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STUDIES

Methodology for Assessing Energy Transition Pathways Through a Multi-Criteria Sustainability Lens

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Outline

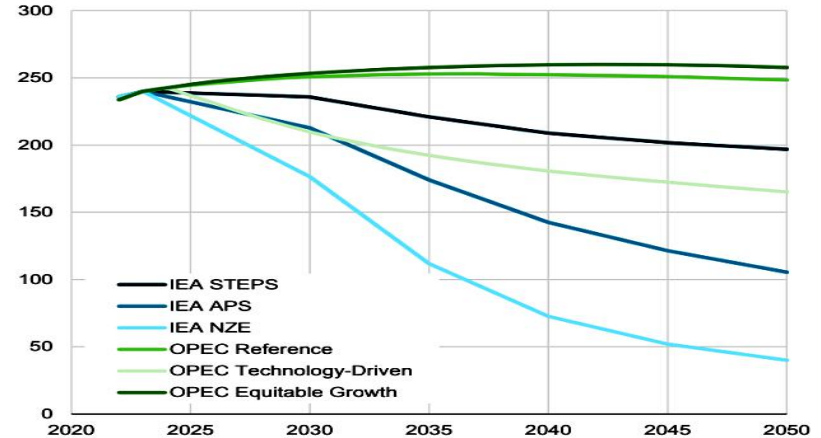
- **Why a multi-criteria evaluation of Energy Transition pathways (including NZE 2050) is needed**
- **Methods and sustainability pillars**
- **Summary of Scenario types of ET, how they perform across key pillars, criteria and trade-offs**
- **Insights on the key scenario of ET (IEA, IPCC, OPEC)**
- **Implications for further research and policy**



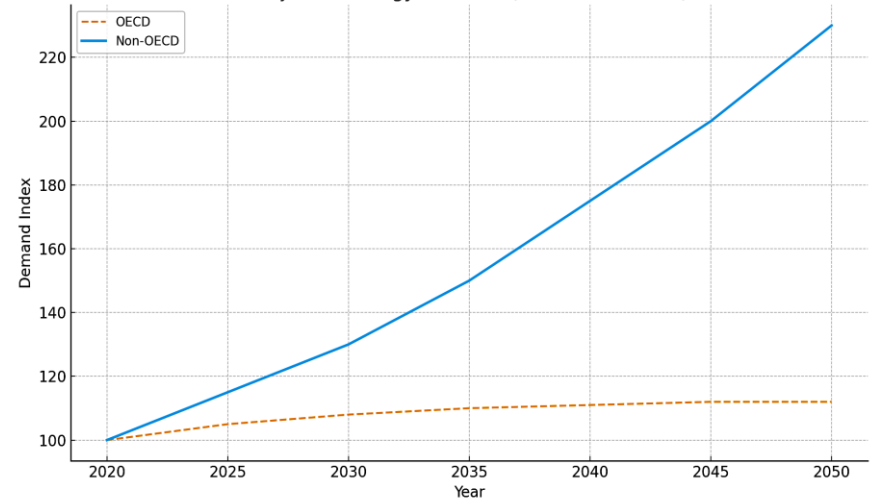
Why Broader NZE Evaluation is Needed

- Emissions focus insufficient on its own
- Energy security as well as cost (economics and affordability) are critical to consider
- Growing demand in non-OECD regions
- Balanced strategy needed

Fossil Fuel Primary Energy Demand Outlook
Million barrels of oil equivalent per day



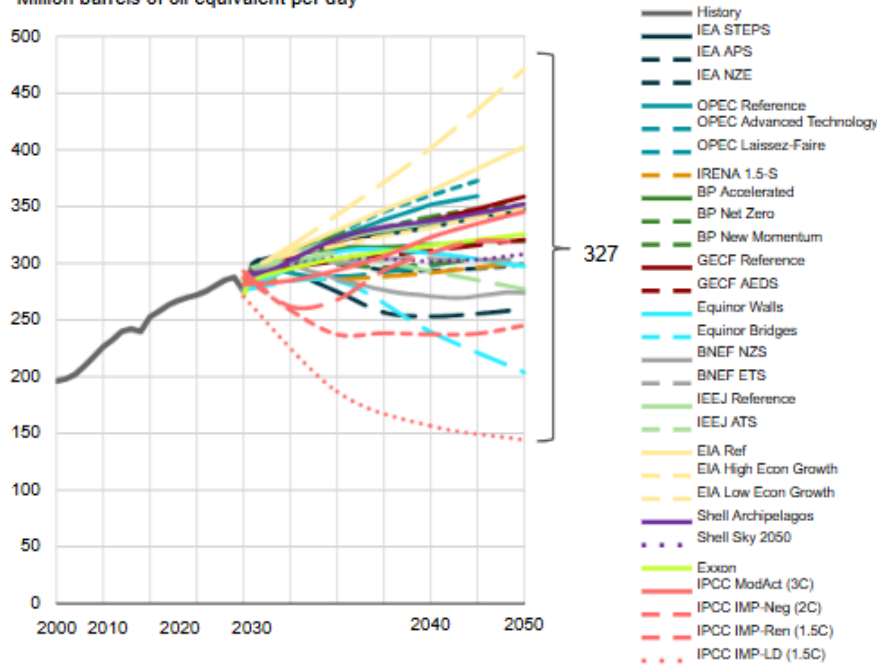
Projected Energy Demand (Index 2020=100)





Projections of future energy growth and mix vary greatly : Renewable development very impressive

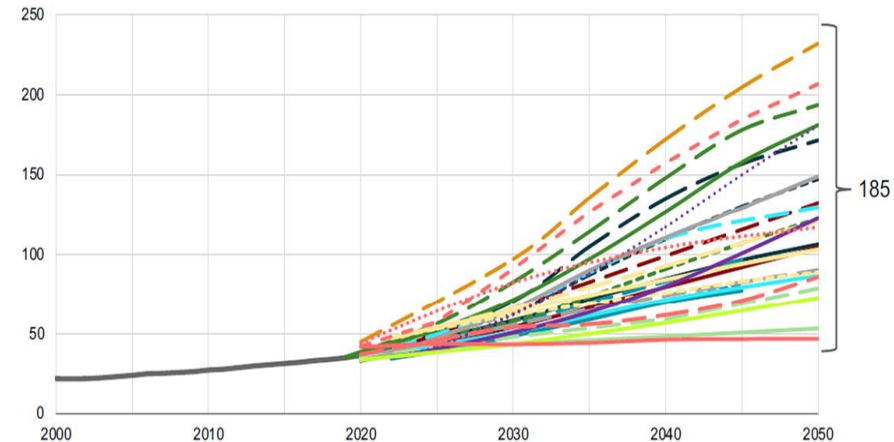
Total Primary Energy Demand Scenarios Through 2050
Million barrels of oil equivalent per day



*Descriptions of the various scenarios are on slide 58

There exists, for example **HUGE uncertainty** for what is the likely Re share of various scenario in 2050, IEF 2025 - reflecting similar large uncertainty in ET

Renewables Demand Scenarios Through 2050
MBOE/D



*Includes wind, solar, geothermal, modern and traditional bioenergy. EIA includes hydro.

Source: IEF, IEA WEO 2023, OPEC WOO 2023, IRENA World Energy Transitions Outlook 2023, BP Energy Outlook 2023, GEFC 2023 Global Gas Outlook to 2050, Equinor Energy Outlook 2024, IEEJ Outlook 2023, EIA IEO 2023, Shell Energy Security Scenarios, Exxon Global Outlook, IPCC AR6



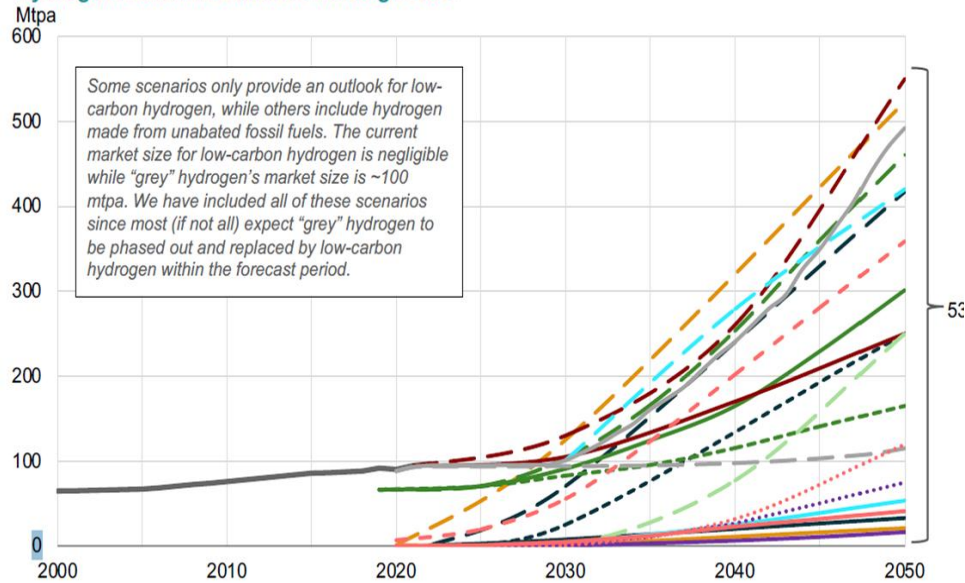


Huge uncertainty about transition pathways towards NZE

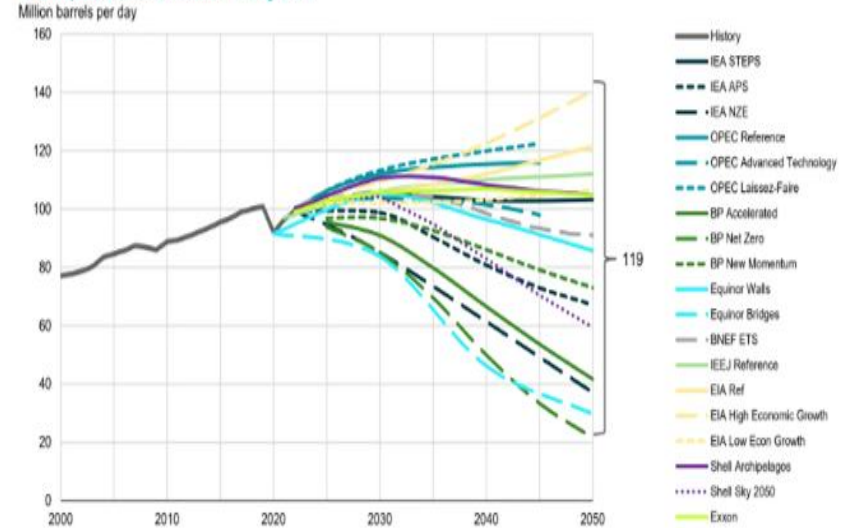
GREEN hydrogen holds potential to decarbonize sectors like heavy industry & transportation. Some NZ scenarios see low carbon hydrogen expanding by **>400x**

Total liquid demand: Several net zero scenarios show oil demand **falling by >75%** by 2050 some reference cases show **15% growth**

Hydrogen Demand Scenarios Through 2050



Total Liquids Demand Scenarios Through 2050



Source: IEF, IEA WEO 2023, OPEC WOO 2023, BP Energy Outlook 2023, Equinor Energy Perspectives 2023, BNEF New Energy Outlook 2024, IEEJ Outlook 2023, EIA IEO 2023, Shell Energy Security Scenarios, Exxon Global Outlook





Frameworks for Evaluating NZE Pathways

Evaluation of ET/NZE strategies requires a sustainability lens to assess performance across:

- Emissions (Environmental impact)
- Economics (Cost, investment, GDP)
- Energy Security (Reliability, resilience)

Approaches blend systems modeling, scenario analysis, and stakeholder criteria.

Key Evaluation Frameworks

1. **Integrated Assessment Models (IAMs):**
 - IPCC, IEA, IIASA: MESSAGE-GLOBIOM, GCAM, REMIND, WITCH...
 - Integrate energy, economy, land-use, and climate systems
2. **Energy-Economy-Environment (E3) Models:**
 - UK MARKAL/TIMES, US NEMS
 - Link macroeconomics with energy pathways
3. **Multi-Criteria Decision Analysis (MCDA):**
 - Weighs emissions, cost, security, and acceptance, other criteria
4. **Life Cycle Assessment (LCA) & TEA:**
 - Track emissions and resource use across full energy chains

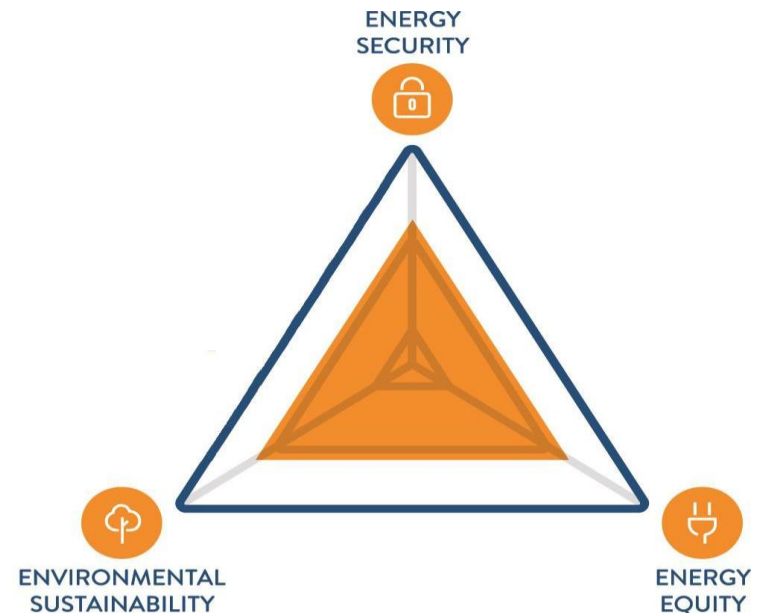
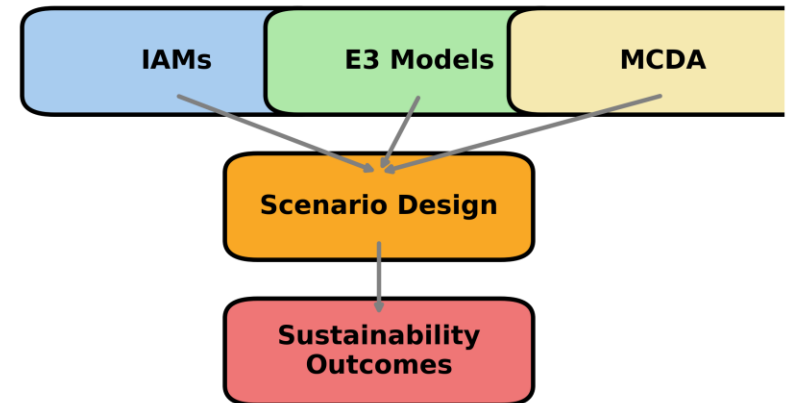


Methodology and Scenarios assessed

- Pathways have varied trade-offs
- Some optimize emissions, others cost or security

No one-size-fits-all solution – therefore need to a combination of criteria across the three Trilema dimensions

- Key types of Scenario assessed using multi criteria (6) methods
- **Scenarios** of IEA, IPCC, OPEC are also assessed, using same same criteria





Generic ET types of Pathways Assessed

Rewables-dominant

Nuclear energy

Fossil fuels with CCS

Hydrogen systems

Bioenergy / BECCS

Demand-side measures



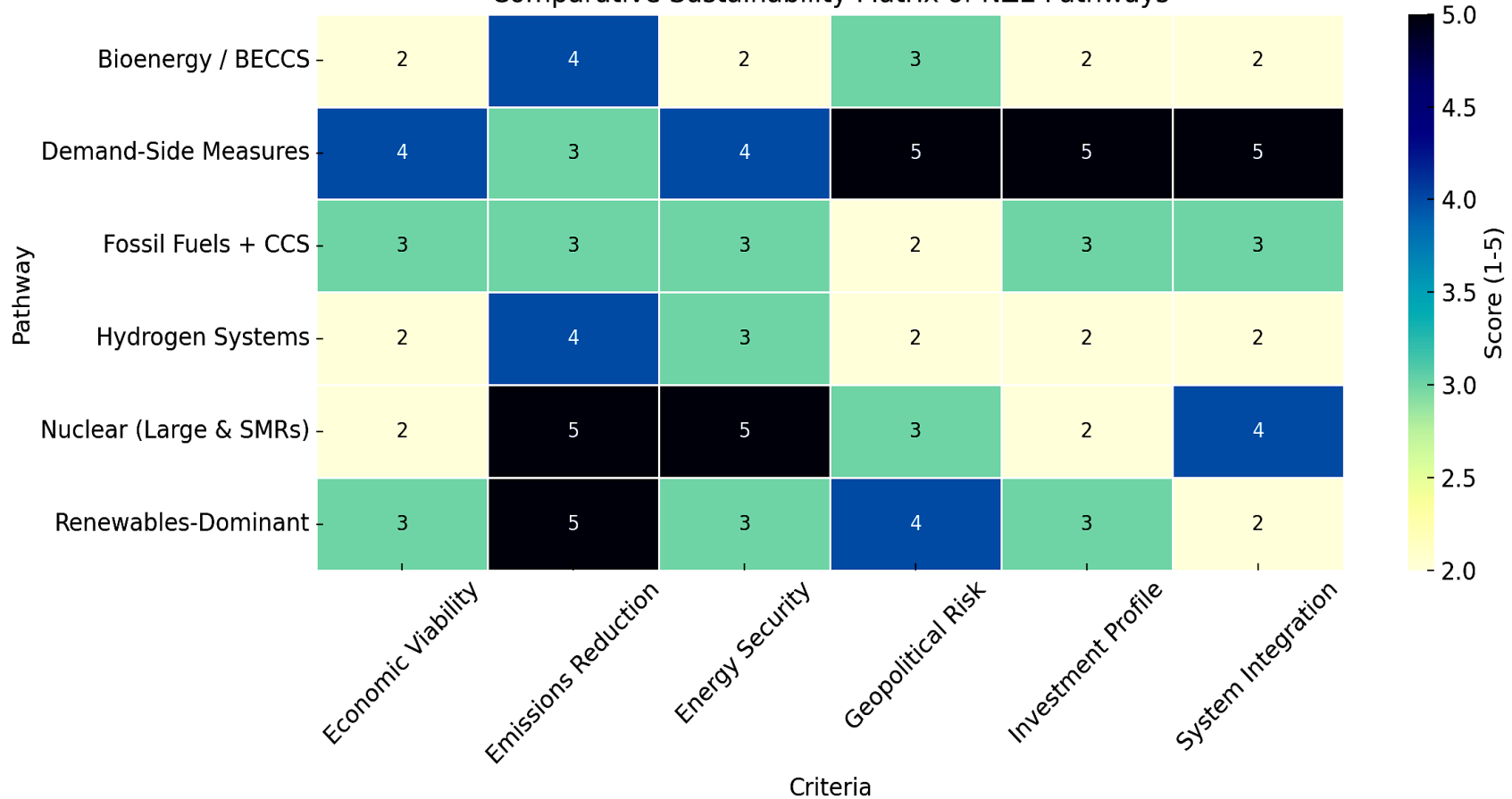
Illustrative Sustainability Matrix of Key ET Scenarios (Pathways), Across 4 Criteria

Pathway / Strategy	Emissions Reduction Potential	Economic Cost / Investment Need	Energy Security Impact	System Integration / Grid Challenges
Renewables-Dominant (e.g. Wind, Solar + Storage)	High (zero-operational emissions)	Moderate to High (storage, grid upgrades)	Improves resilience, but variable supply risk	High (variability, storage needs)
Nuclear Expansion (Large & SMRs)	High (zero-operational emissions)	High upfront, long asset life	High security, stable base-load	Low (dispatchable)
Fossil Fuels + CCS	Medium-High (residual emissions + leakage risk)	Moderate, depends on carbon price & retrofit cost	Depends on fuel source stability	Medium (infrastructure adaptation)
Hydrogen Economy	Medium-High (depends on production pathway)	High (infrastructure intensive)	Depends on trade and domestic production	High (new networks, end-use tech)
Electrification + Efficiency	High (reduced demand + low-carbon supply)	Moderate (cost-effective in long term)	Improves efficiency, lowers import needs	Low-Medium (depends on pace)
Bioenergy + BECCS	High (carbon-negative if sustainably sourced)	High (feedstock and land competition)	Mixed (land and water stress possible)	Medium-High (logistics, sustainability)
Behavioral / Demand-side Measures	Medium (reduces demand, less technological)	Low-Medium (policy-driven savings)	Improves resilience, lowers peak loads	Low (behavioral implementation)



Matrix of Experts' Assessed Values (1-5) of Key ET Scenarios (Pathways) Across 6 key Criteria

Comparative Sustainability Matrix of NZE Pathways



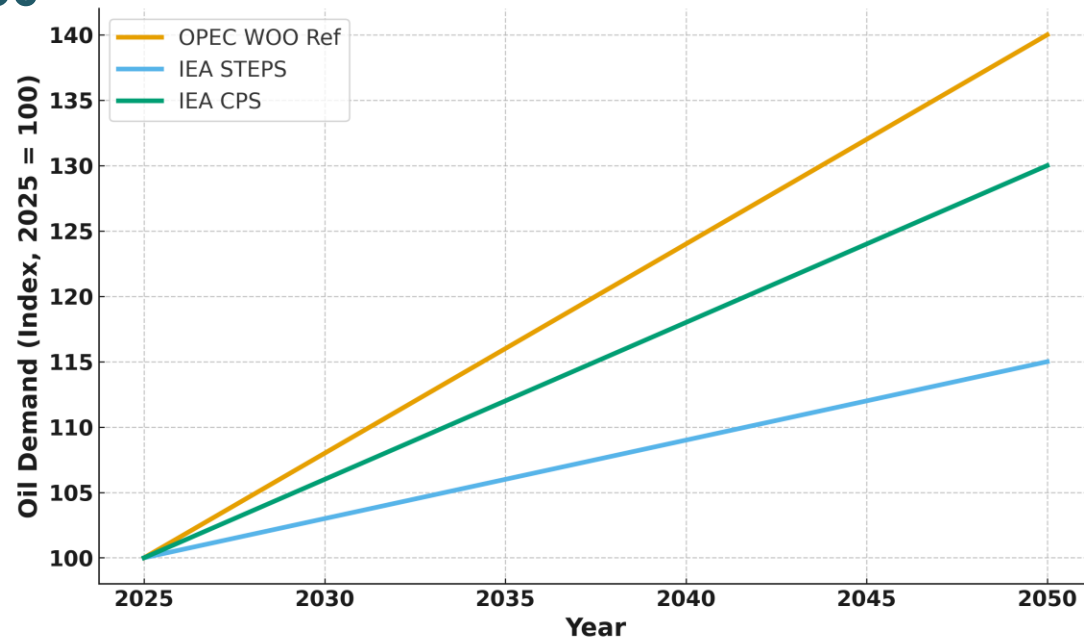


Focus on IEA OPEC, 2025 ET Scenarios

OPEC's 2025 Ref. case & IEA's STEPS, CPS (WOO 205, WEO 2025)

- Oil demand to rise in recent IEA's WEO/CPS and WOO ref. scenarios through 2050
- Driven by non-OECD development
- Annual emissions remain near 40 Gt

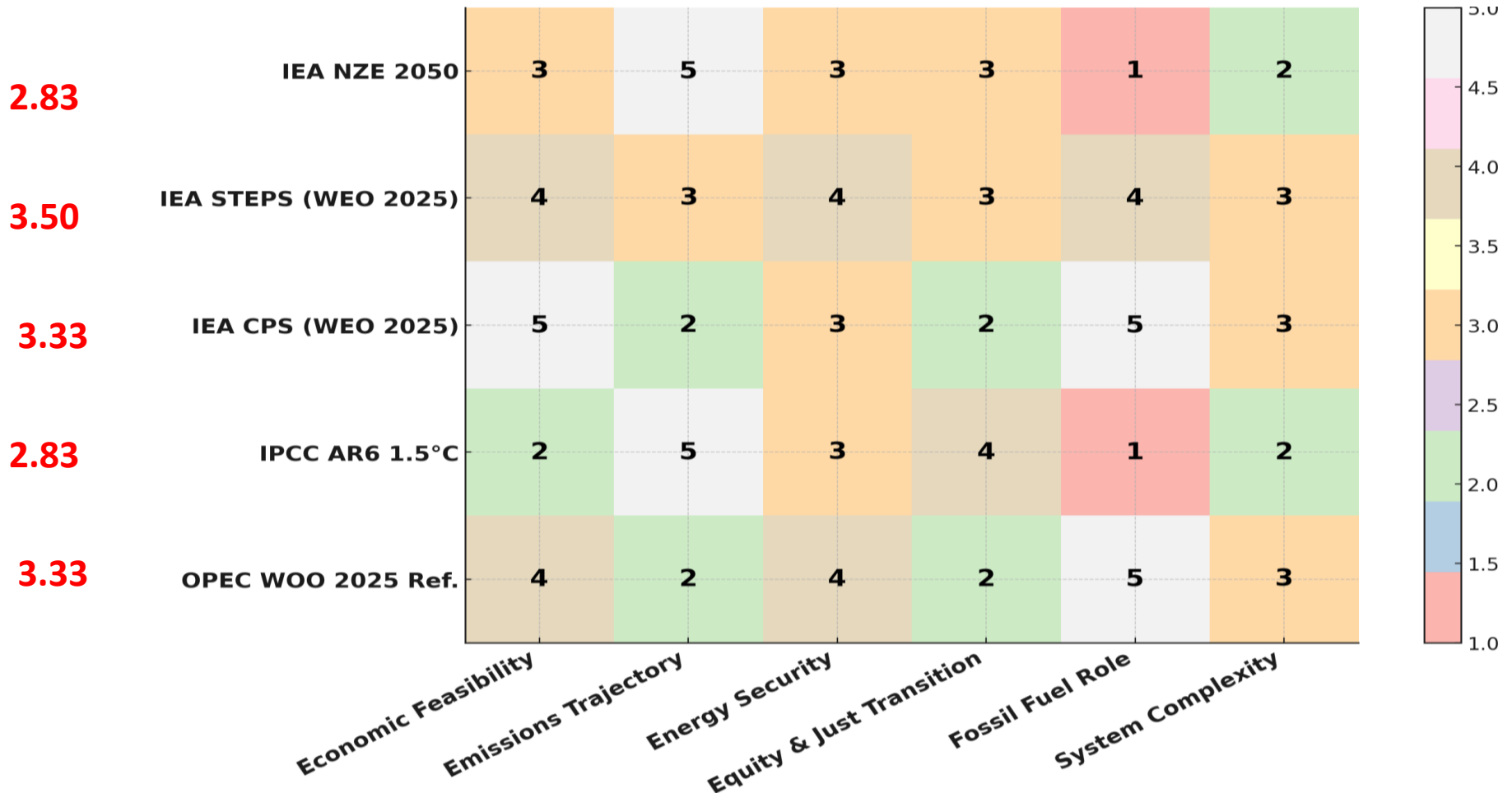
Oil Demand Outlook to 2050 (IEA, OPEC)





Matrix of Assessed Values (1-5) of IEA, IPCC and OPEC ET Scenarios (Pathways) Across 6 Criteria

Avg. Scenario Score





How the Scenario Criteria Scoring Was Constructed

- Scoring uses a 1–5 scale across six criteria:
 - ✓ Economic feasibility, Emissions, Security, Equity, Fossil Fuel Role, System Complexity.
- Current values reflect **expert judgment** informed by:
 - ✓ IEA WEO 2025 (NZE, STEPS, CPS); OPEC WOO 2025 Reference Case; IPCC AR6 1.5°C pathways
- Scores represent the relative performance of each scenario **based on published trends and scenario narratives.**



Improving the Scoring Methodology

- **Steps for rigorous quantitative scoring:**
 - Define measurable indicators per criterion:
 - Costs, emissions, dispatchability, fossil share, equity indices, system build-out.
- **Extract numerical values from authoritative sources:**
 - IEA WEO 2025 Annex Tables
 - OPEC WOO 2025 Statistical Annex
 - IPCC AR6 Scenario Explorer (IIASA)
- **3. Normalize indicator values to a 1–5 scale:**
 - Min–max or percentile mapping.
- **Compute composite scores per criterion and scenario.**



Future Research Areas

Area

Multi-criteria sustainability assessment of ET pathways

Energy systems resilience under transition scenarios

Decarbonization policy sequencing and investment timing

Developing country-specific NZE frameworks

Open-source scenario tools and dashboards

Why It Matters

Need to explicitly model trade-offs across emissions, economics, and security

Understand risks from intermittency, cyber threats, geopolitical supply risks

Explore optimal policy mixes and minimize stranded assets

Customized pathways needed for national context, finance, and capacity

Democratize access and usability of complex models for policymaker



Some Recent Research Results (2019–2024) - I

- Multi-criteria NZE studies reveal major trade-offs between **land-use, minerals, cost, and security**.
 - van den Berg et al. 2020 (Nature Climate Change)
 - Grubler & Wilson 2019 (Nature Energy)
- **Resilience analyses show 20–30% more backup is required** for weather-driven stress events.
 - Bloomfield et al. 2021 (Nature Communications)
 - Ruhnau & Qvist 2022 (Joule)
- **Optimal sequencing improves feasibility and lowers costs**.
 - Metcalf & Stock 2020 (REEP)
 - Pisani-Ferry 2023 (PIIE)
- High-renewables systems need major firm capacity.
 - Sepulveda 2019 (Joule)
 - Jenkins 2021 (E&E Science)



Some Recent Research Results (2019–2024) - II

- Recent **Renewable megaprojects face large delays** due to permitting and social acceptance.
 - **IEA 2023 (Permitting Barriers Report)**
- Carbon pricing only **viable with revenue recycling**.
 - Carattini et al. 2019 (Nature Climate Change)

Major gaps remain:

- Energy security under stress (geopolitics, grid)
- **Behavioral and political economy constraints**
- Equity impacts and just transition assessment
- **Tipping points and climate-economic feedbacks**
- High-resolution modeling in key sectors (industry, transport)



Future Research Focus

- Multi-criteria sustainability assessment of NZE target year options
- **Resilience modeling of energy systems under stress**
- Transition timing and policy sequencing
- **Developing country-tailored NZE frameworks**
- **Open-source modeling tools for wider policy access** (public, open, transparent analytical tools that allow any policymaker or researcher—especially in developing countries—to run energy scenarios without needing expensive commercial software.)



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Thank You