters estimated from history may not hold under deep structural transformation. Not optimization-based — cannot find "optimal" pathways, only simulate policy impacts.	61 regions (all EU members individually + major economies + grouped rest-of-world); up to 69 sectors.	Requires long historical time series for econometric estimation. Well-calibrated for OECD; sparser for developing regions.
WITCH	Exogenous drivers: population, GDP. Endogenous: energy technology costs with learning-by-doing & R&D. Fuel resource bases (coal, oil, gas, biomass); land availability; water	Optimal energy investment & technology mix; emissions (CO_2, multi-GHG); GDP & consumption; carbon prices; climate variables (temperature, radiative forcing via linked climate module); welfare/consum	Climate mitigation & adaptation under long-term growth; endogenous technological change (learning + R&D); cost–benefit of carbon taxes, caps, and technology policies.	Open-source (WITCH 5.0 on GitHub, RFF-CMCC EIEE). Code and documentation publicly available.	Intertemporal optimization, perfect foresight (recursive runs possible). 5-yr steps; base year 2005, horizon to 2150.	Coarse spatial coverage (17 regions). Water module is simplified (supply curves, no hydrology). Land use soft-linked to GLOBIOM — no endogenous land competition. No minerals/metal	17 world regions; no within-region (country-level) resolution.	Relies on published macrodata (e.g. OECD projections) for calibration. Data scarcity mainly affects regional productivity and technology learning-rate inputs.

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularity	Data scarcity
	availability (supply-curve); damage-function parameters.	ption losses under policy.				s. Simplified damage functions. Coupling to high-resolution climate/hydrology models is non-trivial due to scale mismatch.		
AIM/CGE	Social Accounting Matrices & national economic data for ~17 regions. Exogenous population & GDP; resource endowments (land, labor, capital, energy); sectoral technology parameters; energy balances; emission factors (CO_2, CH_4, N_2O, F-gases, air pollutants); baseline land-use data.	Regional GDP, consumption, trade flows, sectoral production; multi-gas emissions by sector; carbon prices/tax revenues; welfare (equivalent variation). Climate outcomes via linked MAGICC.	Global climate mitigation policy & economic impacts; energy–economy interactions via nested CES production functions; multi-GHG coverage.	Not open-source. Developed by NIES (Japan); usage requires collaboration or license.	Recursive-dynamic CGE (myopic, period-by-period equilibrium). 5–10 yr steps to 2100.	No explicit water module (water–energy trade-offs external). Land-use included at aggregate level — cannot model basin-level irrigation or local land constraints. No water infrastructure or river flows. Economic closure (fixed saving ratios, no foresight) complicates coupling to optimization-based IAMs.	~17 world regions; each a single representative economy. No sub-regional detail.	Relies on global economic & energy statistics; missing/uncertain data in developing regions introduces uncertainty.
IMACLIM-R (CIRED)	Macro SAM calibrated to national accounts; bottom-up sectoral modules (energy, transport, industry) with physical-unit data (MToe,	GDP, sectoral output, prices (dual monetary + physical accounting); energy demand/supply by fuel; CO_2 & GHG emissions; carbon prices; welfare;	Hybrid CGE + bottom-up energy: captures transition frictions, imperfect markets, path dependence. Dual (monetary + physical) accounting ensures	Not open-source. Implemented in Scilab + C solver. Usage requires CIRED collaboration.	Recursive-dynamic simulation; annual steps (2001–2100). Yearly static CGE equilibria interlinked by dynamic sectoral modules.	No land, water, or mineral modules — energy-economy only. Complexity of hybrid structure makes extension difficult.	12–16 world regions (version-dependent). Expandable but computationally costly.	Requires national accounts + physical energy/transport data for hybrid calibration. More demanding than pure CGE for

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularity	Data scarcity
	passenger-km, tons of steel/cement). Exogenous population; endogenous GDP. No land or water modules.	employment; trade flows. Captures second-best effects: market imperfections, inertia, stranded assets.	engineering consistency. Designed for realistic assessment of climate policy costs under non-ideal conditions.			Limited user community outside CIRED. Not used in IPCC SSP marker scenarios (lower visibility).		initial setup.
POLES	Exogenous GDP & population. Detailed energy resource bases (coal, oil, gas reserves by region); technology costs & potentials (power, fuels, end-use); baseline energy demands. Calibrated to historical energy balances (updated annually).	Energy supply & demand by sector; international energy prices; GHG emissions (combustion + process); marginal abatement cost curves; energy system costs; fuel import/export balances; CO_2 prices under policy.	Global energy system & climate policy; decarbonization scenarios; technology rollouts (renewables, CCS, hydrogen); energy-market dynamics. Energy-only — no water or land module.	Proprietary (Enerdata / European Commission). Not open-source; access requires affiliation or license.	Recursive simulation, annual time-steps. Year-by-year equilibration with endogenous fuel prices; horizon to 2050.	Partial-equilibrium: no economy-wide (GDP) feedbacks. No water, land/food, or mineral modules — cannot model water–energy, land–energy, or resource nexus trade-offs. Climate is external (emissions output only, no endogenous damages/adaptation). Coupling to land/water models requires external harmonization.	54 individual countries + 12 aggregate regions — relatively high resolution for a global energy model.	Requires detailed energy data (reserves, technology costs), updated annually by Enerdata. Gaps in emerging-technology or resource data affect projections.
TIAM-UCL	Exogenous population & GDP; energy service demands (heat, transport, industry). Hundreds of technology data sets (efficiencies,	Cost-optimal energy supply/demand by fuel & technology; emissions (CO_2, CH_4, N_2O); global temperature (linked climate module); carbon	Long-term least-cost decarbonization; energy technology assessment; carbon budgets & policy instruments (taxes, caps, subsidies).	Not open-source. TIMES framework is proprietary; UCL implementation requires license. Document	Intertemporal linear optimization, perfect foresight. 5-yr steps (2005–2070), 10-yr thereafter to 2100. Sub-annual time-slices for	Bottom-up energy model with no full macroeconomic feedback (GDP exogenous). No water module (cooling, irrigation absent). Land-	16 world regions (UK as separate region). Regional emissions and prices.	Requires vast technology-level data (costs, efficiencies, learning rates). Heavy detail makes it highly

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularity	Data scarcity
	costs, learning curves); fossil & renewable resource potentials; non-CO_2 emission factors (CH_4, N_2O). No water module.	prices/budgets; discounted mitigation costs; technology deployment paths; endogenous energy prices.	Perfect foresight.	ation is public.	power dispatch.	use change only via prescribed CO_2 pathways — no endogenous land allocation. Cannot capture water–energy–land nexus. Highly sensitive to technology cost assumptions.		sensitive to data assumptions.
MAgPIE–LPJmL	MAgPIE socioeconomics & policies + LPJmL biophysics (yields, water, carbon at 0.5°) + clustering/aggregation rules.	Land allocation & intensification consistent with biophysical constraints; yield/water feedback (design-dependent); carbon fluxes.	Land-system decisions grounded in process-based biophysics; assessment of climate/CO_2 impacts on agricultural productivity.	Depends on MAgPIE stack (GAMS) + LPJmL ecosystem; openness varies by component and version.	Recursive-dynamic (MAgPIE) + external biophysical time slices (LPJmL); requires consistent time alignment.	Mapping crop functional types ↔ economic crop classes is non-trivial. Irrigation/water accounting conventions differ. Aggregation from 0.5° to clusters can influence marginal land signals. No energy-system module.	High spatial detail in biophysical constraints; economic decisions remain regional/clustered. Country studies require re-regionalization.	Data-heavy but can leverage global gridded datasets where national statistics are missing; uncertainty management is critical.
GCAM–DEMETER	GCAM regional land allocations + base-year gridded land cover/suitability + DEMETER spatial transition rules.	Gridded land-use maps consistent with GCAM regional totals; spatially explicit change maps for ESM/impacts coupling.	Bridging IAM land outputs to spatial impact modelling; improved interoperability with gridded land-cover datasets.	GCAM code public; DEMETER open research software; no commercial solver needed for the downscaling step.	GCAM recursive-dynamic + DEMETER slice-by-slice downscaling.	Land-class harmonization; suitability-map sensitivity; risk of false spatial precision. Economics remain at GCAM regional scale — downscaling adds no new economic	Can provide country/grid-scale land maps, but economic/policy levers remain GCAM regional unless redesigned.	More feasible than full national IAM rebuilding — if GCAM regional totals and global covariates for downscaling are accepted.

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularity	Data scarcity
						behavior. No water or mineral modules.		
DEMETER	Regional IAM land-use outputs (typically GCAM); base-year gridded land cover; suitability/constraint maps; spatial transition rules.	Gridded land-use/land-cover consistent with IAM regional totals; spatial hotspots for land conversion; products for ESM/impacts pipelines.	Spatial downscaling/disaggregation — bridging IAM regional land outputs to gridded ESM/impact models.	Open research software; no commercial solver dependence.	Runs per scenario time-slice; inherits time structure from parent IAM. Not an economy-wide dynamic model.	Downscaling adds spatial detail but no new economics. Can create false precision if regional totals are uncertain. Results depend strongly on suitability maps and base-year land cover. Land-class harmonization (crop types, pasture, forest definitions) is a frequent friction point.	Adds subnational /gridded spatial detail for land patterns; policy and economic levers remain at the parent model's regional scale.	More tolerant than full IAMs: needs parent-model land totals and reasonable spatial covariates. Can produce gridded outputs even where national statistics are incomplete.
DICE / PAGE / FUND	Exogenous population & productivity growth (→ GDP); carbon-cycle & climate-sensitivity parameters; aggregate damage functions; policy instruments (tax trajectories, caps). No explicit energy technology, water, or	Global/few-region GDP & consumption; atmospheric CO_2 & temperature; optimal emission reductions & carbon taxes; climate damages; social cost of carbon; welfare measures. FUND adds sectoral damages (agriculture, health); PAGE adds probabilistic	Aggregate cost–benefit analysis of climate policy; optimal emissions paths; social cost of carbon estimation. Highly stylized macro-climate interaction (Ramsey growth + damage functions).	Equations published; code available (DICE in GAMS, FUND in Excel) but no free-software license. Usage may require permission.	Long-horizon optimization/simulation. Typically 5–10 yr steps to 2100+. Very fast to run; can extend over millennia.	Highly aggregated — no energy technologies, no water, no land-use interactions, no resource nexus detail. Climate damages via simple (and contested) damage functions. Cannot capture sectoral or spatial trade-offs. Large uncertainty in outputs (SCC	DICE: 1 global region. RICE: ~12 regions. PAGE: ~8 regions. FUND: ~16 regions. No sub-national detail or trade.	Low data requirements (macro aggregates only), but damage-function parameters are largely expert-guessed. Incompatible with detailed WEL nexus analysis.

Model	Inputs	Outputs	Focus	Open source	Time-step / dynamics	Weaknesses, gaps, & compatibility issues	Spatial granularit y	Data scarcity
	land-use modules.	uncertainty ranges.				sensitive to discount rate & damage assumptions).		

Table 3.A.2. Harmonized NDC Assessment across 128 Countries

Country	Publication Date	Language	Target Year	Overall Focus	Level of Detail	GHG Emissions Target (MtCO2)	Renewables in Final Energy (%)	Renewables in Electricity (%)	Final Energy Consumption	Reliance on Imports	Export Target	Afforestation Target
Algeria	October 2016	French	2035	Balanced	Descriptive	122.7	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Egypt	June 2023	English	2030	Balanced	Descriptive	266.5	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
Morocco	September 2025	French	2035	Balanced	Detailed	55.99	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Tunisia	September 2025	English	2035	Balanced	Descriptive	15.66	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
Benin	December 2021	French	2035	Balanced	Detailed	11.26	Not specified	Not specified	Not specified	Not specified	Not specified	Yes
Burkina Faso	September 2021	French	2050	Balanced	Descriptive	10.62	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Cameroon	October 2021	French	2035	Balanced	Detailed	11.46	Not specified	25%	Not specified	Yes	No	Yes
Cote d'Ivoire	October 2025	French	2035	Balanced	Detailed	8.54	Not specified	46.3%	Not specified	Not specified	Not specified	Yes
Ghana	April 2021	English	2030	Balanced	Descriptive	20.58	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Niger	December 2021	French	2030	Balanced	Moderately detailed	2.23	Not specified	Not specified	Not specified	Not specified	Not specified	Yes
Nigeria	September 2025	English	2035	Balanced	Not specified	150.6	Not specified	50–52%	Not specified	Yes	Not specified	No
Senegal	December 2020	French	2030	Balanced	Moderately detailed	11.6	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Togo	December 2021	French	2030	Balanced	Detailed	1.79	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Chad	October 2021	French	2030	Fuel-focused	Detailed	1.72	Not specified	Not specified	Not specified	Yes	No	Yes
Democratic Republic of the Congo	December 2021	French	2030	Balanced	Detailed	4.22	Not specified	Not specified	Not specified	No	No	Yes
Republic of the Congo	August 2021	French	2035	Balanced	Detailed	5.15	Not specified	Not specified	Not specified	No	No	Yes
Equatorial Guinea	October 2022	Spanish	2030	Balanced	Detailed	1.97	Not specified	Not specified	Not specified	No	No	Yes
Gabon	July 2022	French	2035	Balanced	Detailed	2.78	Not specified	Not specified	Not specified	No	Not specified	Yes
Ethiopia	September 2025	English	2035	Balanced	Descriptive	14.54	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Kenya	April 2025	English	2035	Balanced	Descriptive	27.36	Not specified	100%	Not specified	Not specified	Not specified	Not specified
Madagascar	November 2022	French	2030	Balanced	Detailed	2.07	Not specified	80%	Not specified	Yes	Not specified	Not specified
Mauritius	September 2025	English	2035	Balanced	Detailed	3.72	Not specified	60%	Not specified	No	Not specified	Yes
Mozambique	November 2025	English	2035	Not specified	Descriptive	11.68	Not specified	Not specified	Not specified	Not specified	Not specified	Yes
Rwanda	May 2020	English	2035	Balanced	Detailed	2.64	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Sudan	September 2022	English	2030	Balanced	Moderately detailed	13.01	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Tanzania	Not specified	Not specified	2030	Not specified	Not specified	14.76	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Uganda	September 2022	English	2030	Balanced	Detailed	9.03	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Zambia	July 2021	English	2030	Not specified	Descriptive	6.34	Not specified	Not specified	Not specified	No	Not specified	Yes
Zimbabwe	February 2025	English	2035	Balanced	Detailed	13.15	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Botswana	December 2024	English	2030	Fuel-focused	Detailed	9.46	Not specified	Not specified	Not specified	No	Not specified	Yes
Eswatini	September 2025	English	2035	Fuel-focused	Detailed	1.15	Not specified	Not specified	Not specified	Yes	Not specified	Yes

Country	Publication Date	Language	Target Year	Overall Focus	Level of Detail	GHG Emissions Target (MtCO2)	Renewables in Final Energy (%)	Renewables in Electricity (%)	Final Energy Consumption	Reliance on Imports	Export Target	Afforestation Target
Namibia	January 2024	English	2030	Balanced	Detailed	3.18	Not specified	Not specified	Not specified	Yes	Not specified	No
South Africa	October 2025	English	2035	Fuel-focused	Detailed	268.0	Not specified	Not specified	Not specified	No	Not specified	No
Canada	February 2025	English	2035	Balanced	Descriptive	279.8	Not specified	Not specified	Not specified	No	Not specified	Yes
United States	December 2024	English	2035	Balanced	Descriptive	1,831.1	Not specified	Not specified	Not specified	No	Not specified	Not specified
Mexico	November 2025	Spanish	2035	Balanced	Detailed	271.3	Not specified	Not specified	Not specified	No	Not specified	Yes
Argentina	2020	English	2030	Balanced	Detailed	181.4	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Bolivia	September 2025	Spanish	2035	Balanced	Detailed	20.09	75%	Not specified	Not specified	Yes	Yes (electricity/H_2)	Yes
Brazil	2024	English	2035	Balanced	Detailed	286.1	~49%	~85%	Not specified	Yes	Not specified	Yes
Chile	2025	Spanish	2035	Balanced	Detailed	71.7	Not specified	Not specified	Not specified	Yes	Yes (green H_2)	Yes
Colombia	December 2025	Spanish	2035	Balanced	Detailed	67.84	~25–30%	>75%	Not specified	Yes	Yes (H_2)	Yes
Ecuador	February 2025	Spanish	2035	Balanced	Detailed	48.4	Not specified	Not specified	Not specified	Not specified	Not specified	Yes
Paraguay	2024	Spanish	2030	Balanced	Detailed	7.4	Not specified	~100%	Not specified	No	Yes (electricity)	Yes
Peru	November 2025	Spanish	2030	Balanced	Detailed	54.73	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Uruguay	2024	Spanish	2035	Balanced	Detailed	5.35	Not specified	~94%	Not specified	Yes	Not specified	Not specified
Venezuela	September 2025	Spanish	2030	Balanced	Detailed	57.36	Not specified	Not specified	Not specified	Not specified	Not specified	Yes
Costa Rica	October 2025	Spanish	2030	Balanced	Detailed	7.21	Not specified	~95%	Not specified	Not specified	Not specified	Yes
Guatemala	May 2022	Spanish	2030	Balanced	Moderately detailed	15.03	Not specified	Not specified	Not specified	No	Not specified	Yes
Honduras	2026	Spanish	2035	Balanced	Detailed	14.57	Not specified	>70%	Not specified	Not specified	Not specified	Yes
Nicaragua	September 2025	Spanish	2030	Fuel-focused	Descriptive	6.15	Not specified	>70–90%	Not specified	No	Not specified	Yes
Panama	2025	Spanish	2035	Balanced	Descriptive	13.96	Not specified	Not specified	Not specified	Not specified	Not specified	Yes
El Salvador	Not specified	Not specified	2035	Not specified	Not specified	6.86	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Dominican Republic	December 2020	Spanish	2035	Balanced	Detailed	25.64	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Haiti	January 2022	French	2030	Balanced	Descriptive	3.87	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Jamaica	September 2025	English	2035	Balanced	Detailed	6.78	Not specified	63%	Not specified	Not specified	Not specified	Yes
Trinidad and Tobago	October 2025	English	2035	Balanced	Detailed	13.84	Not specified	Not specified	Not specified	Not specified	Not specified	Yes
China	November 2025	Chinese	2035	Balanced	Descriptive	10,328.6	Not specified	Not specified	Not specified	Not specified	Not specified	Yes
Hong Kong	Not specified	Not specified	2035	Not specified	Not specified	19.44	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Japan	February 2025	English	2040	Balanced	Detailed	348.5	Not specified	Not specified	Not specified	Not specified	Not specified	No
Republic of Korea	December 2025	English	2035	Balanced	Detailed	258.4	Not specified	≥30%	Not specified	Not specified	Not specified	Yes
Mongolia	September 2025	English	2035	Balanced	Detailed	9.2	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Taiwan	Not specified	Not specified	2030	Not specified	Not specified	191.6	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Brunei	September 2025	English	2035	Balanced	Descriptive	8.76	Not specified	Not specified	Not specified	Not specified	Not specified	Yes

Country	Publication Date	Language	Target Year	Overall Focus	Level of Detail	GHG Emissions Target (MtCO2)	Renewables in Final Energy (%)	Renewables in Electricity (%)	Final Energy Consumption	Reliance on Imports	Export Target	Afforestation Target
Cambodia	July 2025	English	2035	Balanced	Detailed	13.73	Not specified	72–80%	Not specified	Not specified	Not specified	Yes
Indonesia	October 2025	English	2035	Balanced	Detailed	605.8	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
Laos	May 2021	English	2030	Balanced	Detailed	7.69	Not specified	Not specified	~3,888 ktoe	No	Not specified	Yes
Malaysia	October 2025	English	2035	Balanced	Descriptive	85.58	Not specified	Not specified	Not specified	Not specified	Not specified	Yes
Philippines	April 2021	English	2030	Balanced	Descriptive	46.26	Not specified	Not specified	Not specified	Not specified	Not specified	No
Singapore	February 2025	English	2035	Balanced	Detailed	41.91	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
Thailand	November 2025	English	2035	Balanced	Detailed	106.4	Not specified	Not specified	Not specified	Yes	Not specified	No
Vietnam	November 2022	English	2030	Balanced	Detailed	141.2	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
Bangladesh	September 2025	English	2035	Balanced	Descriptive	151.2	Not specified	25%	Not specified	Yes	Not specified	Yes
India	August 2022	English	2030	Balanced	Descriptive	2,981.0	Not specified	~50%	Not specified	Not specified	Not specified	Yes
Nepal	May 2025	English	2035	Balanced	Detailed	14.23	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Pakistan	June 2025	English	2035	Balanced	Descriptive	325.4	Not specified	62–69%	Not specified	Yes	Not specified	Not specified
Sri Lanka	September 2025	English	2035	Balanced	Detailed	21.65	Not specified	70%	~30,000 GWh	Yes	Not specified	Not specified
Kazakhstan	April 2023	English	2035	Fuel-focused	Descriptive	174.8	Not specified	Not specified	Not specified	No	Not specified	Yes
Kyrgyzstan	September 2025	English	2035	Balanced	Descriptive	6.97	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Tajikistan	October 2021	English	2030	Balanced	Descriptive	7.69	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Uzbekistan	October 2021	English	2035	Consumption-focused	Descriptive	150.7	Not specified	Not specified	Not specified	No	Not specified	Yes
Armenia	2021	English	2035	Fuel-focused	Descriptive	6.71	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Azerbaijan	November 2025	English	2035	Balanced	Descriptive	34.25	Not specified	Not specified	Not specified	No	Not specified	Yes
Georgia	May 2021	English	2035	Not specified	Descriptive	13.68	Not specified	Not specified	Not specified	No	Not specified	Yes
Bahrain	December 2025	English	2035	Consumption-focused	Descriptive	26.48	Not specified	20%	Not specified	No	Not specified	Yes
Iran	Not specified	Not specified	2030	Not specified	Not specified	592.2	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Iraq	November 2025	Arabic	2035	Consumption-focused	Detailed	127.7	Not specified	Not specified	Not specified	No	Not specified	No
Israel	July 2021	English	2030	Fuel-focused	Detailed	55.77	Not specified	30%	Not specified	Yes	Not specified	No
Jordan	October 2021	English	2035	Balanced	Detailed	23.28	Not specified	Not specified	Not specified	Yes	Not specified	Yes
Kuwait	October 2021	English	2035	Balanced	Descriptive	92.56	Not specified	Not specified	Not specified	No	Not specified	No
Lebanon	September 2025	English	2035	Fuel-focused	Detailed	20.51	Not specified	25–30%	Not specified	No	Not specified	Yes
Oman	November 2023	English	2035	Fuel-focused	Detailed	46.73	Not specified	Not specified	Not specified	No	Not specified	No
Qatar	November 2025	English	2040	Balanced	Descriptive	84.5	Not specified	Not specified	Not specified	No	Not specified	No
Saudi Arabia	October 2021	English	2040	Consumption-focused	Descriptive	591.9	Not specified	Not specified	Not specified	No	Not specified	Not specified
Syria	November 2018	English	2030	Fuel-focused	Detailed	18.05	Not specified	10%	Not specified	No	Not specified	Yes
Turkey	November 2025	English	2035	Balanced	Descriptive	292.7	Not specified	Not specified	Not specified	No	Not specified	No

Country	Publication Date	Language	Target Year	Overall Focus	Level of Detail	GHG Emissions Target (MtCO2)	Renewables in Final Energy (%)	Renewables in Electricity (%)	Final Energy Consumption	Reliance on Imports	Export Target	Afforestation Target
United Arab Emirates	November 2024	English	2035	Balanced	Detailed	85.98	Not specified	60%	Not specified	No	Not specified	Yes
Austria	December 2024	Not specified	2050	Balanced	Detailed	6.25	Not specified	Not specified	884 PJ	Yes	Not specified	Not specified
Belgium	December 2023	Not specified	2050	Not specified	Detailed	9.07	56.6%	Not specified	Not specified	Not specified	Not specified	Not specified
Bulgaria	January 2025	Not specified	2050	Balanced	Detailed	4.27	Not specified	Not specified	6,544 ktoe	Yes	Yes (6,010 GWh)	Not specified
Croatia	July 2023	Not specified	2050	Fuel-focused	Descriptive	1.61	65%	93%	6,334 ktoe	Yes	Not specified	Not specified
Cyprus	December 2024	Not specified	2050	Balanced	Detailed	0.65	95%	Not specified	1,996 ktoe	Not specified	Not specified	Not specified
Czechia	December 2024	Not specified	2050	Fuel-focused	Detailed	7.7	65%	52%	Not specified	Yes	Yes (2.8 TWh)	Not specified
Denmark	July 2024	Not specified	2040	Balanced	Detailed	7.6	82.3%	Not specified	17,798 ktoe	Yes	Yes (160 PJ)	Not specified
Estonia	August 2023	Not specified	2050	Fuel-focused	Detailed	1.6	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
Finland	July 2024	Not specified	2040	Consumption-focused	Detailed	4.9	Not specified	Not specified	21,927 ktoe	Yes	Not specified	Not specified
France	July 2024	Not specified	2050	Consumption-focused	Descriptive	22.5	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Germany	August 2024	Not specified	2050	Balanced	Detailed	71.99	Not specified	Not specified	6,238 PJ	Yes	Yes (28,368 MW)	Not specified
Greece	Not specified	Not specified	2050	Not specified	Not specified	6.28	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Hungary	October 2024	Not specified	2050	Balanced	Detailed	4.52	62%	Not specified	Not specified	Yes	Not specified	Not specified
Ireland	July 2024	Not specified	2050	Balanced	Detailed	3.6	Not specified	Not specified	11,541 ktoe	Yes	Not specified	Not specified
Italy	July 2024	Not specified	2050	Balanced	Descriptive	32.31	42.3%	69%	95,400	Yes	Not specified	Not specified
Latvia	July 2024	Not specified	2040	Balanced	Detailed	2.7	Not specified	Not specified	3,331 ktoe	Yes	Not specified	Not specified
Lithuania	October 2024	Not specified	2040	Consumption-focused	Descriptive	5.8	95%	Not specified	Not specified	Yes	Yes (43,000 tonnes)	Not specified
Luxembourg	July 2024	Not specified	2040	Balanced	Detailed	0.9	Not specified	Not specified	29,168 GWh	Yes	Not specified	Not specified
Malta	January 2025	Not specified	2040	Consumption-focused	Detailed	0.475	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
Netherlands	June 2024	Not specified	2050	Balanced	Detailed	15.7	Not specified	Not specified	55,046 ktoe	Yes	Not specified	Not specified
Poland	March 2024	Not specified	2050	Balanced	Detailed	30.35	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
Portugal	December 2024	Not specified	2040	Fuel-focused	Detailed	3.6	88%	100%	Not specified	Yes	Not specified	Not specified
Romania	October 2024	Not specified	2050	Fuel-focused	Detailed	6.96	86.1%	86.9%	16,512	Yes	Yes (82%)	Not specified
Slovakia	September 2023	Not specified	2040	Consumption-focused	Descriptive	1	32.7%	Not specified	6910 (estimated)	Yes	Not specified	Not specified
Slovenia	January 2025	Not specified	2040	Balanced	Detailed	3.6	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
Spain	September 2024	Not specified	2050	Balanced	Descriptive	11.8	Not specified	100%	Not specified	Not specified	Not specified	Not specified
Sweden	July 2024	Not specified	2040	Consumption-focused	Detailed	4.7	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
United Kingdom	January 2020	Not specified	2050	Balanced	Descriptive	36.15	Not specified	Not specified	Not specified	Yes	Not specified	Not specified
Switzerland	January 2025	Not specified	2050	Balanced	Detailed	3.4	Not specified	Not specified	Not specified	No	Not specified	Not specified
Albania	October 2024	Not specified	2050	Fuel-focused	Detailed	2.6	73%	93%	111.7 PJ	Yes	Yes (570 ktoe)	Not specified
Serbia	July 2024	Not specified	2050	Balanced	Detailed	11.4	64.5%	90.6%	9,537 ktoe	Yes	Yes (oil)	Not specified

Country	Publication Date	Language	Target Year	Overall Focus	Level of Detail	GHG Emissions Target (MtCO2)	Renewables in Final Energy (%)	Renewables in Electricity (%)	Final Energy Consumption	Reliance on Imports	Export Target	Afforestation Target
Norway	January 2021	Not specified	2050	Balanced	Descriptive	3.92	Not specified	Not specified	Not specified	No	Not specified	Not specified

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.

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