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Applied Systems Analysis
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science for global insight

Draft results: Modelling Carbon Neutrality - UNECE

14 July 2021



IIASA, International Institute for Applied Systems Analysis

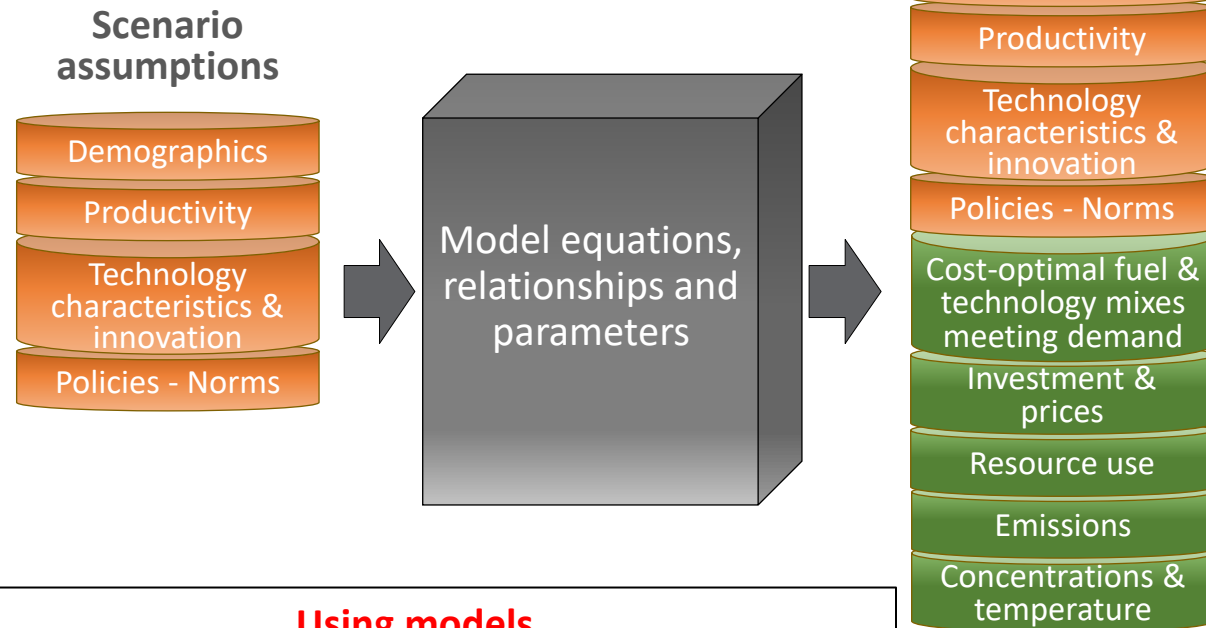
Models? Not crystal balls!

Processing data and assumptions

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- Energy models are simplified mathematical representations of real-world systems and relationships, calibrated with historical data
- Assumptions required to parameterize models
 - Integral part of the model design
 - Future rates of technological development
 - Socio-economics
 - Policy changes
- The model solves the mathematical relationships, given the input assumptions
- Scenarios explore different assumptions about inputs
- Policies can be defined through changes to model assumptions or specific policy goals



Using models

Models **can** inform policy makers on the implications of proposed domestic or international policies

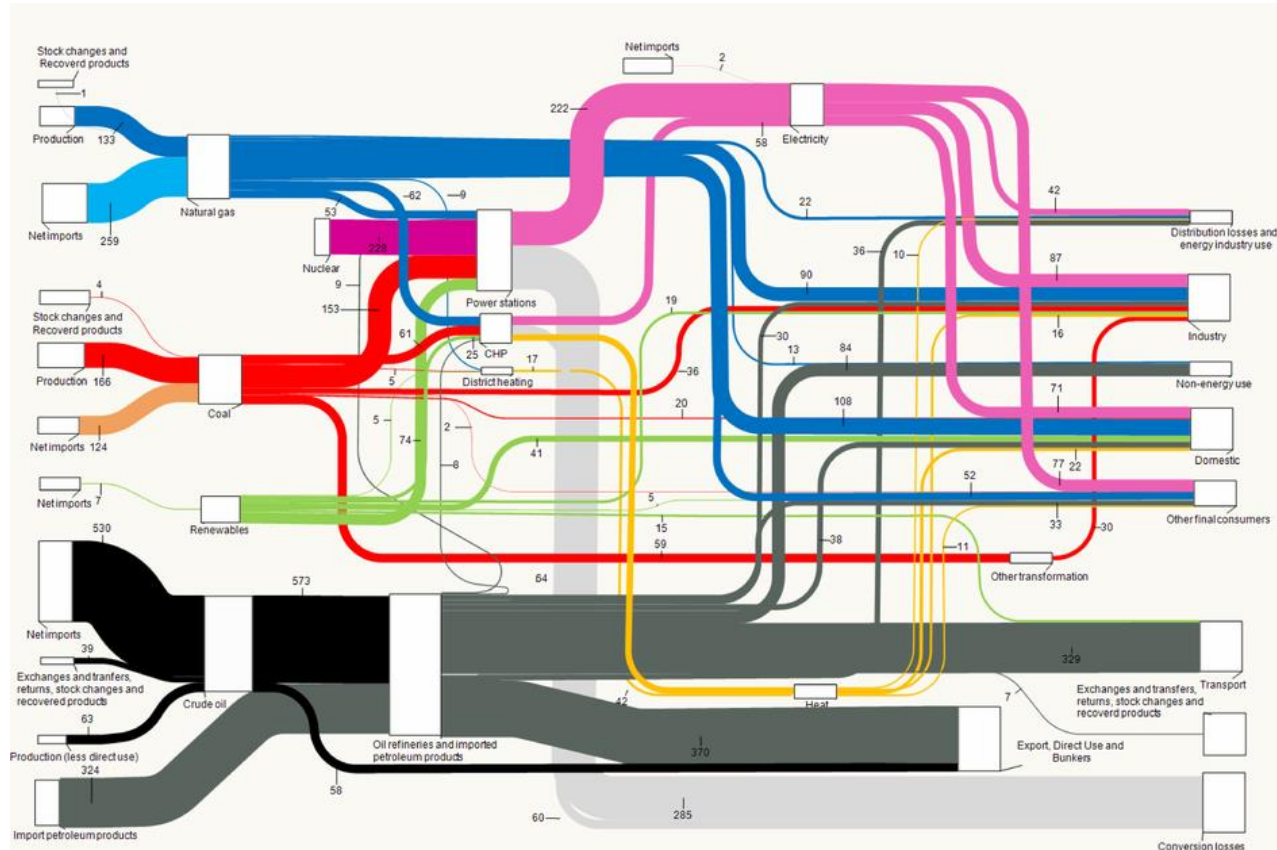
Models **cannot** determine the “best” technology or policy options

Essence of energy systems modeling

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- Energy is not an end in itself
- Energy is a 'complex system'
 - account for technologies, infrastructures, costs, variability of demand, technology limitations, policy constraints, security of supply, among others
- ensure that demand is always met in an efficient way (and now also sustainably)
- identify the most important drivers of the system with a quantification of their inter-relations



MESSAGE: Model for Energy Supply System Alternatives and their General Environmental Impacts



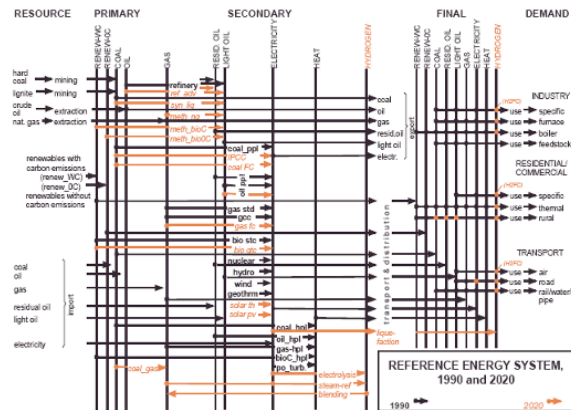
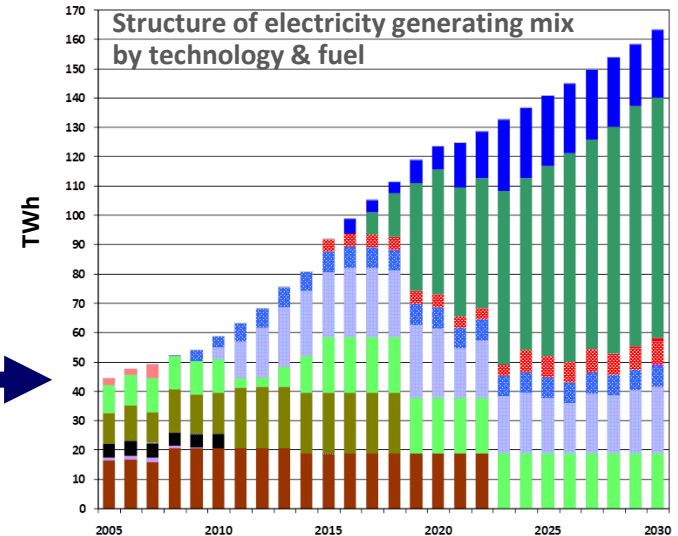
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INPUT

- Energy system structure (including vintage of plant and equipment)
- Base year energy flows and prices
- Energy demand (e.g., via link to MACRO)
- Technology and resource options & their techno-economic performance profiles
- Learning and innovation
- Technical and policy constraints



OUTPUT



- Primary and final energy mix
- Electricity generating mix, capacity expansion/retirement, investments
- GHG missions, air pollution, wastes
- Health and environmental impacts - via link to GAINS and LCA module
- Resource use - energy, water, land (via link to GLOBIOM), materials
- Trade & import dependence
- Prices

MESSAGE_{ix}

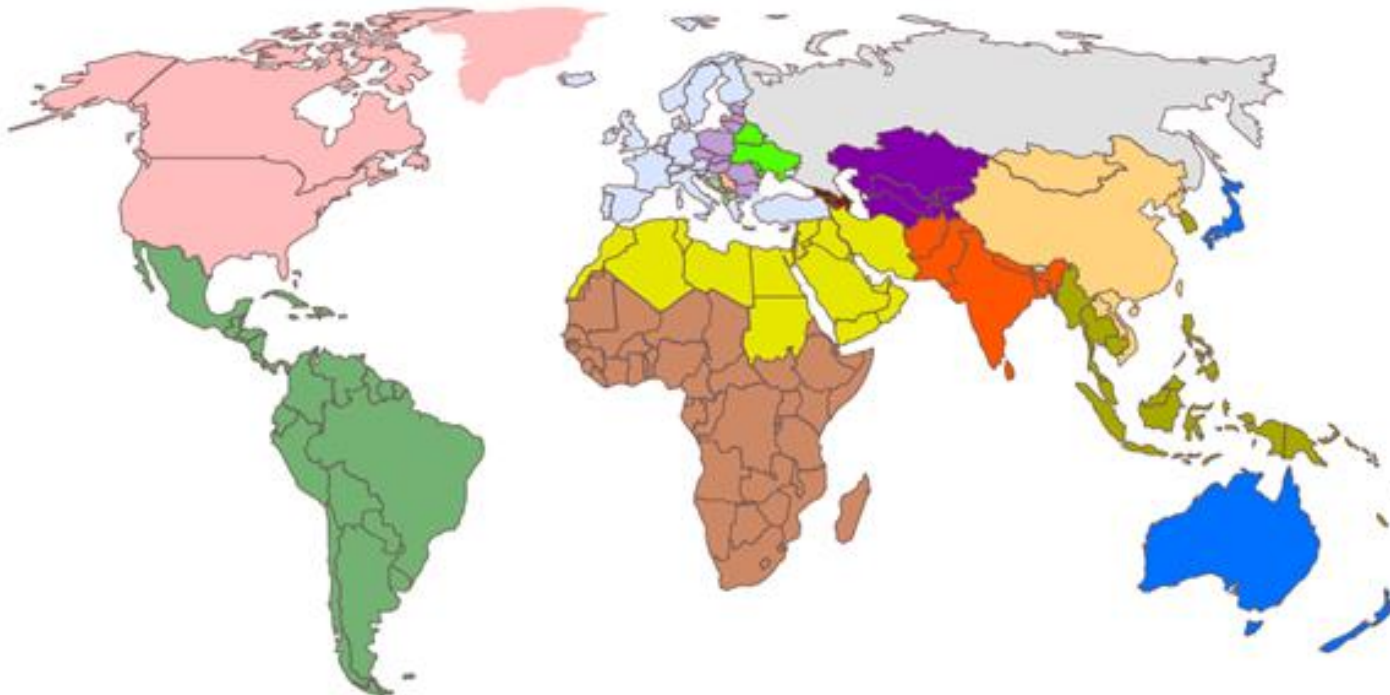
Regions Modelled

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AFR	Sub-Saharan Africa	LAC	Latin America and the Caribbean	RUS	Russian Federation
BMU	Belarus, Moldova, Ukraine	MEA	Middle East and North Africa	SAS	South Asia
CAS	Central Asia	NAM	North America	SCS	South Caucasus
CPA	Centrally planned Asia & China	PAO	Pacific OECD	SEE	South Eastern Europe/Western Balkan
CEE	Central and Eastern Europe	PAS	Other Pacific Asia	WEU	Western Europe

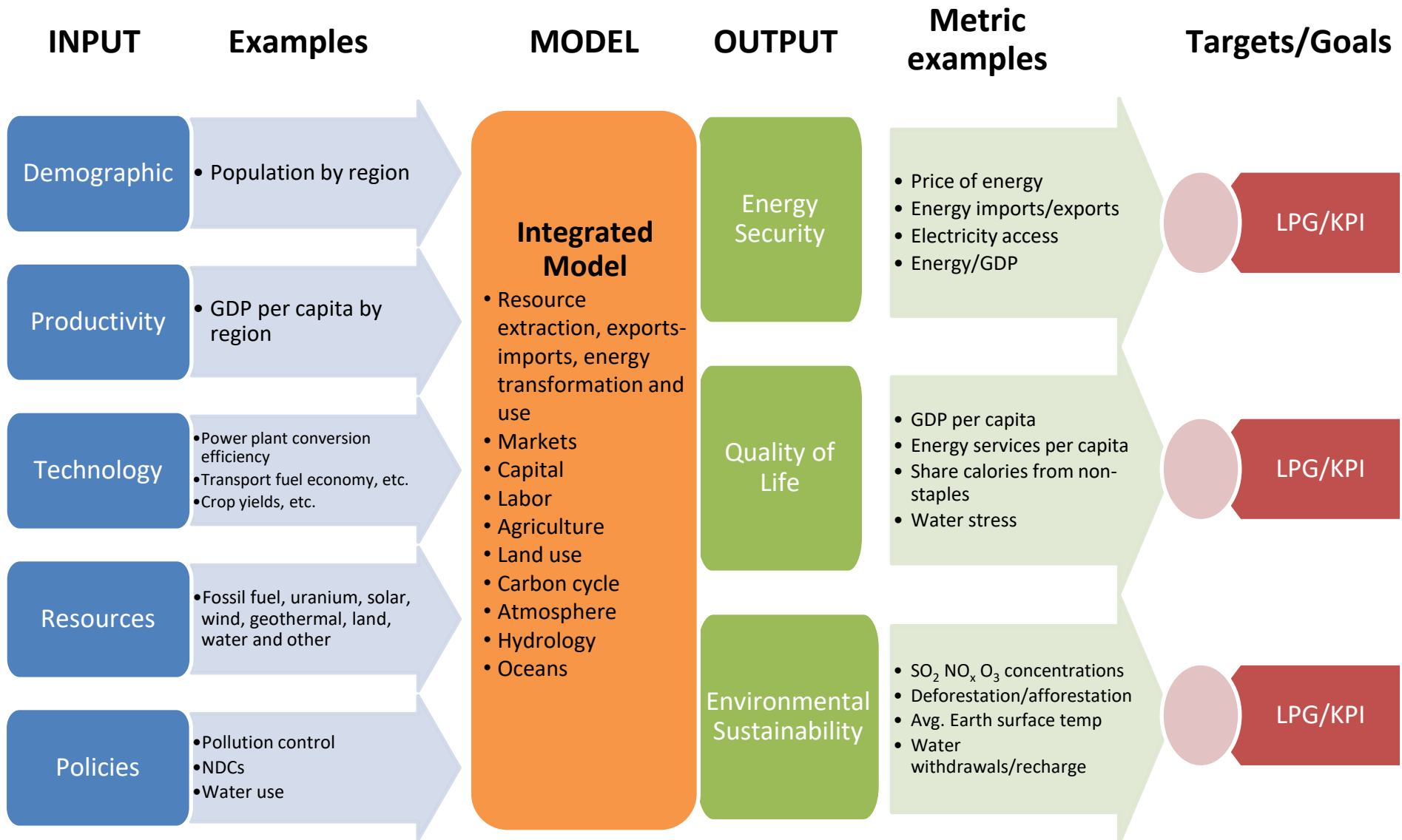
15 regions (8 of which are UNEC regions) covering the world



Scenario development

Illustration of scenario design

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I. Reference scenario (REF)

Based on SSP 2* as point of departure, i.e., without dedicated sustainable energy or climate policies (essentially the REF scenario of the Pathways Project)

II. Carbon neutrality scenario (Neutrality)

Normative scenario mandating carbon neutrality of UNECE's aggregate energy system by 2050 (and beyond)

III. Special technology scenarios (so far on the table....)

- a) Hydrogen – production options and markets (H2)
- b) Carbon capture, utilization and storage options; carbon dioxide removal and direct air capture (CCUS)
- c) Nuclear energy – realizing its potential, new application and markets (NUC)
- d) Low energy demand (extreme energy efficiency and intensity advances – (LED)

SSP: Shared Socio-economic pathway to 2100. Pathway 2 is a middle of the road future

Technology Deep Dives: ECE

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- **Three deep dives with selected sensitivity tests have been investigated:**
- CCUS: Carbon capture and storage (CCS) and direct air capture (DAC)
- NUC: Nuclear energy with focus on Small Modular Reactors (SMR)
- H2: Hydrogen pathways (production, synthesis and end use)

Sensitivity tests

- Load following nuclear – (Nuc_x)
- Hydrogen with fast learning of solid oxide technology – (H2_so)
- Hydrogen in absence of direct air capture – (H2_nD)
- Carbon neutrality with all deep dive features – (CN_all)
- Carbon neutrality with all deep dive features but neutrality reached by 2020 (or only 90% by 2050) – (CN_all)

Objectives of deep dives:

- Improving the model for better representation of technologies/processes
- Exploring the role of innovation (cost reduction) and new use cases in diffusion of chosen technologies
- Sensitivity analyses and looking into technology interplays

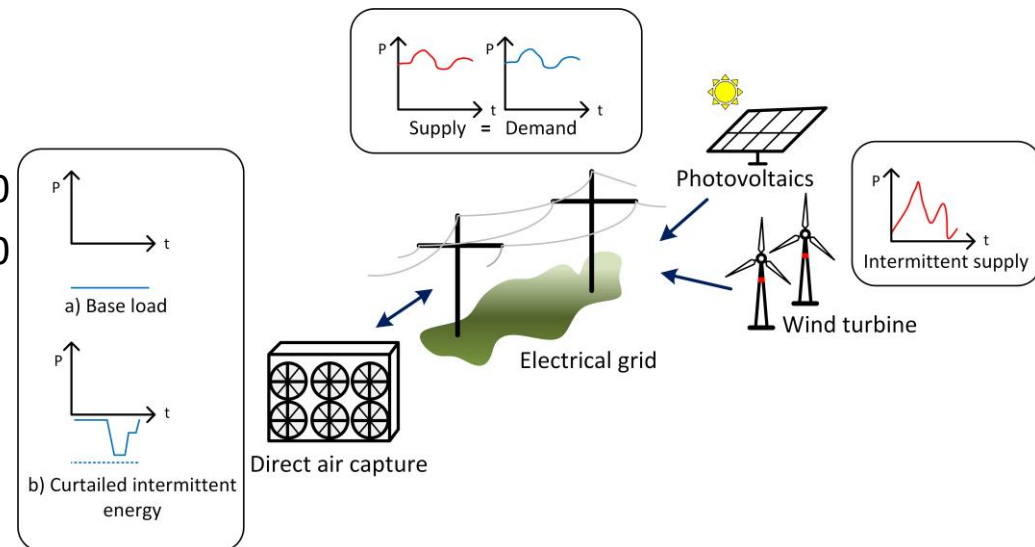
CCUS Deep Dive: ECE

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■ Main features of the carbon capture, utilization and storage (CCUS) scenario:

- Direct Air Capture (DAC) and CO₂ storage
- Representation of DAC in four different technology configurations
- Two DAC configurations with a flexible electricity demand: contribution to power balancing and reduction of renewable energy curtailment
- Regional CO₂ storage potentials
- Cost assumptions:
 - CAPEX of 4 650 - 5 000 US\$/tC/yr in 2020
 - CAPEX of 3 060 - 3 380 US\$/tC/yr in 2050



DAC Technologies: ECE

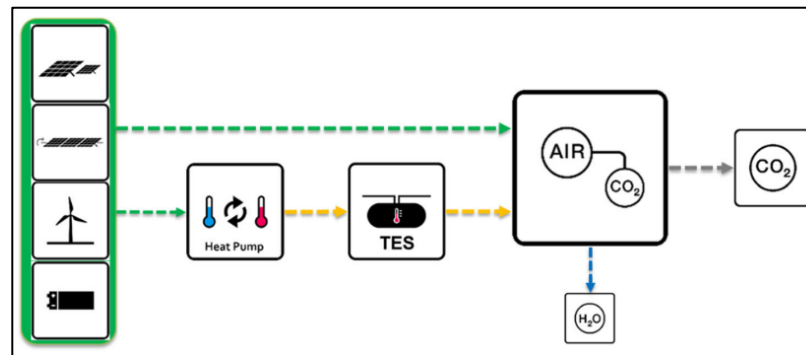
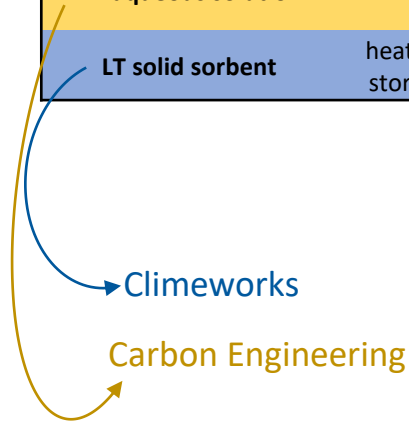
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Four DAC designs added to MESSAGE

Techno-economic assessment

Technology	Thermal energy input	Operability	Energy input		Economics		Water input usage (t/tCO ₂)	Effective FLh
			kWh _{el} /t	kWh _{th} /t	capex (€/tco ₂ *a)	opex (€/tco ₂ *a)		
HT aqueous solution	electrical (+battery)	Intermittency	1535.0	0.0	1160.4	39.6	4.3	8000
HT aqueous solution	electrical	Base load	1535.0	0.0	815.0	30.2	4.3	8000
HT aqueous solution	natural gas	Base load	0.0	2450.0	1032.0	38.2	4.3	8000
LT solid sorbent	heat pump (+ heat storage) + battery	Intermittency	888.8	0.0	1272.3	39.2	0.0	8000



Source: Breyer, C., Fasihi, M., & Aghahosseini, A. (2020). Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling. *Mitigation and Adaptation Strategies for Global Change*, 25(1), 43-65.



Main features of the nuclear (NUC) scenario:

- Representation of Small Modular Reactors (SMR) in the model
- Contribution of SMR to power balancing services (flexible operation)
- SMR providing low-temperature district heat (DH) in the cogeneration mode
- SMR producing high temperature process heat in the industry
- SMR combination with other processes, e.g., in hydrogen production
- Cost assumptions equal to large reactors per unit of capacity (\$/kW)
- Lower technology learning rates of DAC (diffusion rates are 25% of the CCUS scenario)

Sensitivity on the flexible operation of large nuclear power plant (Nuc_x):

- Large nuclear plants can operate in two modes: 1) “baseload” mode with high capacity factor (95%) but low flexibility, or 2) “flexible” mode with 75% capacity factor and flexibility as much as combined cycle gas power plants

Hydrogen Deep Dive: ECE

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Main features of the hydrogen (H₂) scenario:

- Additional hydrogen pathways
- Enhanced representation of hydrogen synthesis and conversion processes (hydrogen to methane, hydrogen to liquids (e-fuels))
- Enhanced representation of high-temperature electrolyzers combined with other technologies (e.g., nuclear SMR) → synergies with NUC deep dive
- Updated techno-economic assumptions for fuel cells in transportation
- Accelerated uptake of hydrogen in end use sectors (switching fuels to hydrogen in industry and res/comm, and favorable policies for hydrogen use in transport)
- Lower technology learning rates of DAC (diffusion rates are 25% of the CCUS scenario)

Sensitivity on the cost of hydrogen solid oxide electrolyzers:

- Hydrogen deep dive with a lower cost for electrolyzers

Other sensitivity scenarios: ECE

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All three deep dives together (CN_all):

- A scenario including all three technological deep dives, including:
 - Enhanced representation of hydrogen processes and usage
 - Enhanced representation of nuclear power
 - CCUS scenario including DAC

A scenario with neutrality in 2060 (CN_60)

- A scenario representing the consequences of delayed climate action, i.e., reaching carbon neutrality in 2060 (with 90% of the target reached in 2050)

A scenario without DAC (H2_nD)

- Deep dives of hydrogen and nuclear and CCUS included but without direct air capture (DAC) technologies

Scenarios and sensitivities at a glance



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Label in charts	Scenario name	Description
REF	Reference	Based on SSP2* as point of departure, i.e., without dedicated sustainable energy or climate policies (essentially the REF scenario of the Pathways Project).
CN	Carbon neutrality	Normative scenario mandating carbon neutrality of UNECE's aggregate energy system by 2050 (and beyond)
CCUS	Carbon capture utilization and storage deep dive	Carbon capture, utilization and storage options; carbon dioxide removal (CDR) and direct air capture (DAC)
NUC	Nuclear energy deep dive	This scenario is built on top of CCUS. Realizing nuclear potential, new applications (Small Modular Reactors) and markets. Thus, it includes DAC technologies.
H2	Hydrogen deep dive	This scenario is built on top of NUC. Inclusion of additional H2 pathways, synthesis and conversion technologies and markets. Thus, it also includes DAC.
CN_all	Neutrality with all deep dives	Neutrality including features from all deep dives
Nuc_x	Nuclear with flexible large nuclear power plants	Built on the NUC scenario. Thus, nuclear energy scenario assumptions including flexible nuclear power plants.
H2_so	Hydrogen solid oxide	Hydrogen deep dive scenario (H2) with low-cost and fast penetration of hydrogen solid oxide electrolyzers
H2_nD	H2 no DAC	Built on top of NUC deep dive, but without DAC techs.
CN_60	Carbon neutrality in 2060	Built on top of CN_all , yet reaching neutrality in 2060.

* [Shared Socioeconomic Pathway](#) up to 2100. Pathway 2 indicates a Middle-of-the-Road future.

Technology Deep Dives: ECE

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■ Summary of Deep Dives

Scenario	Label	Neutrality target	Direct air capture	Nuclear SMR	Accelerated H2 "end use"
Reference	REF	No	No	No	No
Neutrality	CN	Yes	No	No	No
CO2 capture and storage deep dive	CCUS	Yes	Yes	No	No
Nuclear deep dive	NUC	Yes	Yes (low learning rate)	Yes	No
Hydrogen deep dive	H2	Yes	Yes (low learning rate)	Yes	Yes

Sensitivity Scenarios: ECE

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Summary of sensitivity scenarios

Scenario	Label	Neutrality target	Direct air capture	Nuclear SMR	Accelerated H2 "end use"
Neutrality incl. all deep dives	CN_all	Yes	Yes	Yes	Yes
Nuclear flexibility	Nuc_x	Yes	Yes (low learning rate)	Flexible large reactors	No
Hydrogen solid oxide electrolyzer low cost	H2_so	Yes	Yes (low learning rate)	Yes	Yes (low cost of H2 supply from electrolyzer)
Hydrogen and nuclear without DAC	H2_nD	Yes	No	Yes	Yes
Neutrality late action	CN_60	Yes (2060)	Yes	Yes	Yes

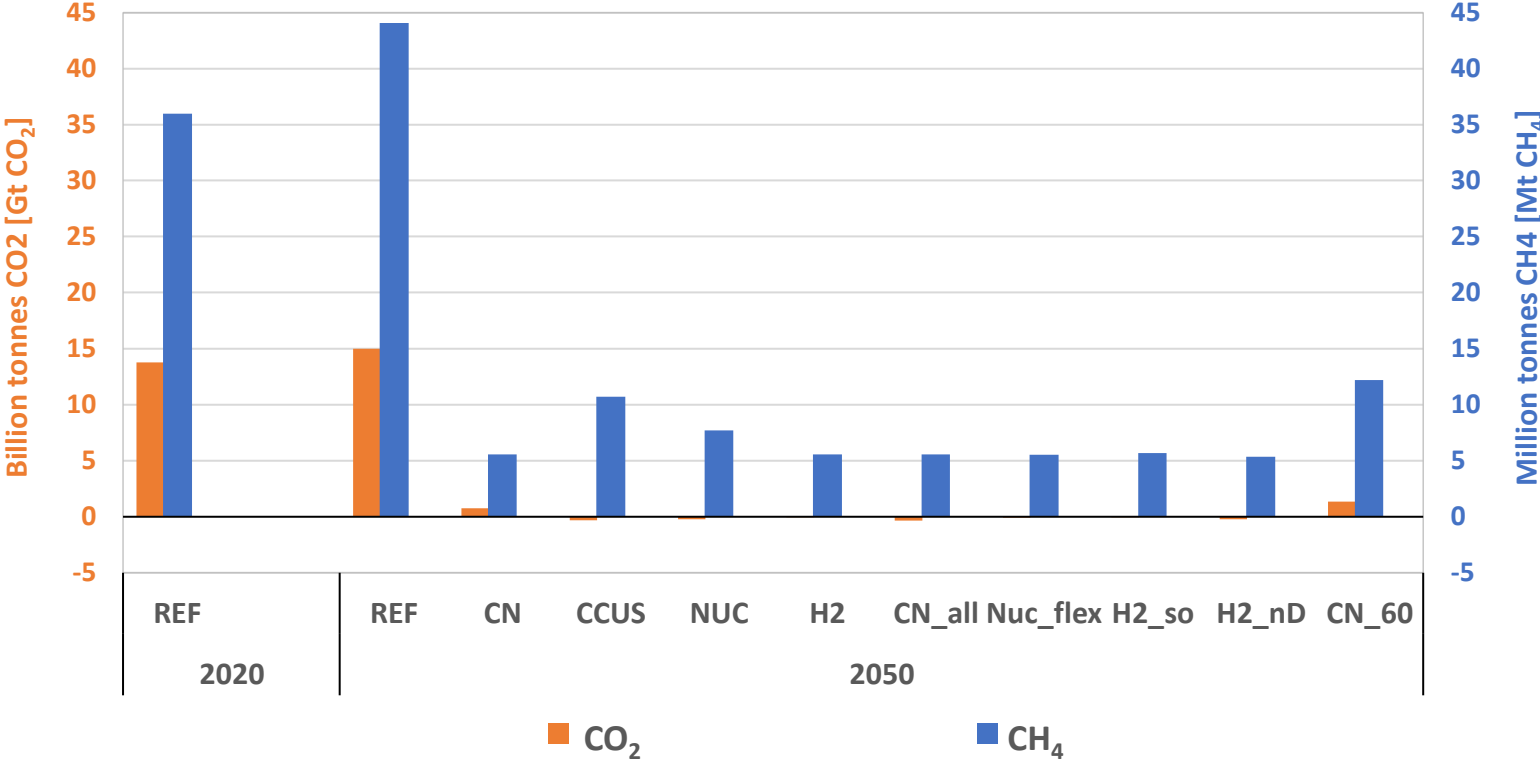
Modeling Results: ECE

Emissions



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Carbon dioxide (CO₂) and methane (CH₄) emissions, ECE Comparison across scenarios, 2020-2050



Modeling Results: ECE

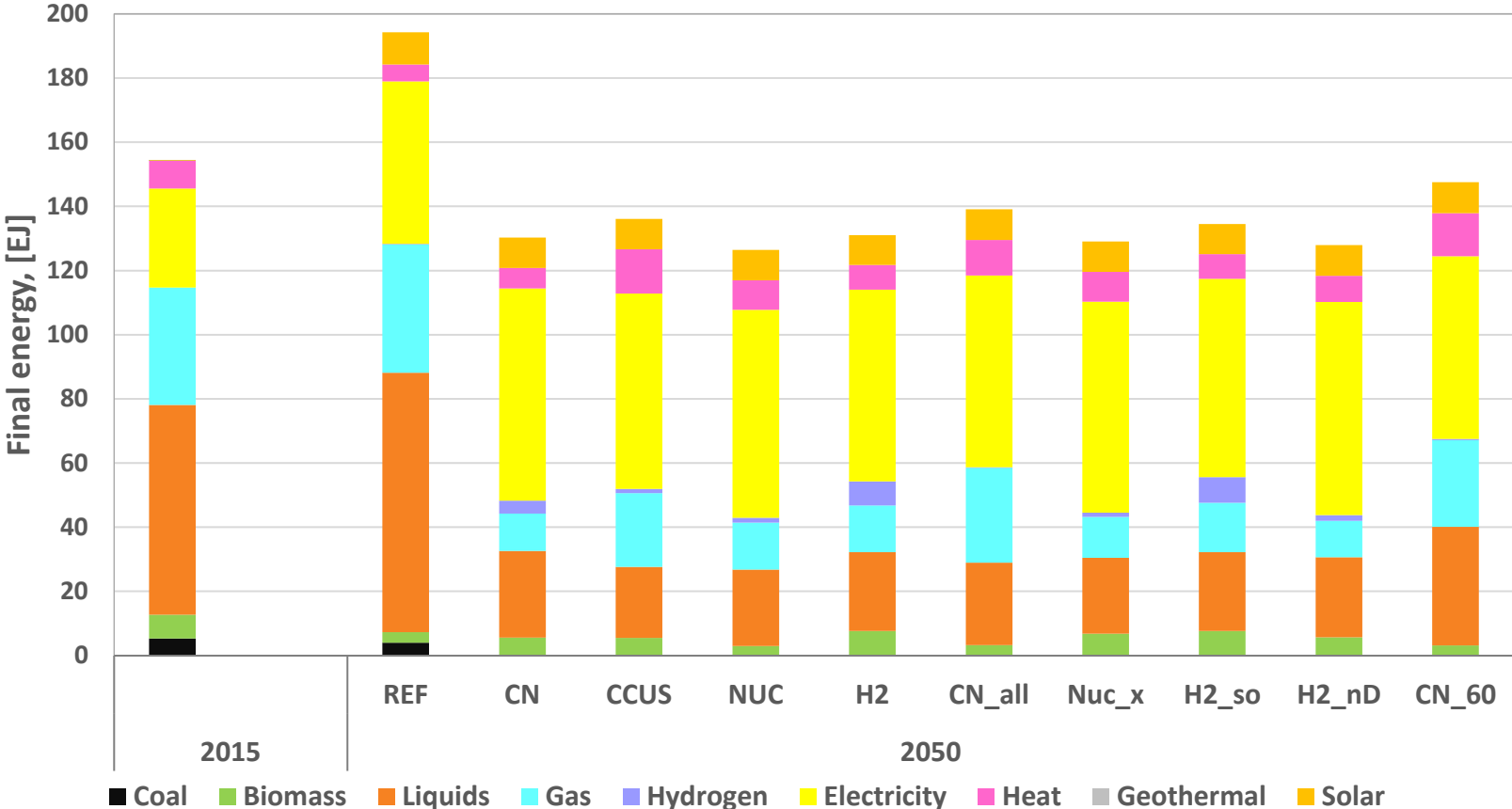
Final energy Mix

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Final energy mix – ECE

Comparison across scenarios, 2015 and 2050



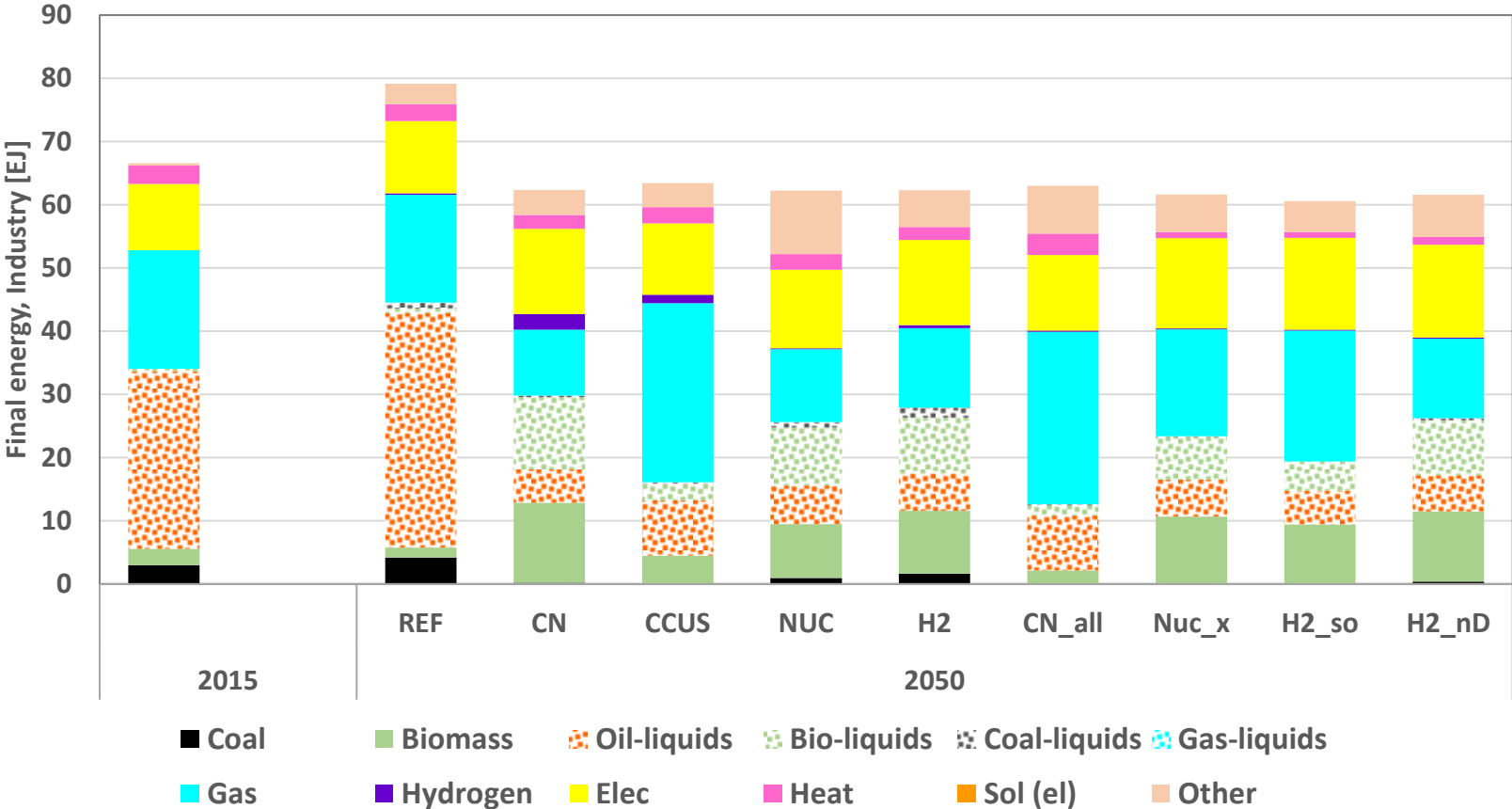
Modeling Results: ECE

Final Industrial energy Mix



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Final energy mix – Industry Comparison across scenarios, 2015 and 2050



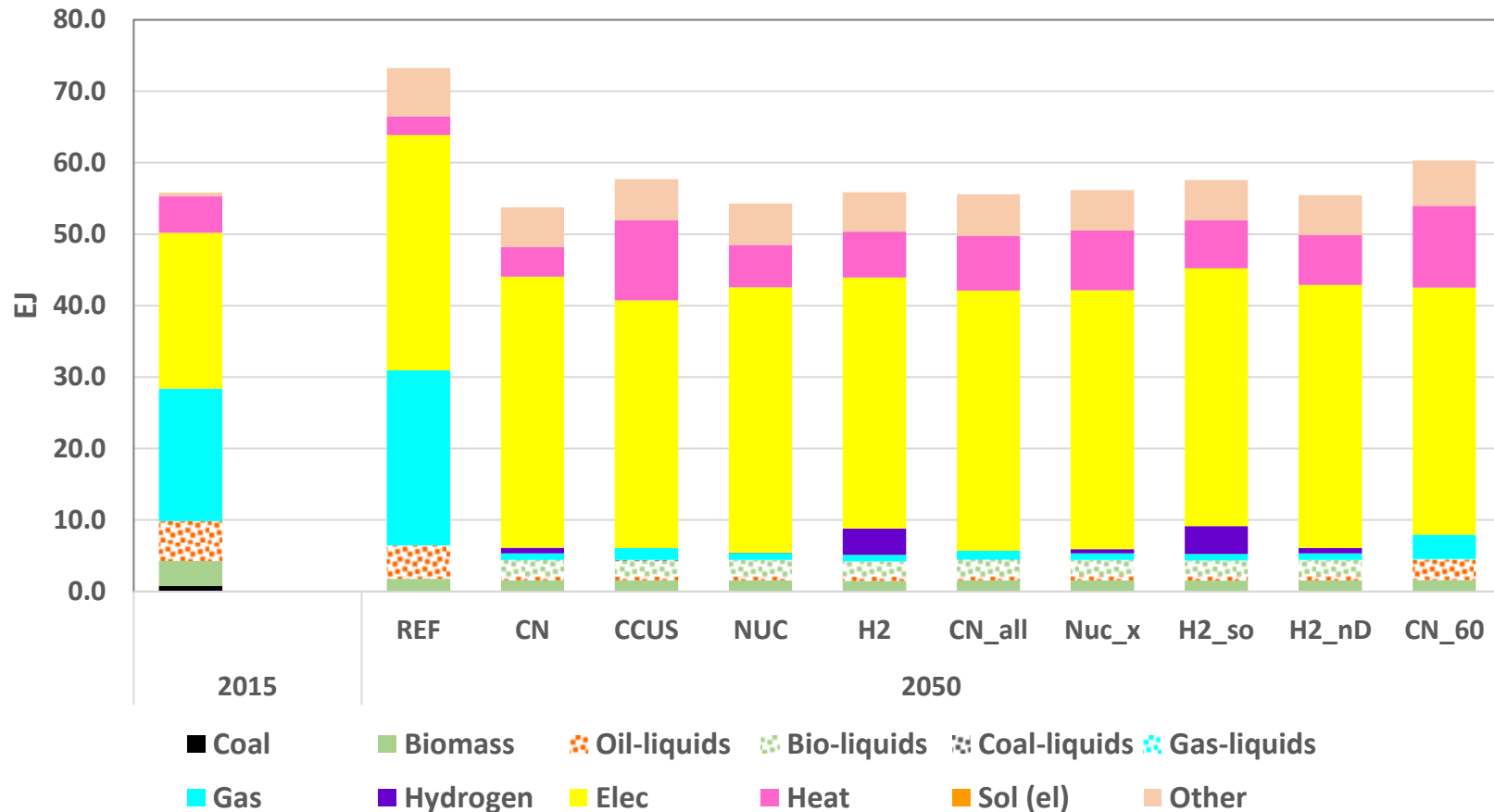
Modeling Results: ECE

Final energy mix Residential/Commercial

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Final energy mix – Residential/Commercial Comparison across scenarios, 2015 and 2050



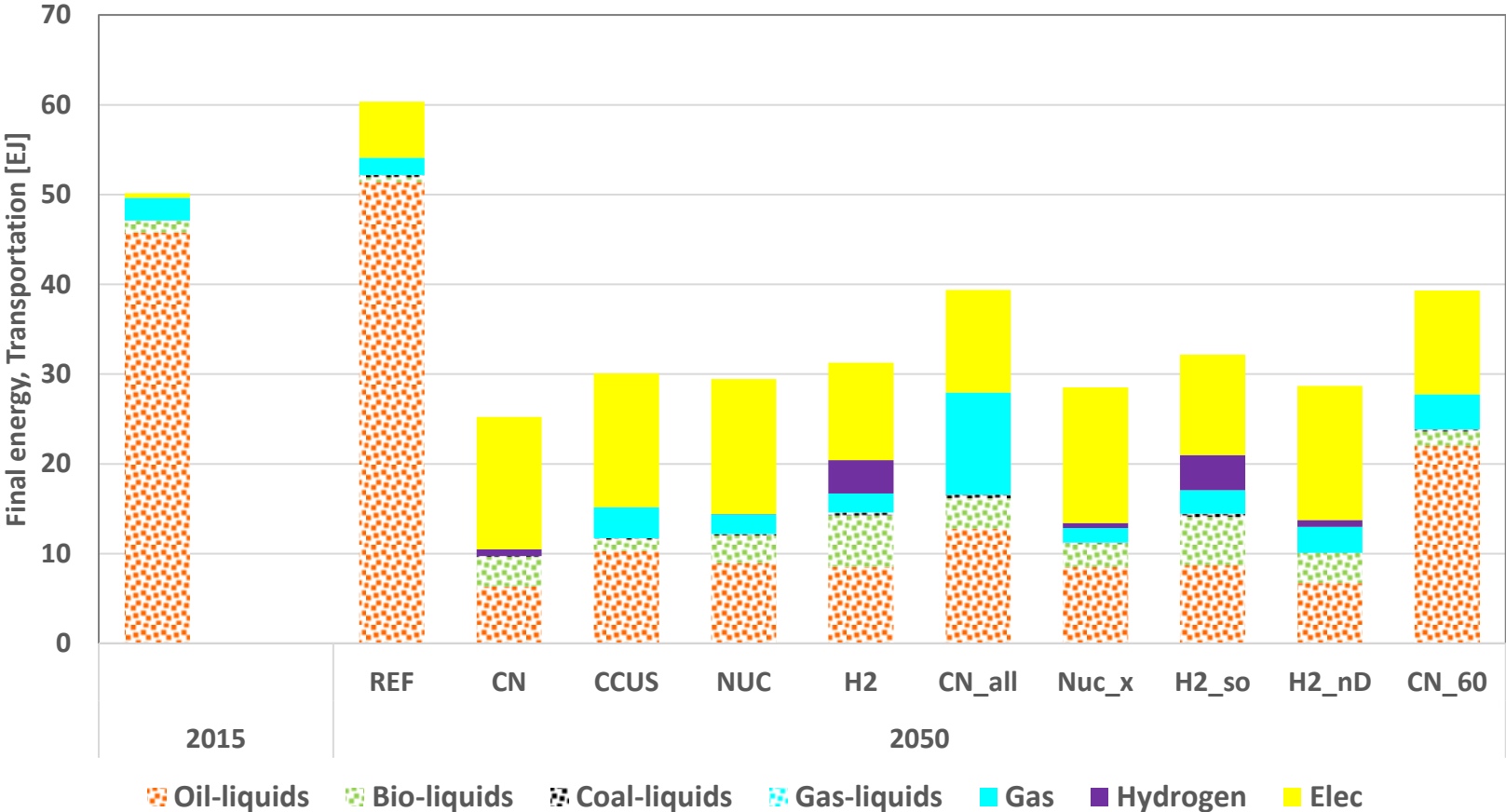
Modeling Results: ECE

Final Transportation Energy Mix

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Final energy mix - Transportation Comparison across scenarios, 2015 and 2050



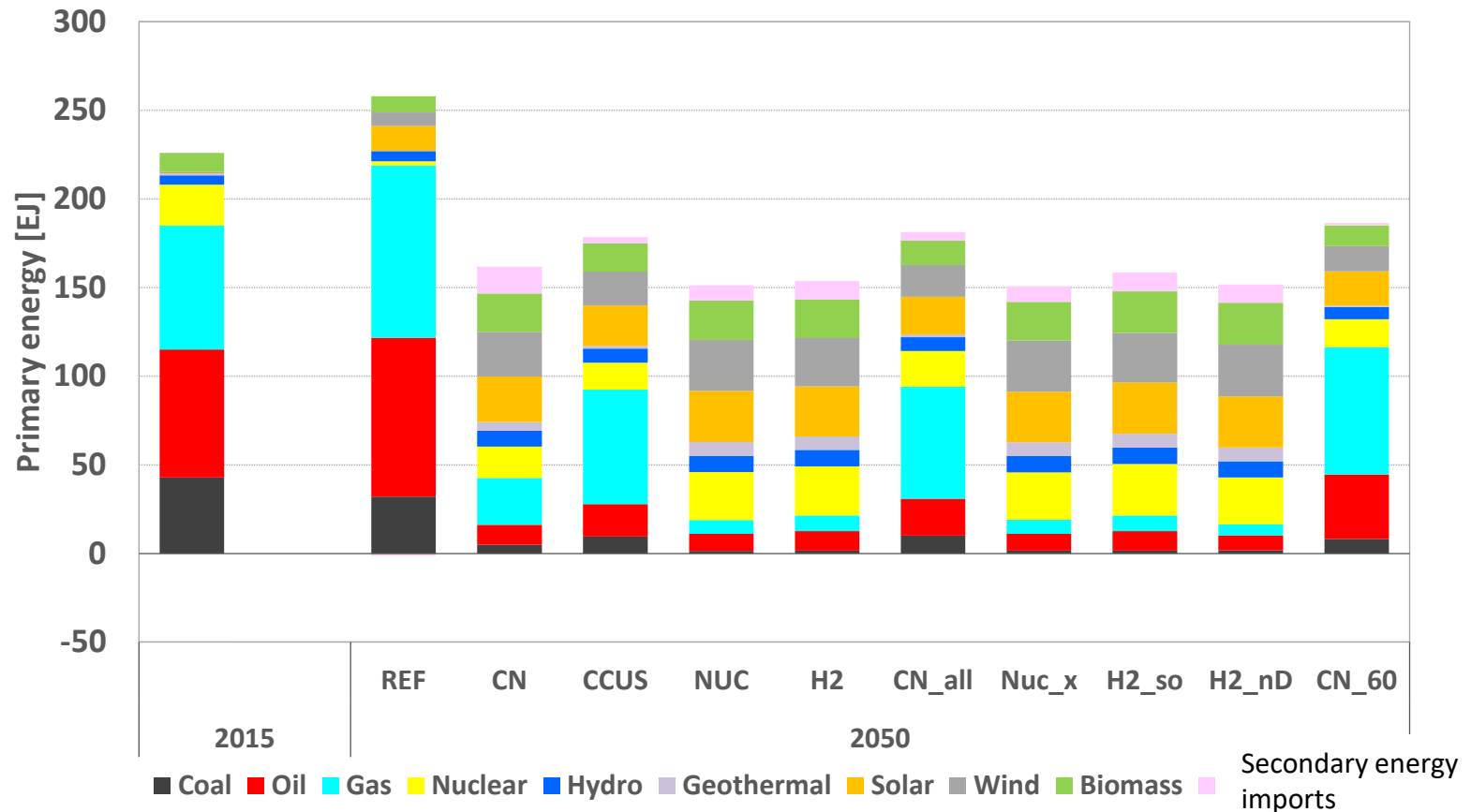
Modeling Results: ECE

Primary Energy Mix

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Primary energy mix - ECE Comparison across scenarios, 2015 and 2050



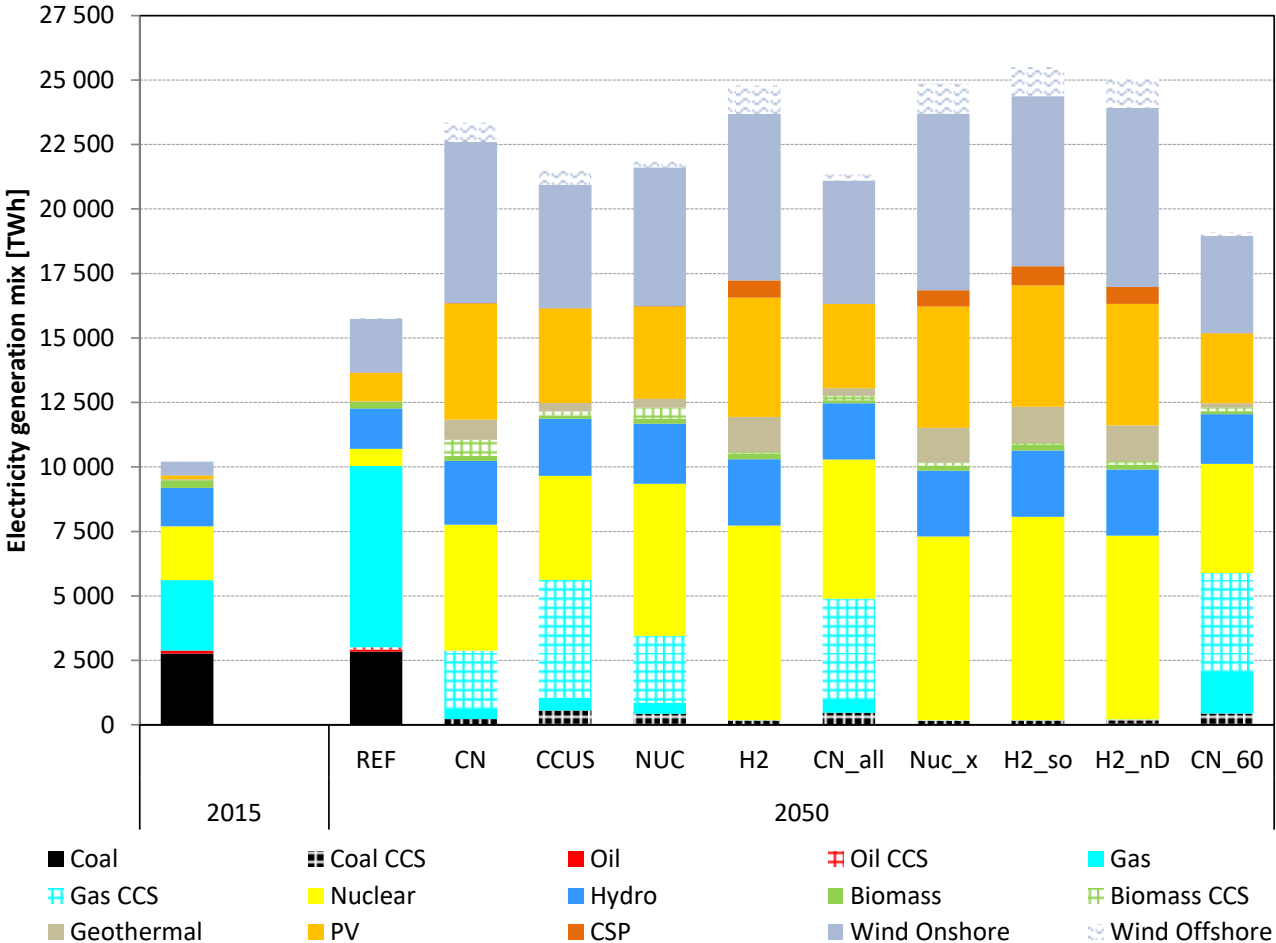
Modeling Results: ECE

Electricity Generation

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Electricity generation by technology - ECE Comparison across scenarios, 2015 and 2050



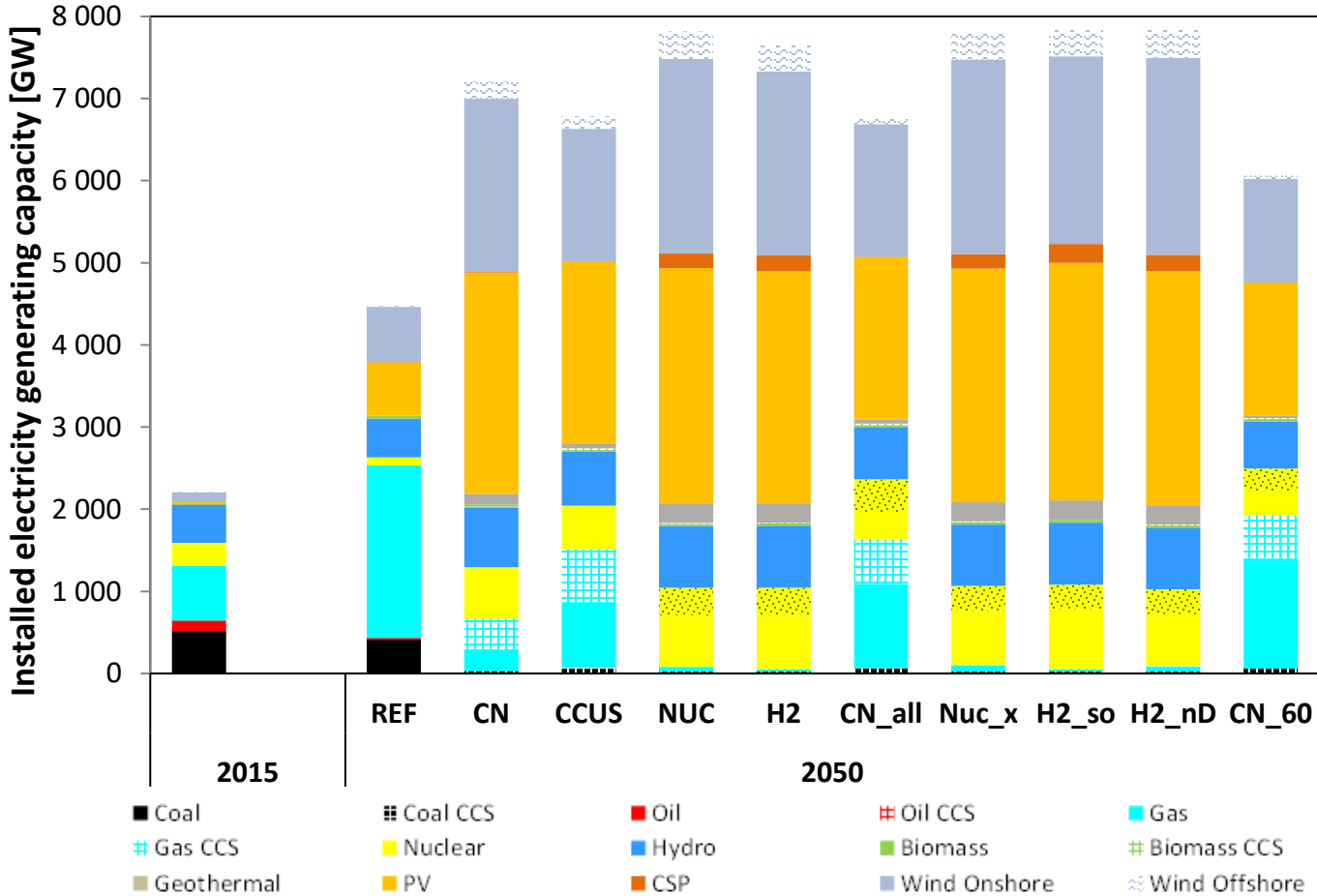
Modeling Results: ECE

Electricity Generating Capacity

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Electricity generating capacity by technology - ECE Comparison across scenarios, 2015 and 2050



Modeling Results: ECE

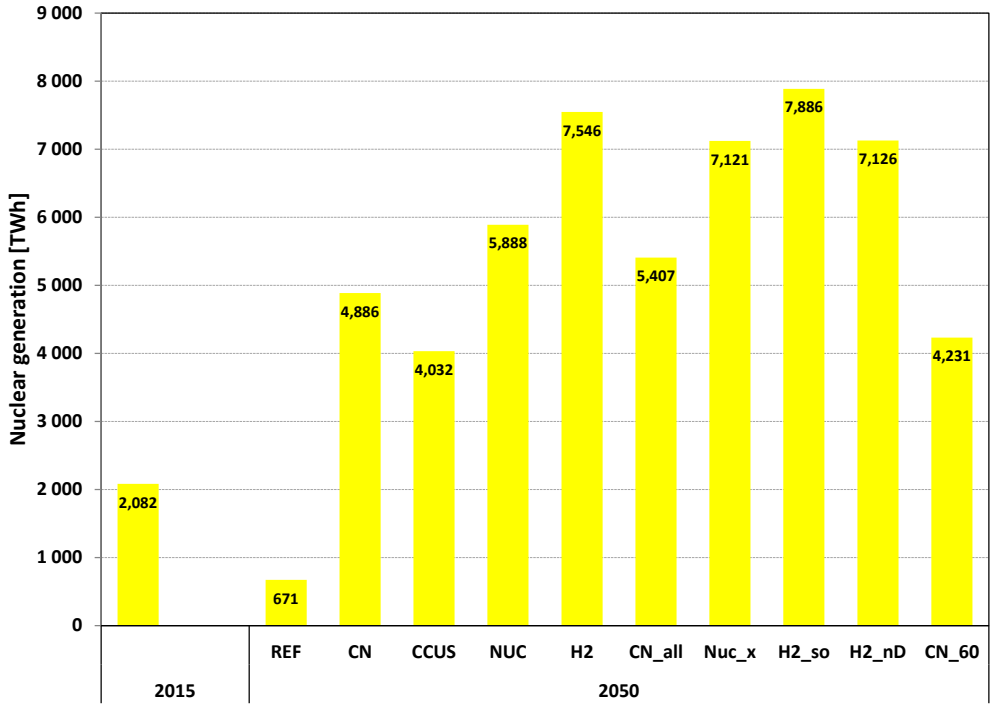
Nuclear Energy



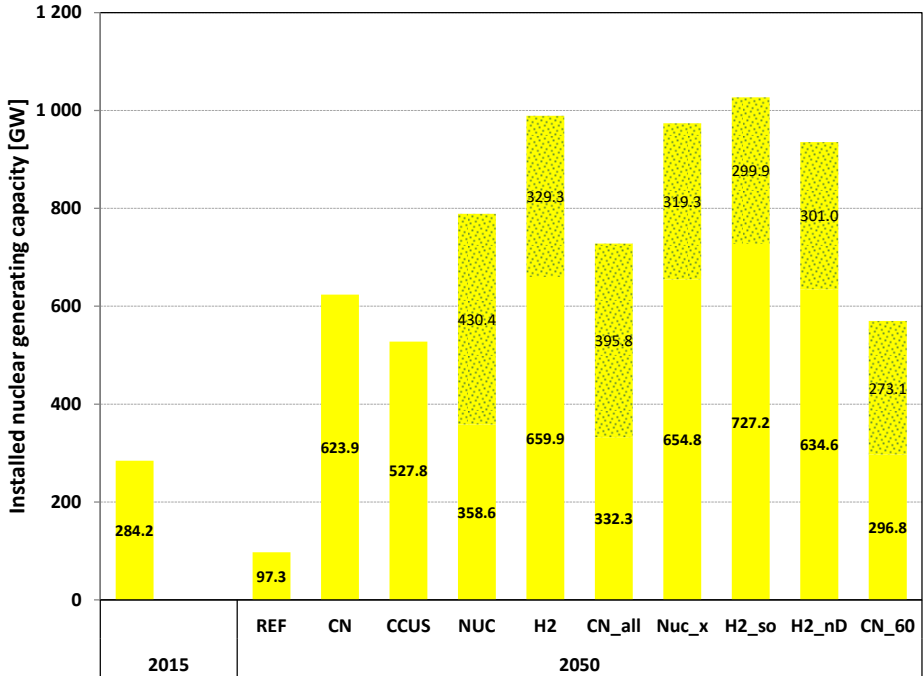
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Nuclear generating capacity - ECE Comparison across scenarios, 2015 and 2050

Generation



Capacity



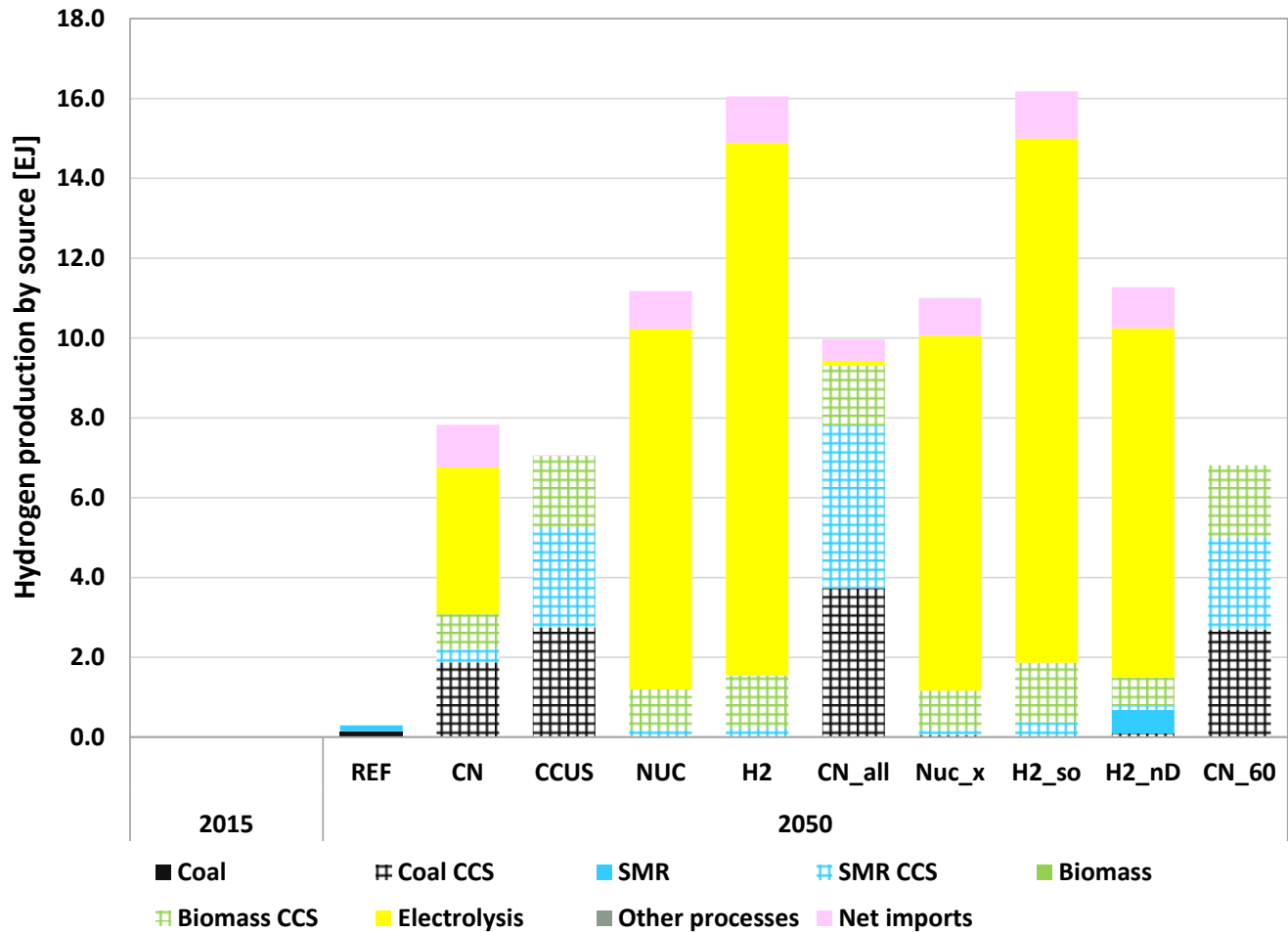
Modeling Results: ECE

Hydrogen Supply

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Hydrogen supply - ECE Comparison across scenarios, 2015 and 2050



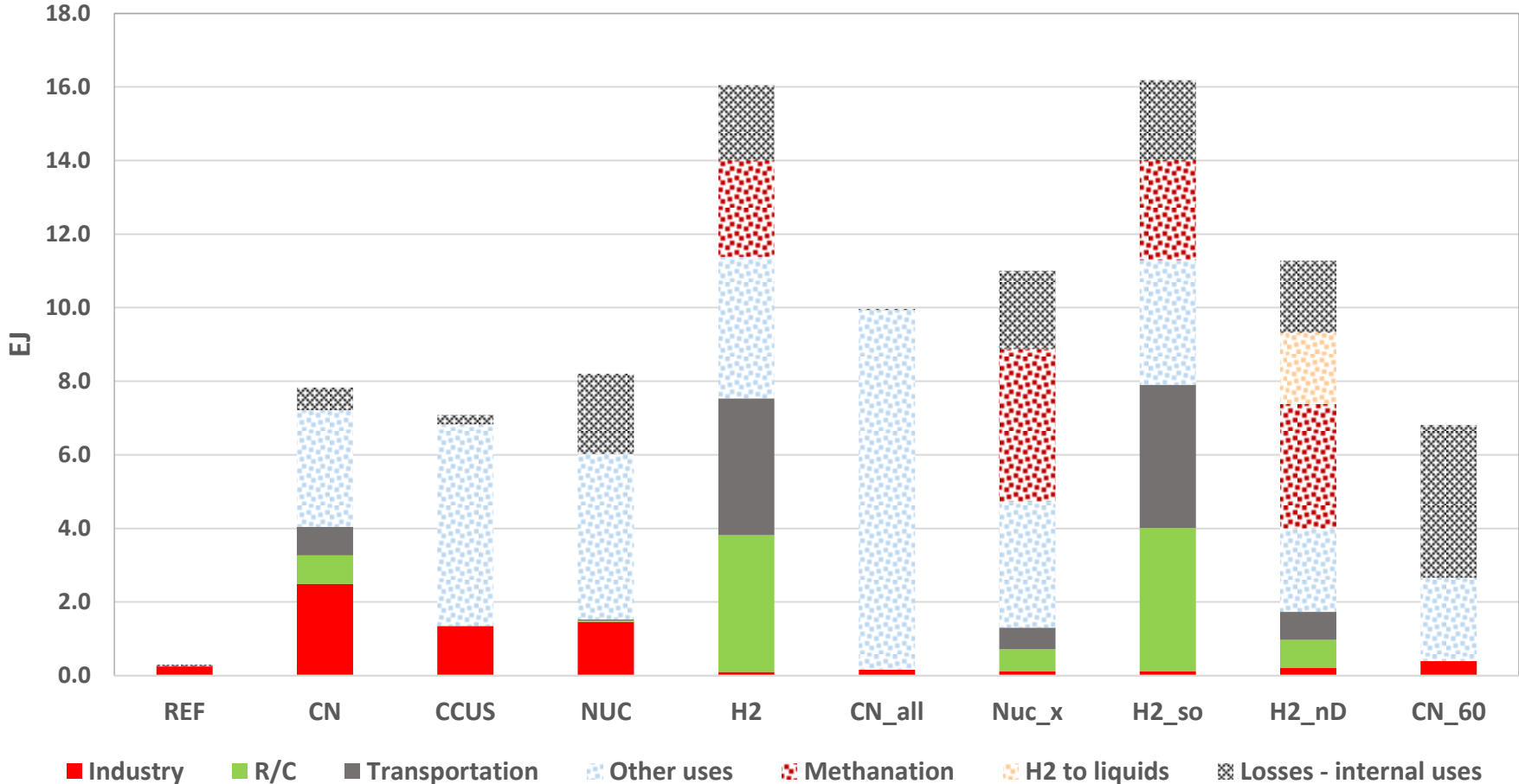
Modeling Results: ECE

Hydrogen Uses



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Hydrogen uses - ECE Comparison across scenarios, 2050



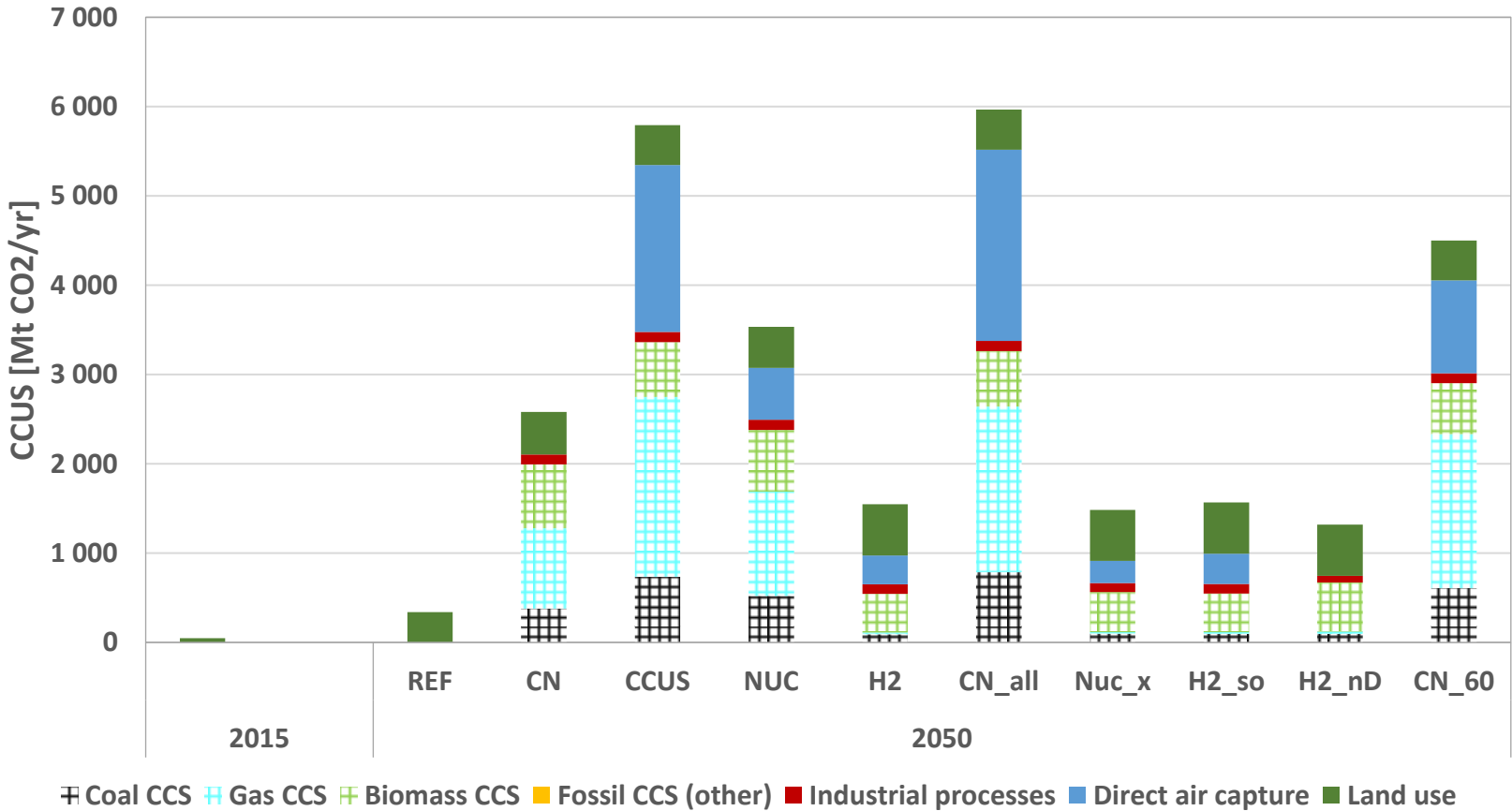
Modeling Results: ECE

CCUS



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Carbon capture, utilization and storage, ECE Comparison across scenarios, 2020-2050



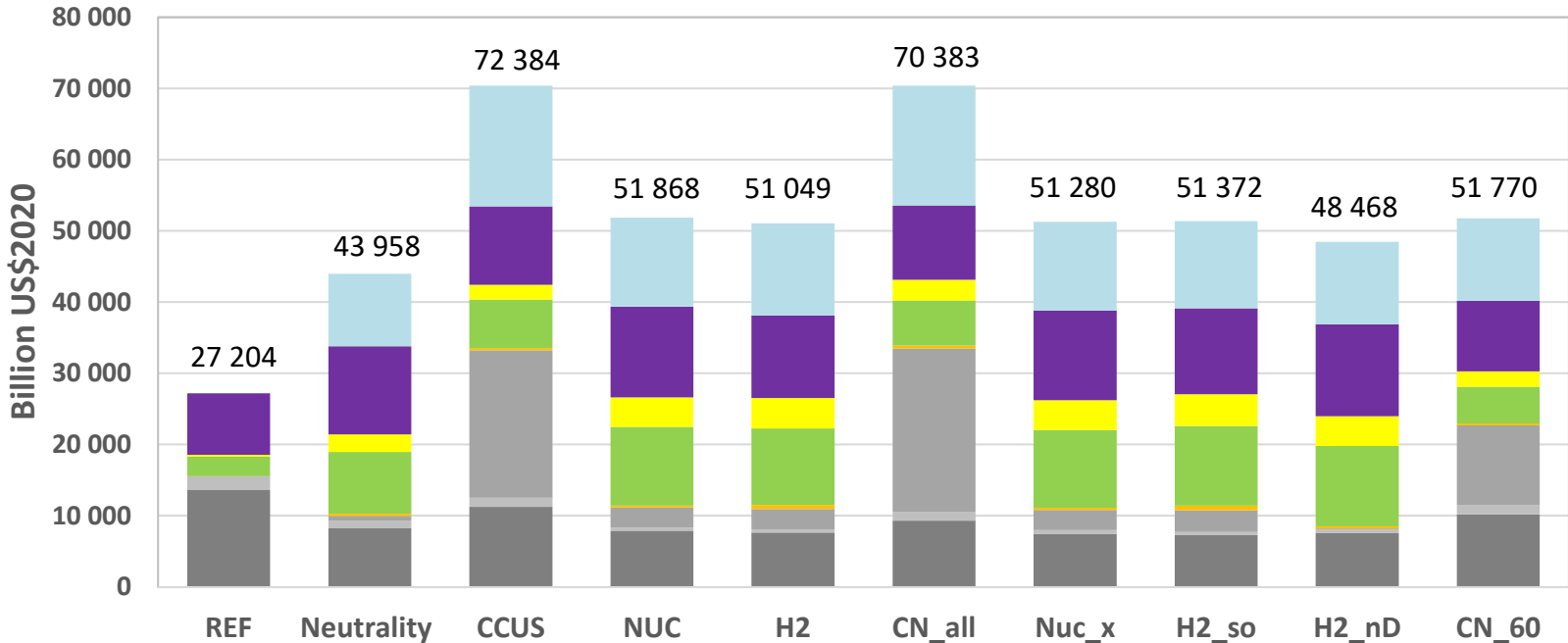
Modeling Results: ECE

Investment Needs



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Cumulative investments and total system costs: ECE Comparison across scenarios, 2020-2050



- Fossil fuel (extraction, transmission, and processing)
- Fossil CCS
- Renewables (incl. biomass CCS)
- T/D and S
- Fossil electricity generation
- Hydrogen
- Nuclear
- Energy efficiency & intensity

■ T&D: transmission and distribution of electricity and district heat
 ■ Investments in US\$ at 2020 prices and exchange rates

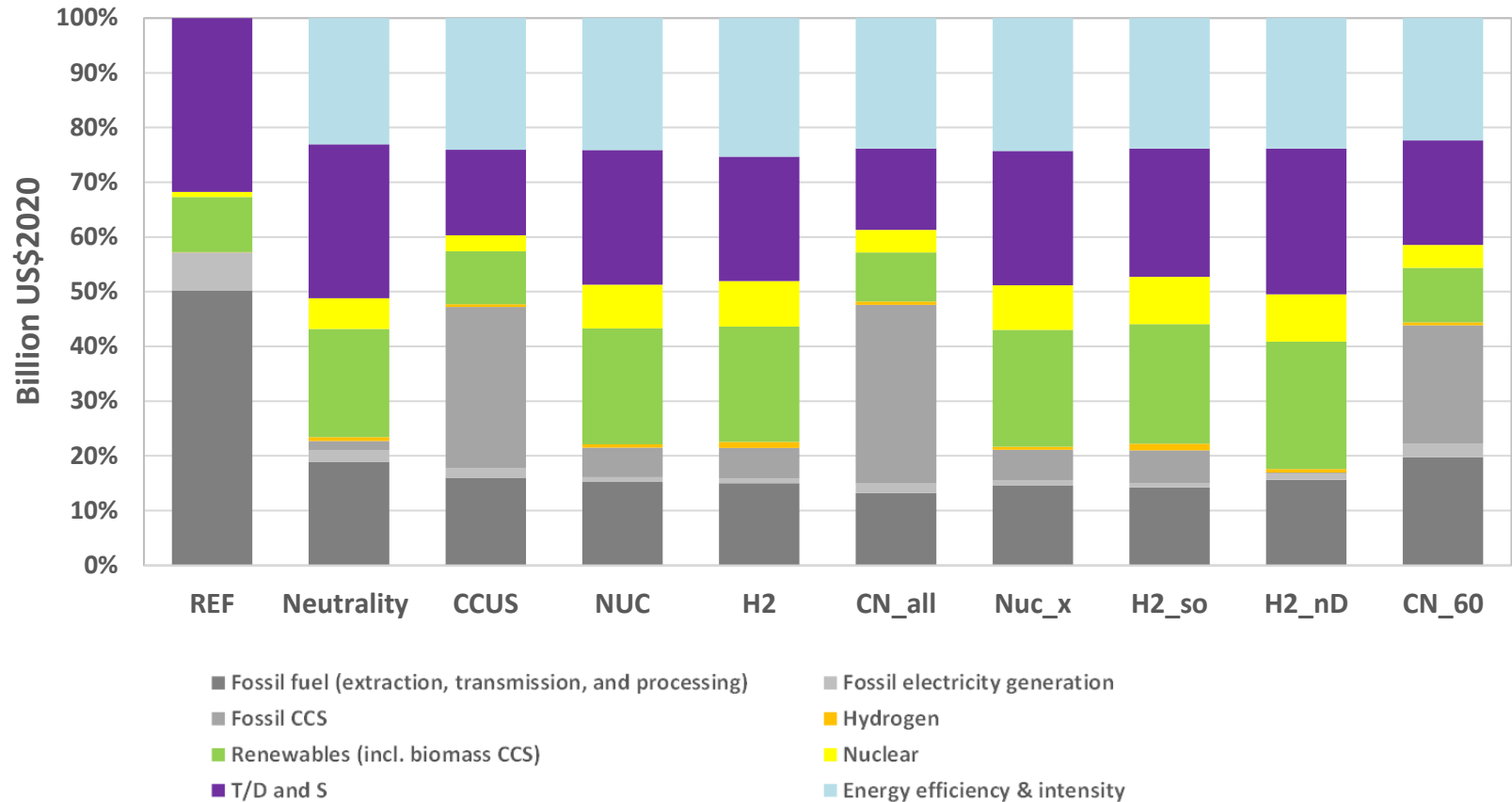
Modeling Results: ECE

Investment Needs

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Relative cumulative investment by technology: ECE Comparison across scenarios, 2020-2050



■ T&D: transmission and distribution of electricity and district heat
■ Investments in US\$ at 2020 prices and exchange rates

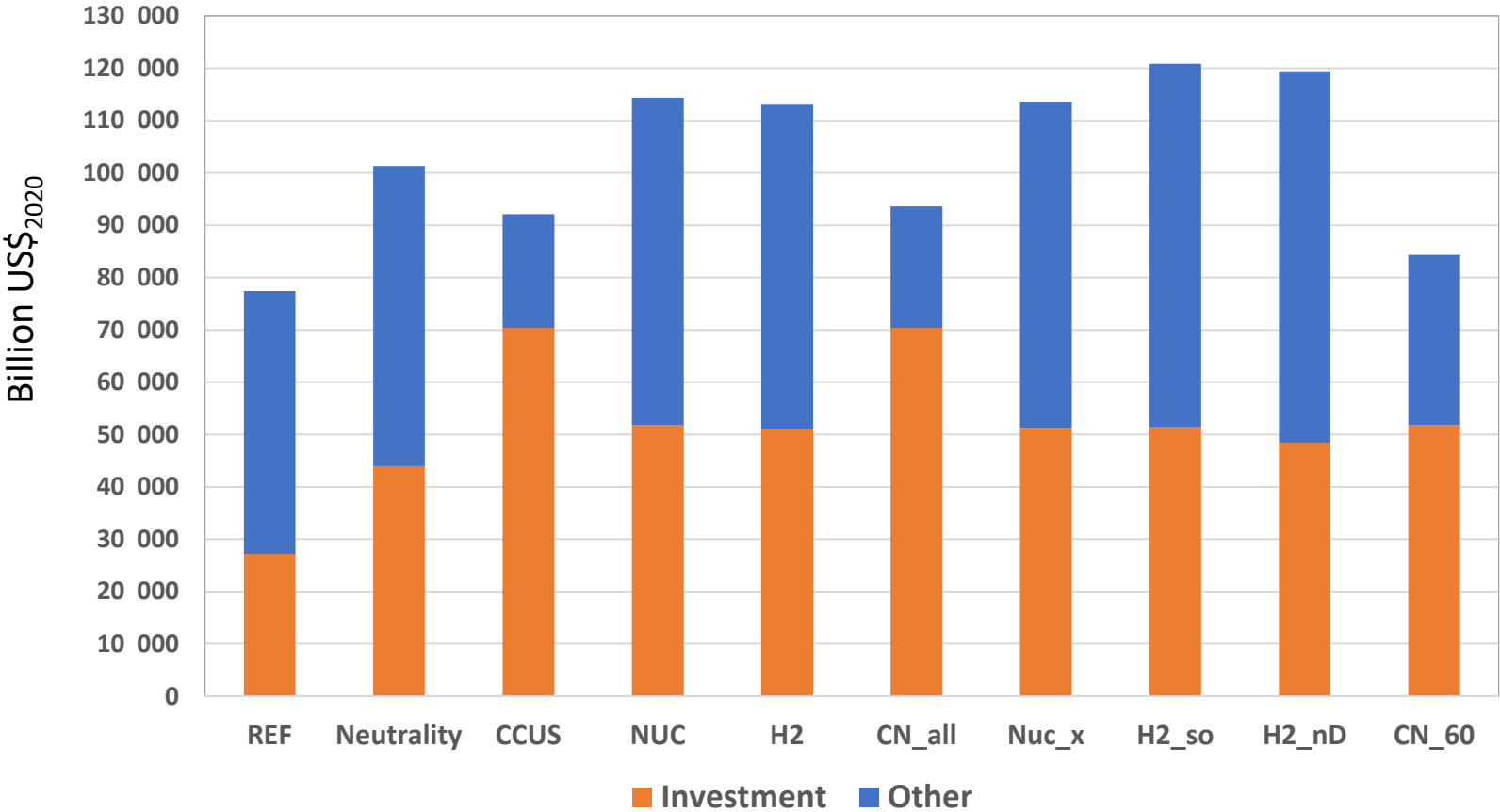
Modeling Results: ECE

Investment Needs



ENERGY

Cumulative investments and total system costs: ECE Comparison across scenarios, 2020-2050



“Other” includes any cost other than CAPEX, for example, O&M costs, fuel import costs (minus export revenues), land use costs, etc.

Modeling Results: ECE

Closing remarks

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Summary comments

- Carbon neutrality from a modeler's perspective is techno-economically feasible based on numerous and highly uncertain assumptions
- The ten cases shown today are only a fraction of scenarios/cases that can (and should) be analyzed
- Supply is primarily a technology/engineering challenge with some socio-political tension which path is the right one
- Demand side, life-style changes and associated infrastructure transformation (finance) remain a key challenge
- The economic burden that a carbon neutrality imposes on society lies outside the analysis domain of MESSAGE
- The analyses have shown that technology exclusion reduces flexibility and increases costs
- No one size fits all – always be aware of trade-offs