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Modelling a Low-Carbon Future: Tools for Energy and Carbon Infrastructure

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CHRISTCHURCH NEW ZEALAND

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25 years ISS

Scarce resources, surrounded by deadly cold vacuum

1 Renewables

Solar PV and Li-ion batteries

2 Energy efficiency

Structures are well-insulated (→ need to release heat)

3 Electrification

All appliances electric

4 Hydrogen

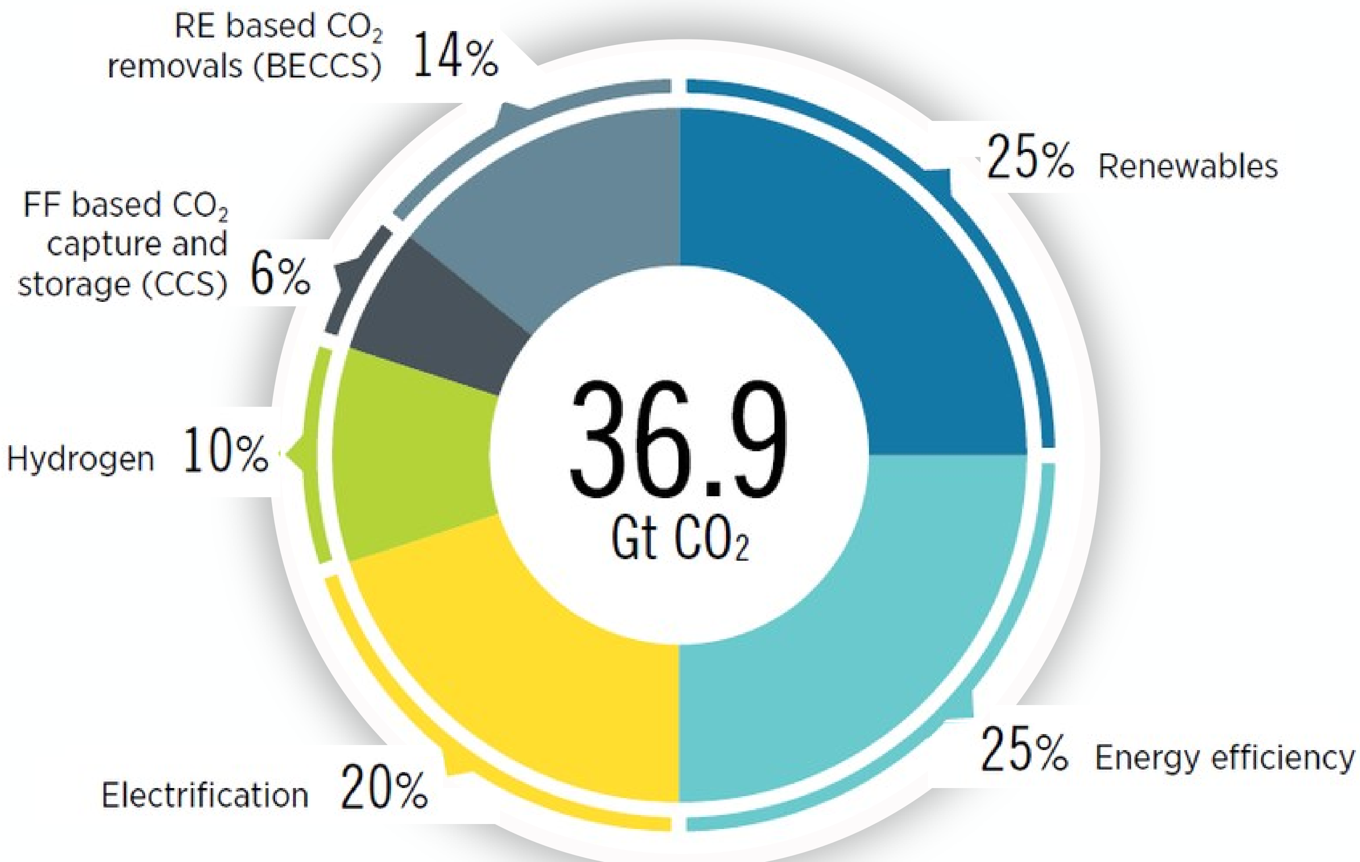
As rocket fuel and for the space shuttle's fuel cells

5 CO_2 capture

CO_2 scrubbers to recycle air

How to achieve net-zero?

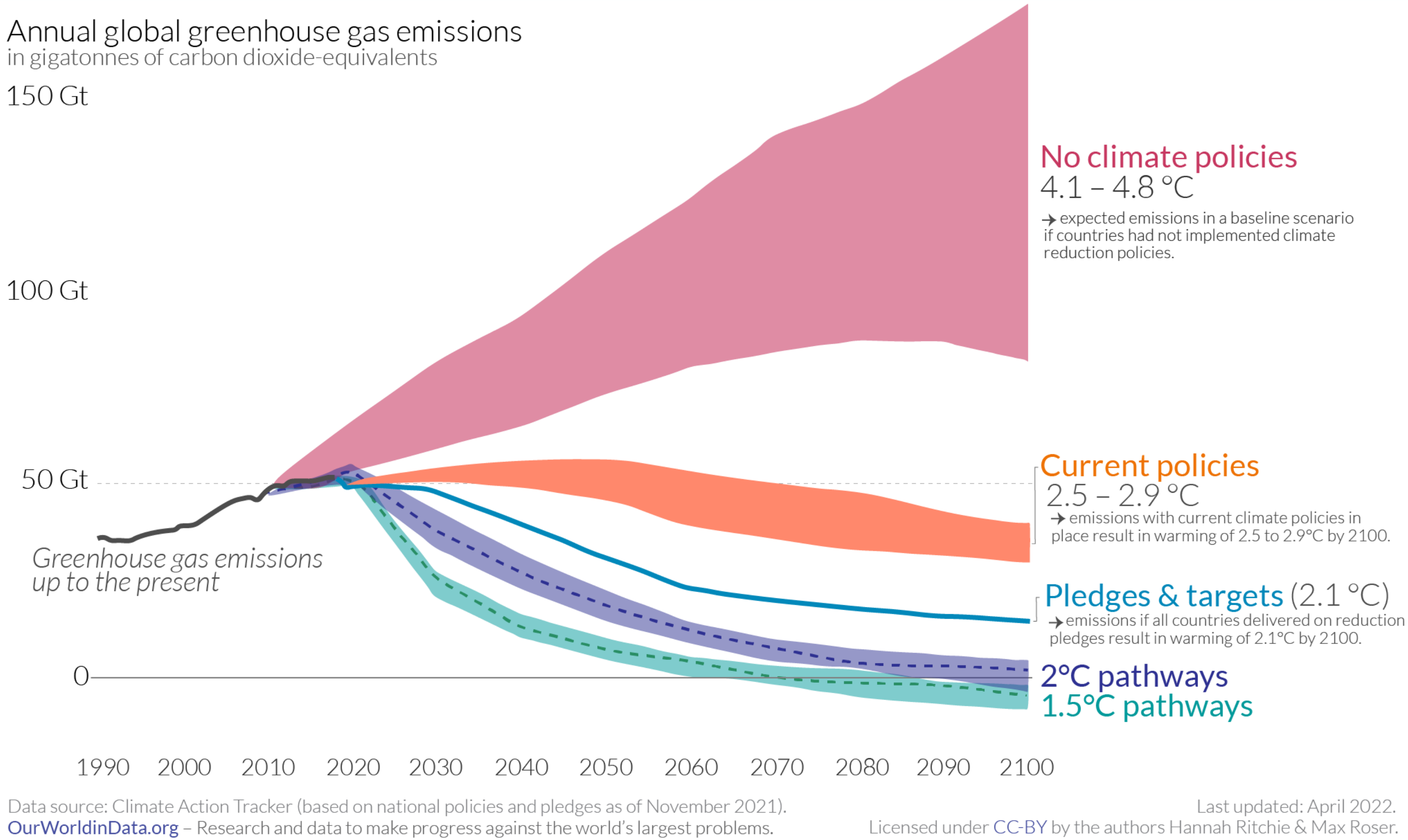
5 pillars: renewables, efficiency, electrification, hydrogen, carbon capture



IRENA (2022) World Energy Transition.

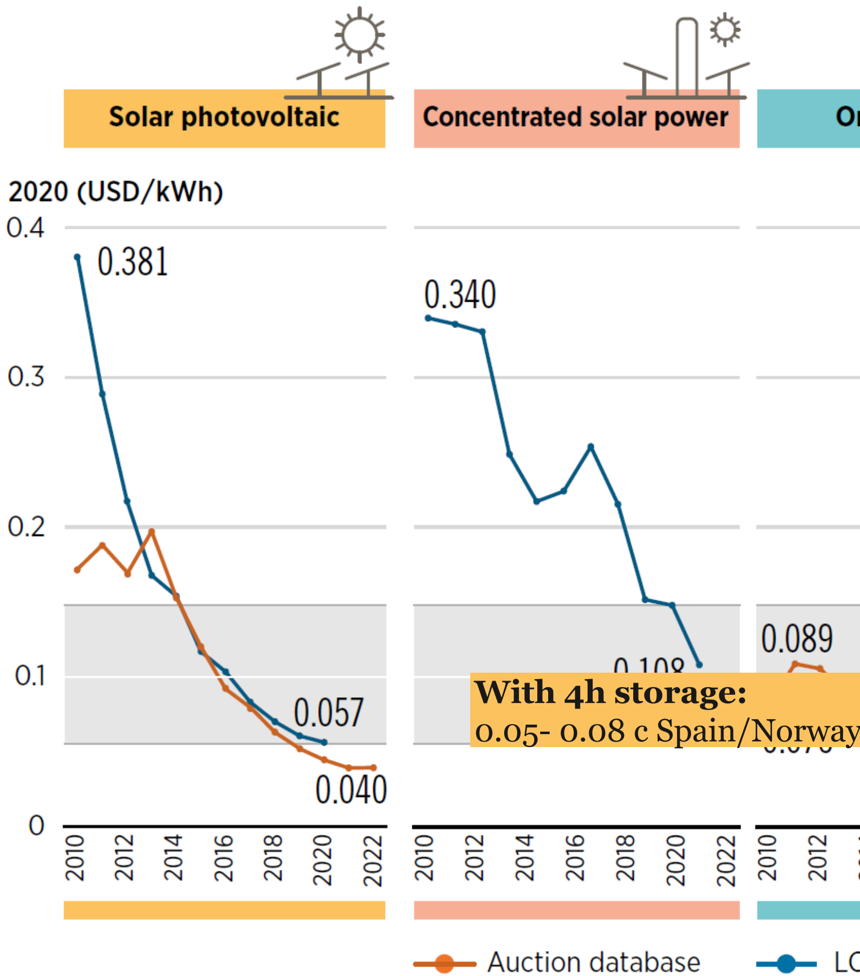
Very little carbon budget left → need for speed!

We can only emit 500-1000 $GtCO_2$ for the rest of the century (1.5-2.0C)

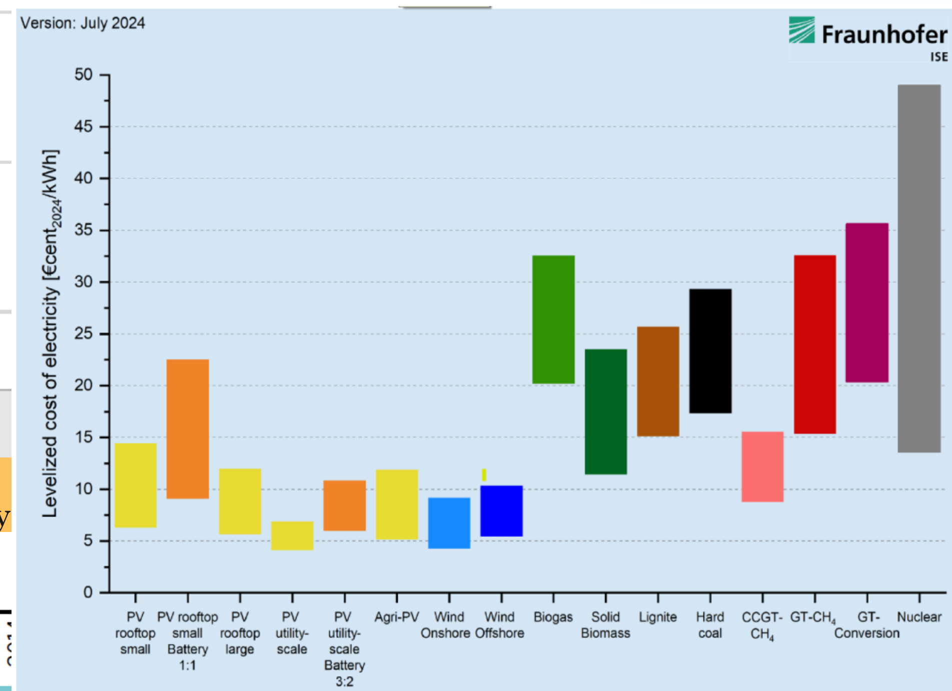


Ritchie, H., Roser, M. (2020) CO2 and Greenhouse Gas Emissions - Our World in Data

Cheap solar and wind



With 4h storage:
0.05- 0.08 c Spain/Norway

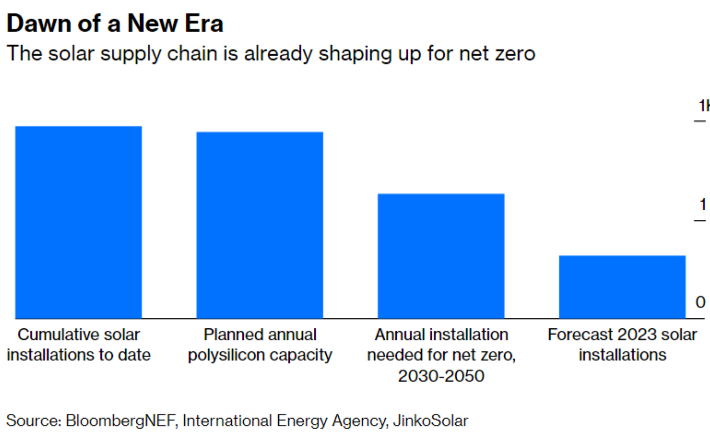


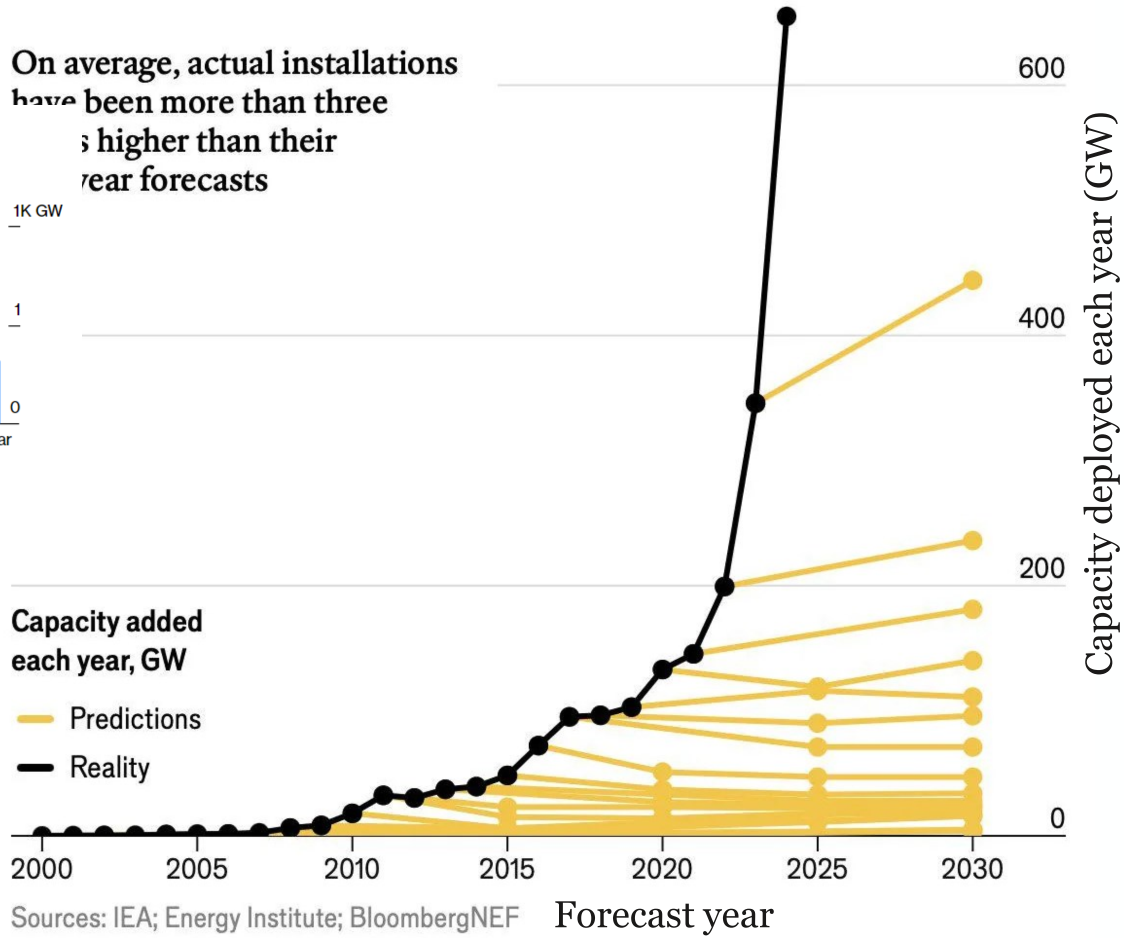
IRENA (2022) World Energy Transitions Outlook

PV with storage: Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV LCOE. Progress in PV. 2024

How solar is outgrowing all expectations

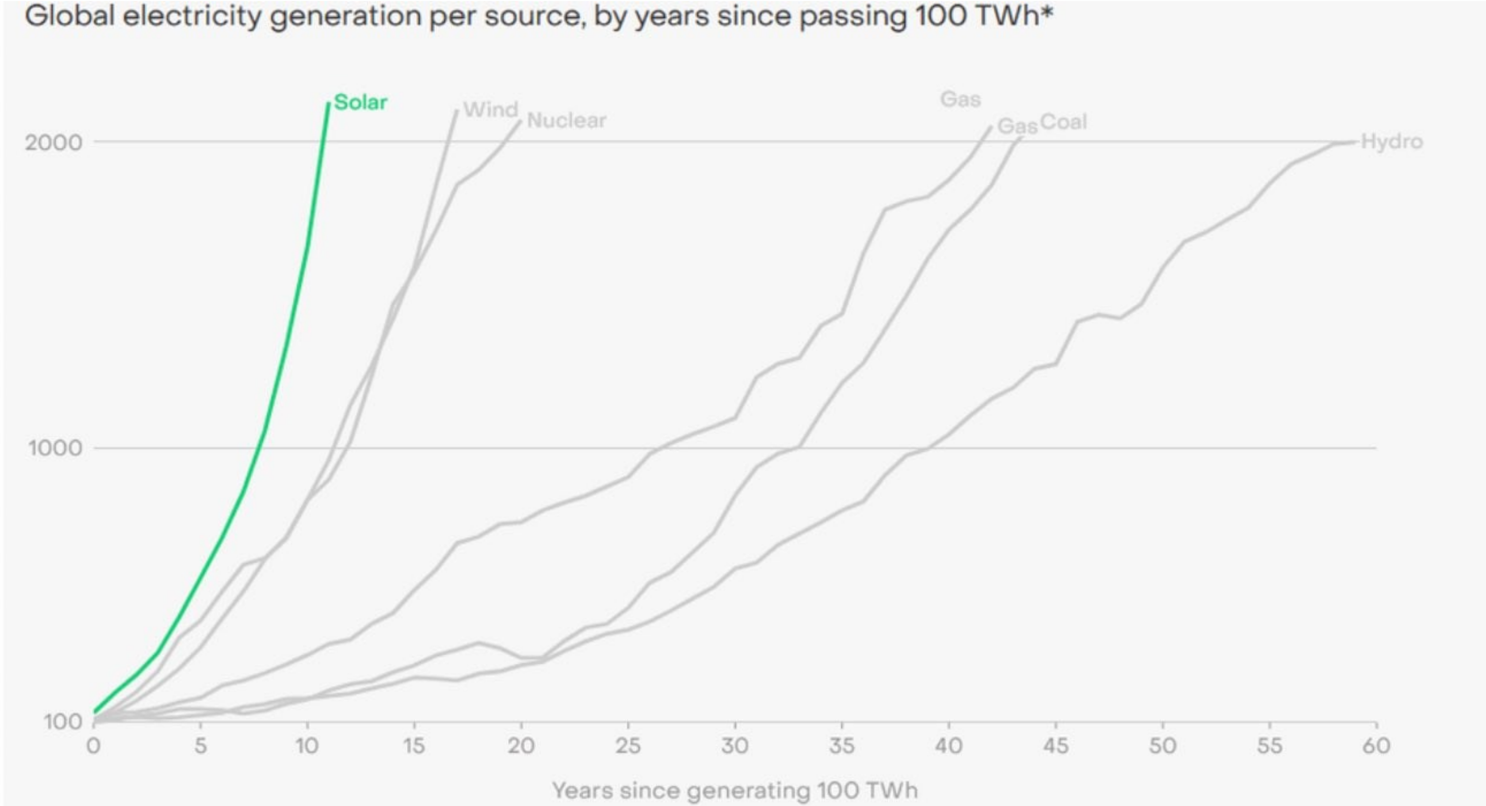
Solar supply chain ready for net-zero





Wind and solar have scaled up faster than any other technology in history

It took 8 years for solar to go from 100 to 1000TWh and then just 3 years to pass 2000 TWh

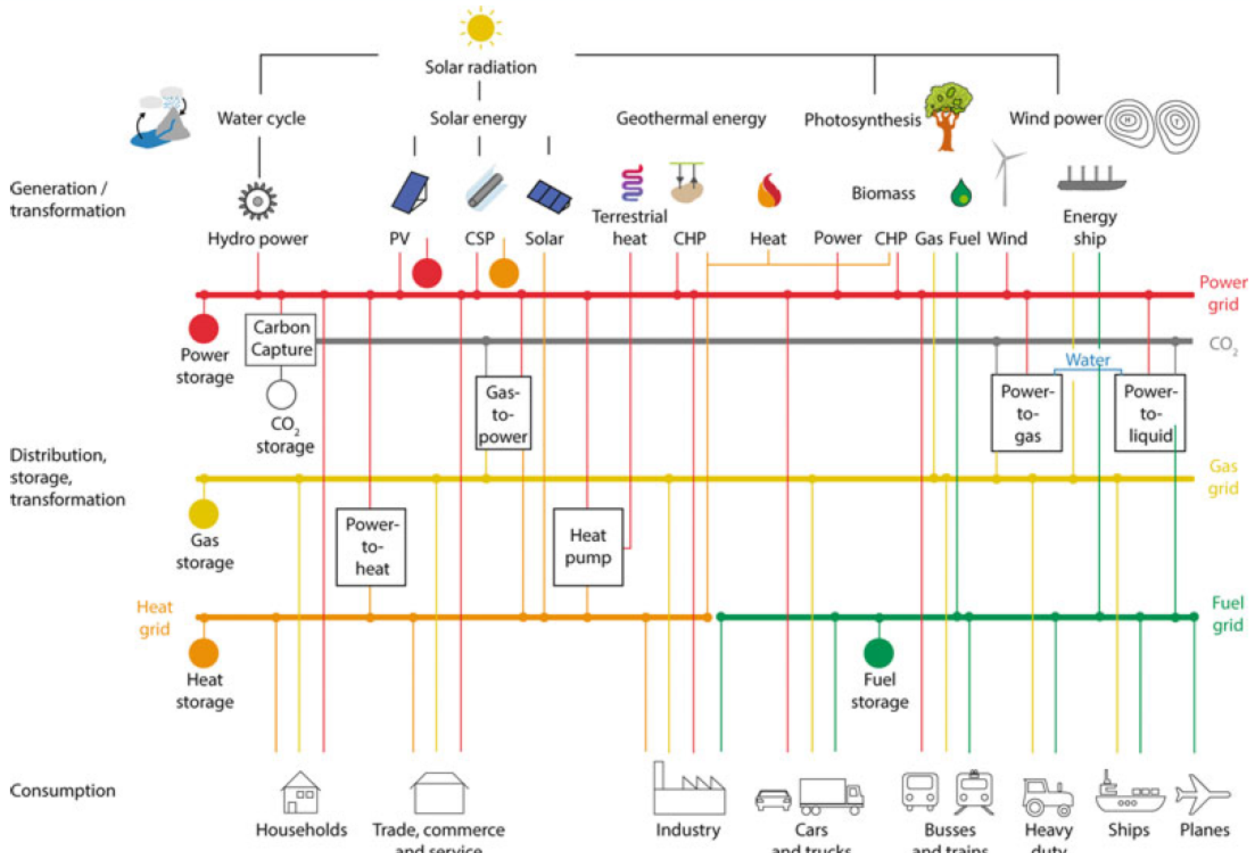


Source: Wind and solar generation data from Ember's yearly electricity data. Nuclear, gas, coal and hydro data from Pinto et al. (2023)
This graphic is based on a chart by Nat Bullard https://www.nathanielbullard.com/presentations
*Data only shown until the point where each source generated just over 2,000 TWh

1 Renewable energy

Large infrastructures, part of one interconnected system

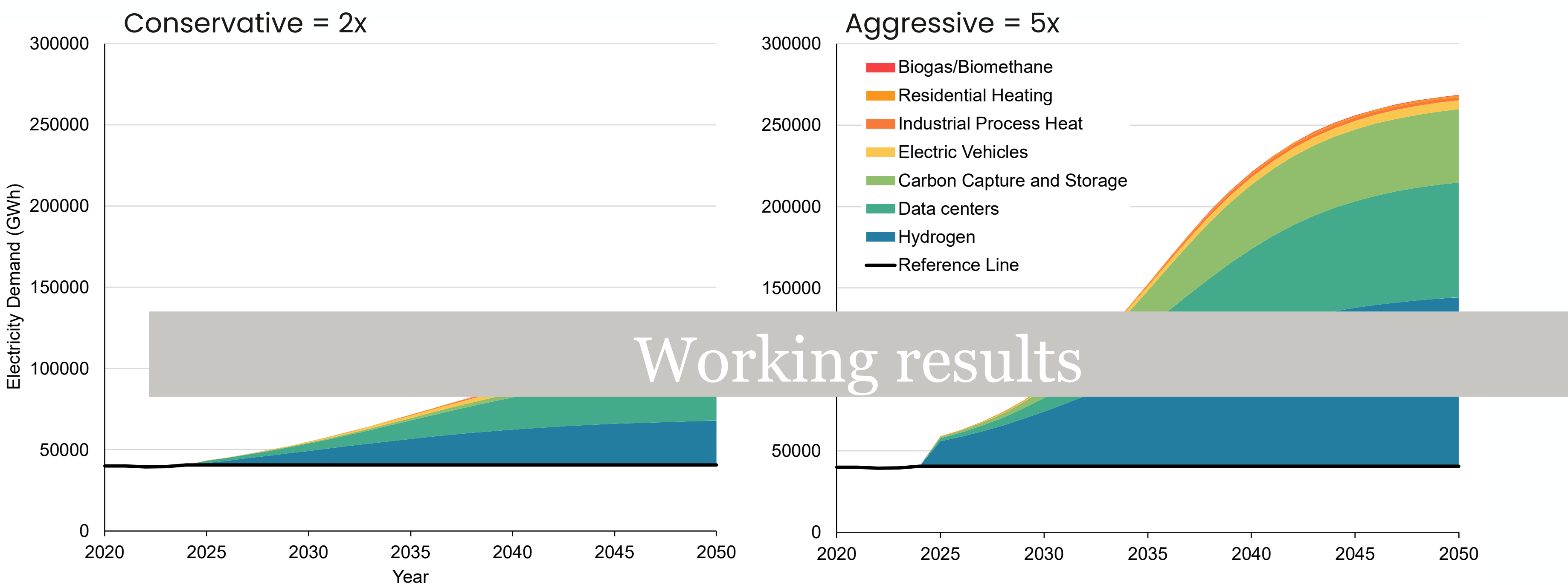
Electricity, heat, gas, CO2, and fuel system



Sterner and Staedler (2019). Handbook of energy storage.

New capacities to serve a quickly growing demand

Future electricity demand might grow 2-5x



Flannagan, Petrie, Peer (2024). Energy megatrends impact on Aotearoa's energy future. Capstone report

To plan this future system, we use optimization

Minimize investment and operation costs, s.t. meeting future demand

REMix

AT LEAST

10-100 techs x 8760 time steps x 11 regions x 3 years

≈5M decision variables

Where does the electricity generated in NZ come from?

Under review

HYDROPOWER AND 0% SOLAR

SOLAR PV AND 11% HYDRO

How much new renewable capacity will we need?

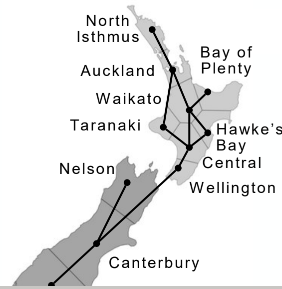
+120GW

10x what we have today!

LCOE by year 2050 **€61/MWh**

$$\min C_{total} = \sum C_{inv,r,p} + C_{OMfix,r,p} + C_{OMvar,r,p} + C_{fuel,r,c} + C_{emission} + C_{unsuppLoad}$$

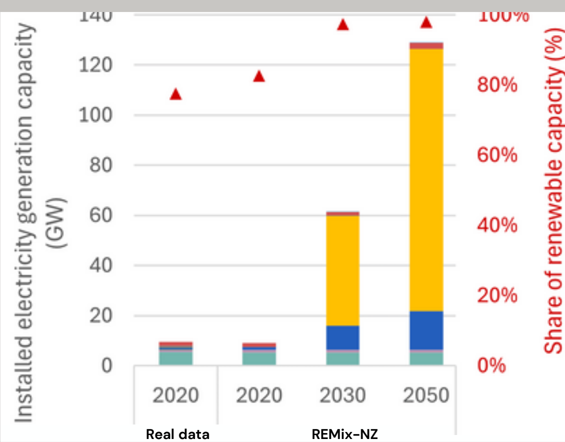
$\forall\, r \in regions,\quad p \in techs,\quad c \in energycarriers$

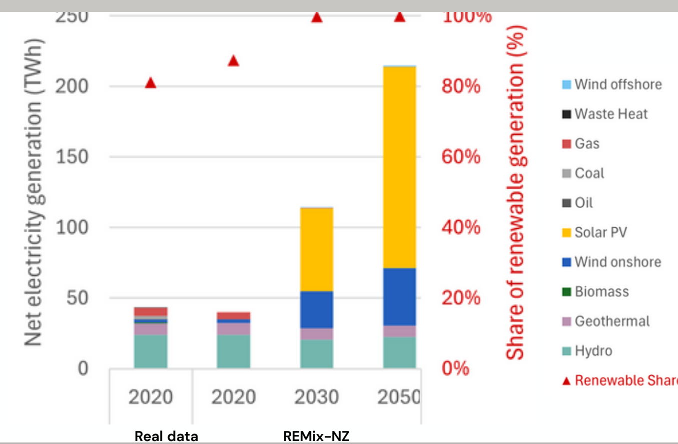


Inputs include:

- Technical parameters and cost projections (2020 ... 2050)
- Renewable generation

Hydropower, diesel, gas, geothermal, wind, Green H_2 (electrolysers, modified GT, fuel cells)

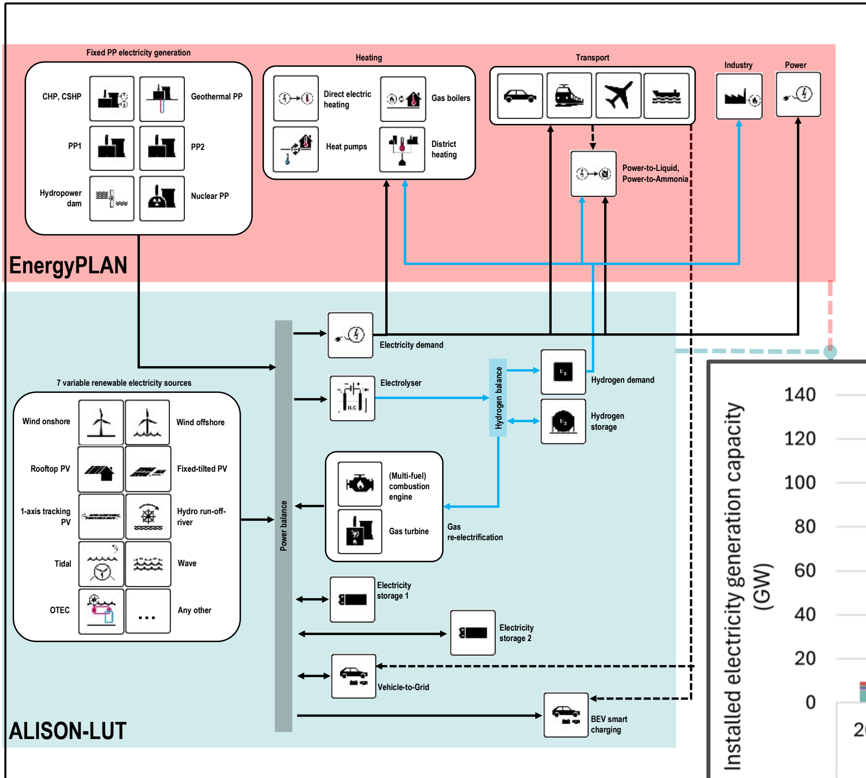




Canessa et al. Optimising New Zealand's Energy Transition: Introducing REMix-NZ's Insights into Transition Pathways and Green Hydrogen Export Scenarios. Submitted.

We compared REMix to EP-ALISON-LUT model

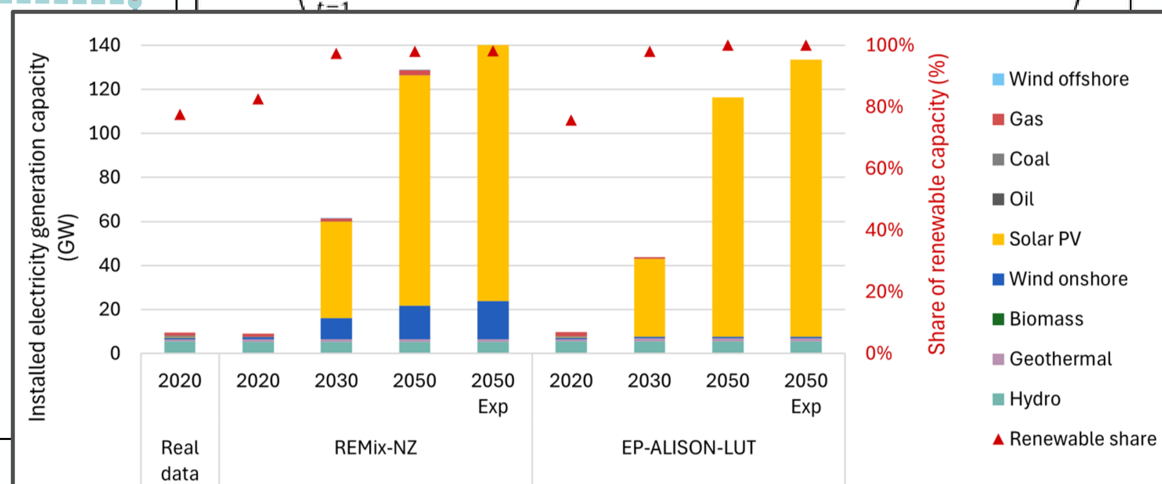
Structure and target function



- Interaction between EnergyPLAN (EP) and add-on model
- Conventional PP and CHP are still modelled in EP
- Total electricity demand and hydrogen demand taken from EP
- Electricity and hydrogen balance in add-on model

Target function: minimum annualised cost of techs in add-on model

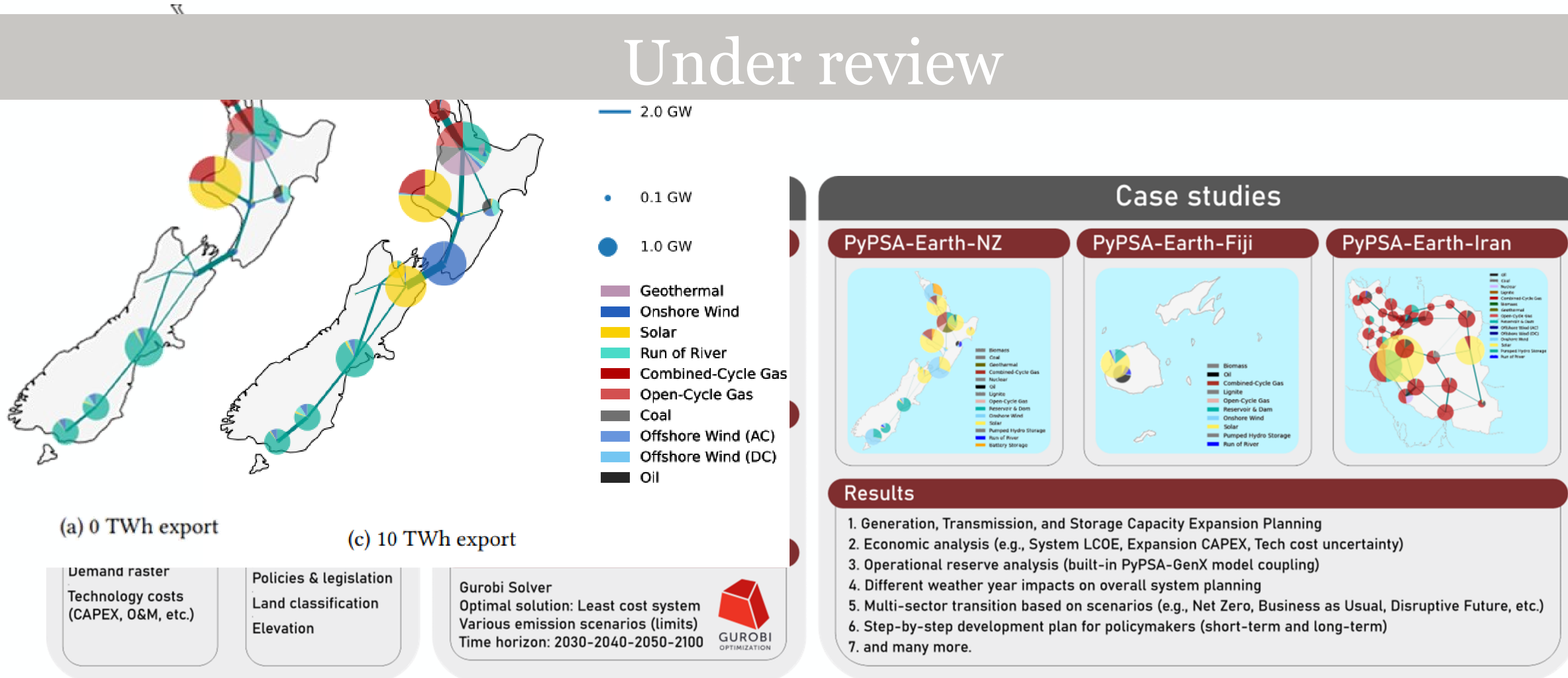
$$\min\left(\sum_{t=1}^{tech}(CAPEX_t \cdot crf_t + OPEXfix_t)\cdot instCap_t + OPEXvar_t \cdot E_{gen,t}\right)$$



Keiner et al. (2023). Future role of wave power in the Seychelles: A structured sensitivity analysis empowered by a novel EnergyPLAN-based optimisation tool.
Gulagi et al. (2025). Analysing techno-economic impacts of integrating wave power to achieve carbon neutrality and e-fuel exports: A case for New Zealand. Energy.

… and against PyPSA

+Impact of hydrogen offtaker regulation on expansion planning



Schumm, Haas, Peer, Sterner: The Role of Hydrogen Offtaker Regulation in Highly Renewable Electricity Systems. Under review in Energy.

Global renewable transitions: costs are manageable

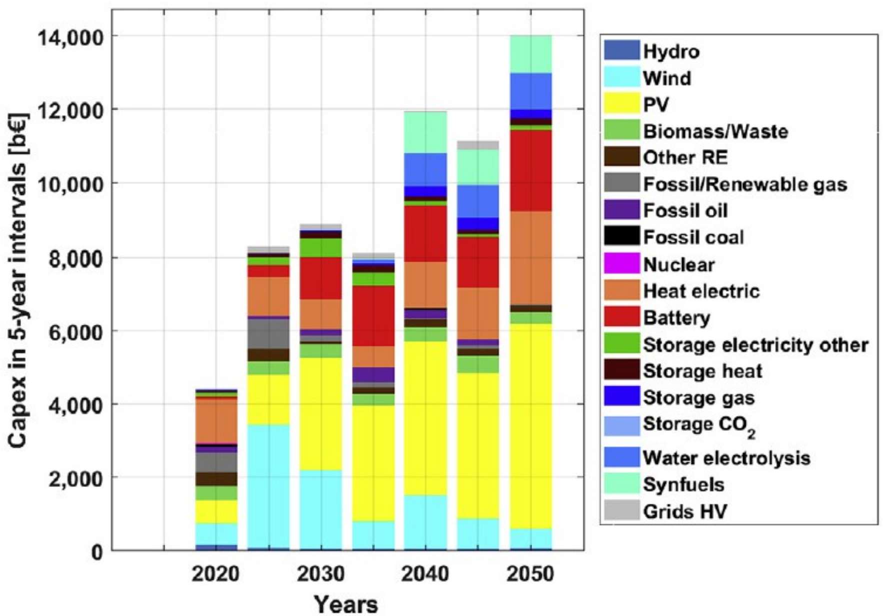
Investments = **2%** of global GDP
(70T€/30y =2.3T/y out of 100T/y)

Global transitions = huge optimization problems

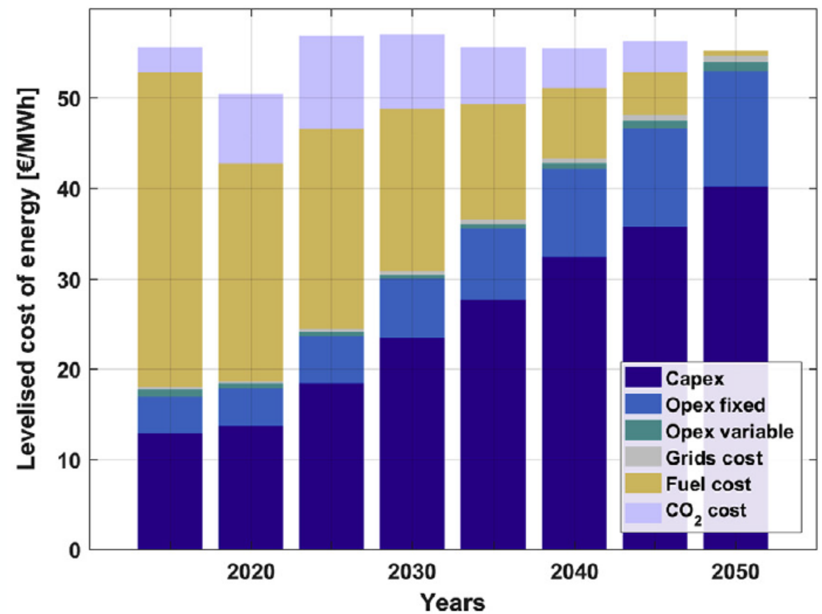
AT LEAST

100 techs x 8760 time steps
x 50 regions x 5 years

≈250 M
decision variables



LCOE stable around 55 €/MWh
with shift from operation to investment costs

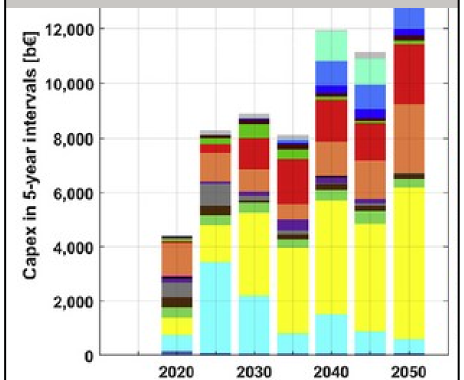


Bogdanov et al (inc. Breyer) (2021) Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy

Largest infrastructure challenge of our time

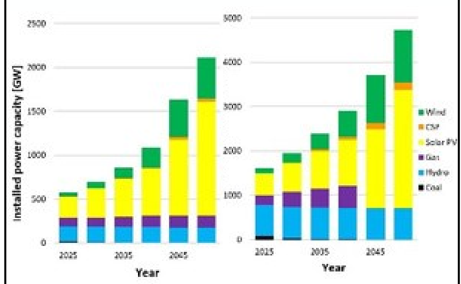
Net zero based on solar!

World



Breyer et al (2021)

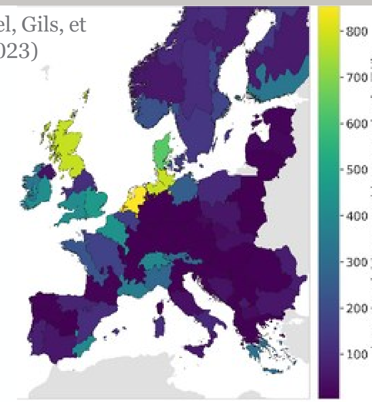
South America



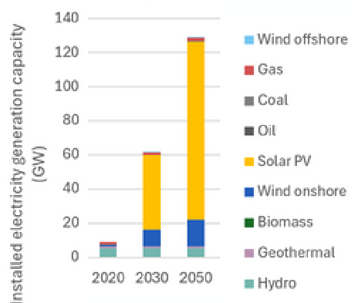
Galvan, Haas et al. (2022)

Europe

Wetzel, Gils, et al. (2023)

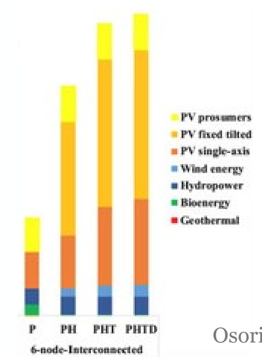


New Zealand



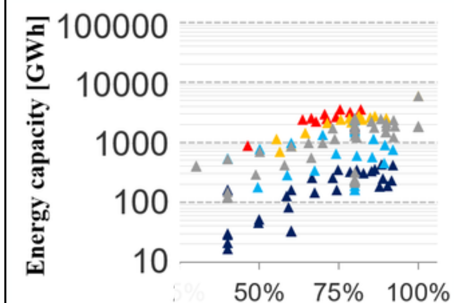
Canessa (inc. Peer and Haas) et al. (2024) (submitted)

Chile



Osorio (inc. Haas) et al. (2023)

US



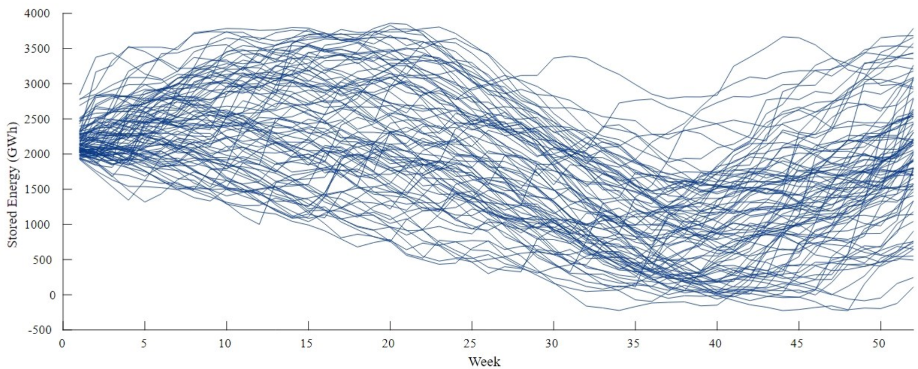
Cebulla, Haas et al. (2018)

How do these expansion models deal with multi-year variability & uncertainty?

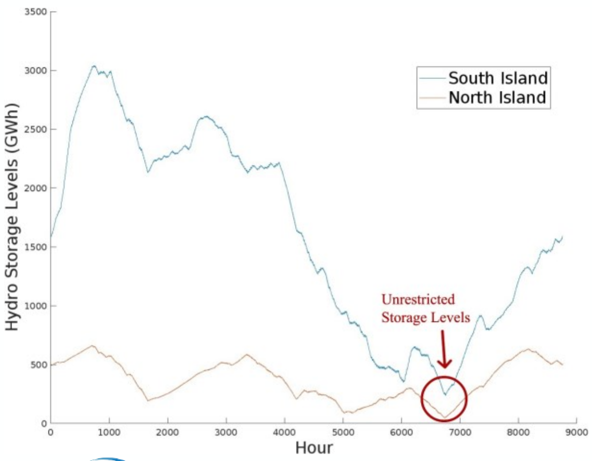
Not Very Well…

Perfect Foresight

- Assumes full knowledge of future weather and inflows, optimizing both investment and dispatch for a single (or multi)"representative" year.
- Unrealistic operations, such as full **depletion of hydro reservoirs**.
- Ignores year-to-year **variability** in renewable resources.
- Fails to reflect real-world **uncertainty** and **forecast errors**.



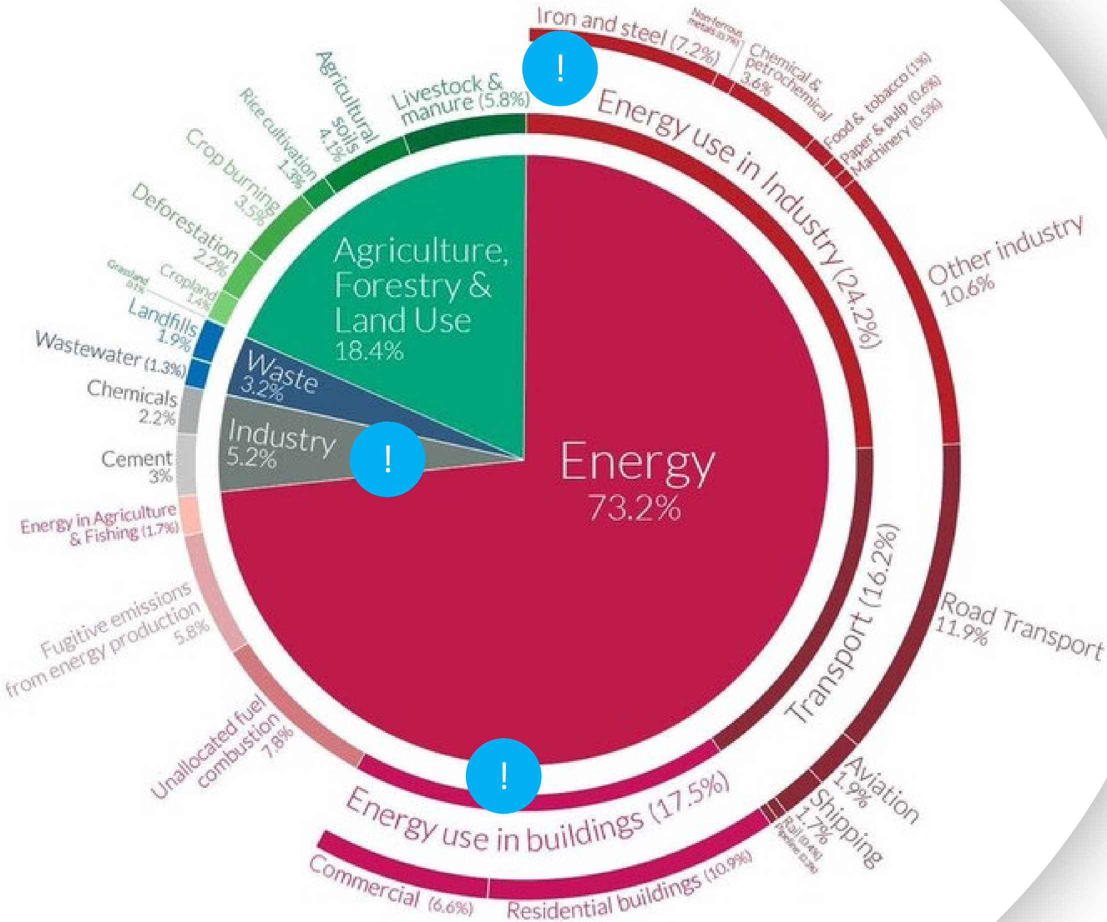
ADE Simulated Historic Hydropower Storage (1932-2022)



REMix-NZ Hydropower Storage Levels (2050)

Zegeer M., Philpott A., Haas J., Peer R., Read E.G. Implicit modelling of Hydropower Uncertainty in Capacity Expansion tools: Understanding long-duration storage from hydrogen and hydropower in New Zealand. Working paper.

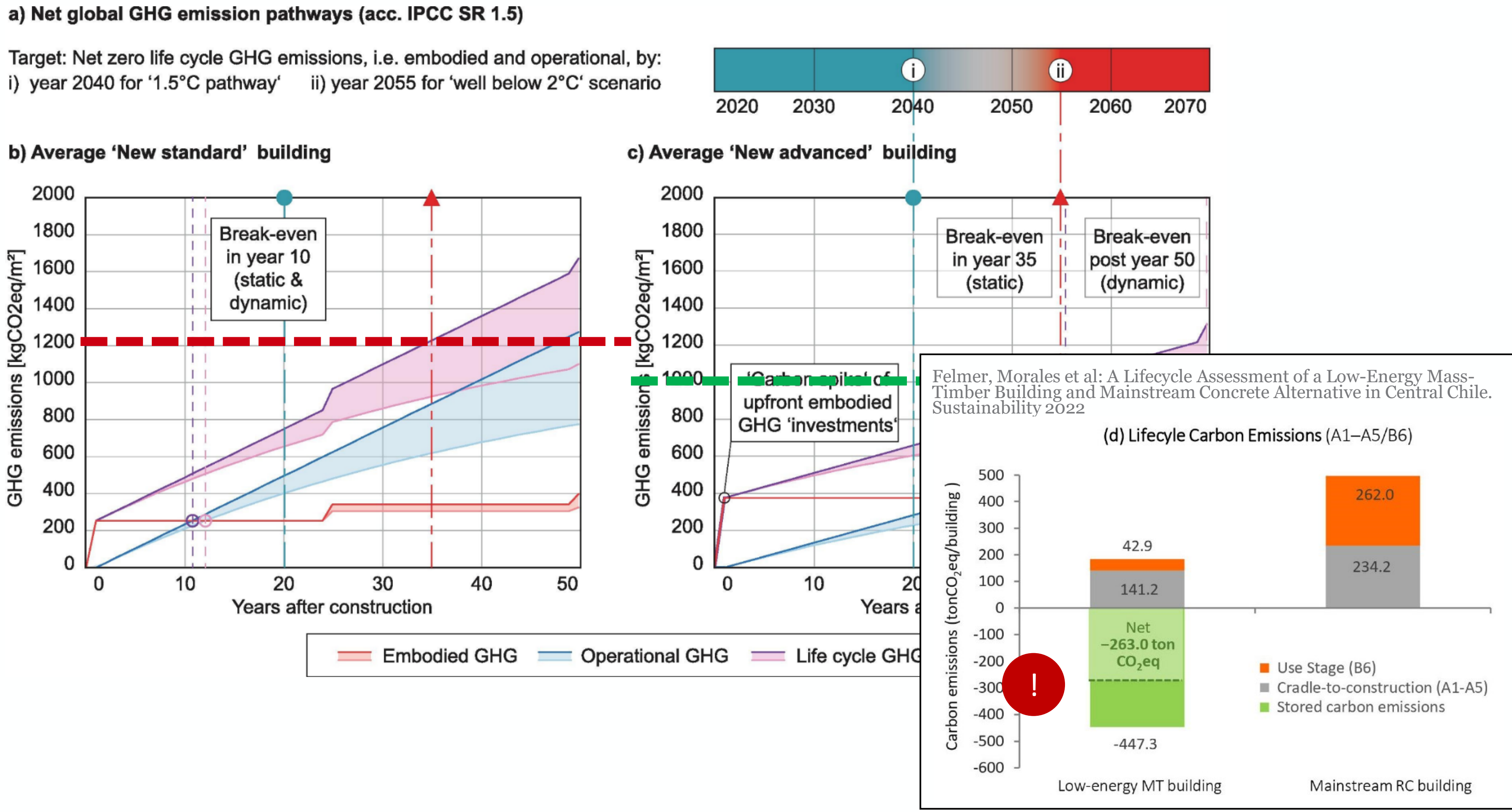
2 Energy and carbon efficiency



Building sector ~30% of emissions

Ritchie, H. (2020) Climate Watch, the World Resources Institute, OurWorldinData.org Research and data to make progress against the world's largest problems.

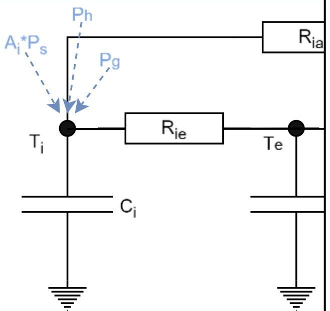
New advanced buildings to save 20%+ emissions



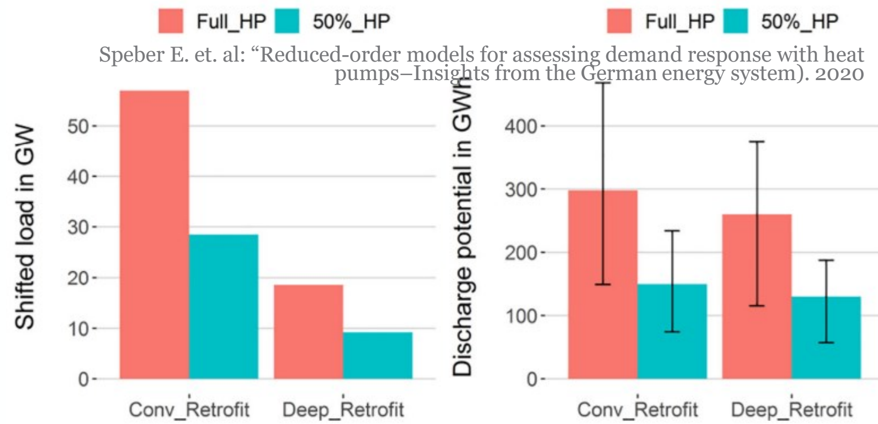
Roeck et al. (2020). Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Applied Energy.

But buildings operations are impacted by future climates

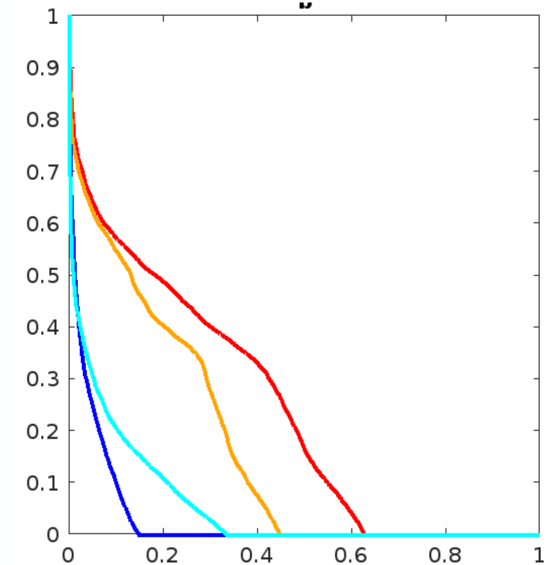
Cooling demand **+100%**. Heating demand **-33%**

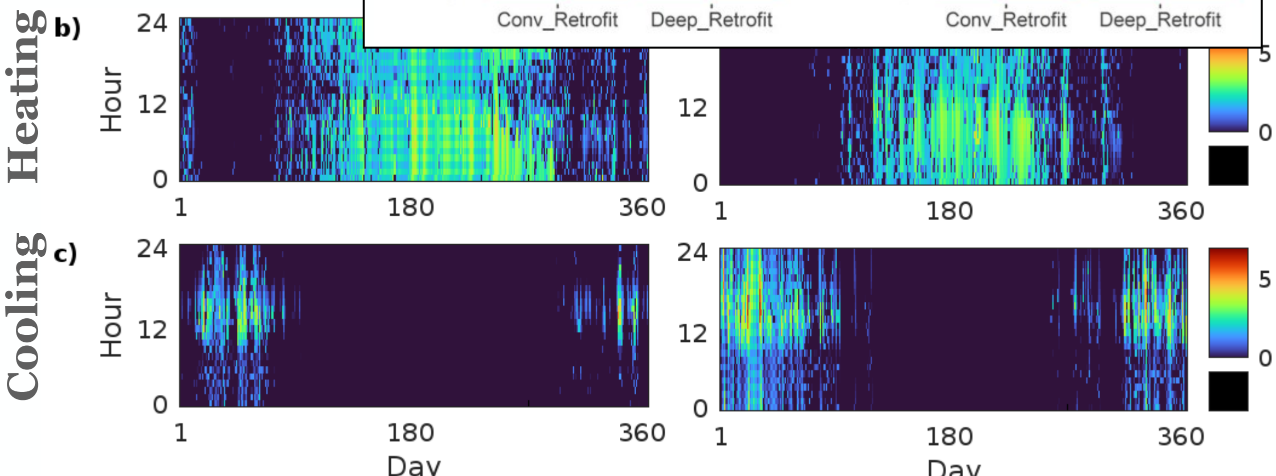


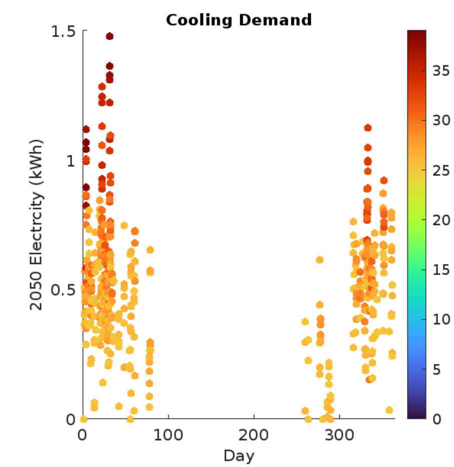
Heat when cheap



Speber E. et. al: "Reduced-order models for assessing demand response with heat pumps–Insights from the German energy system). 2020

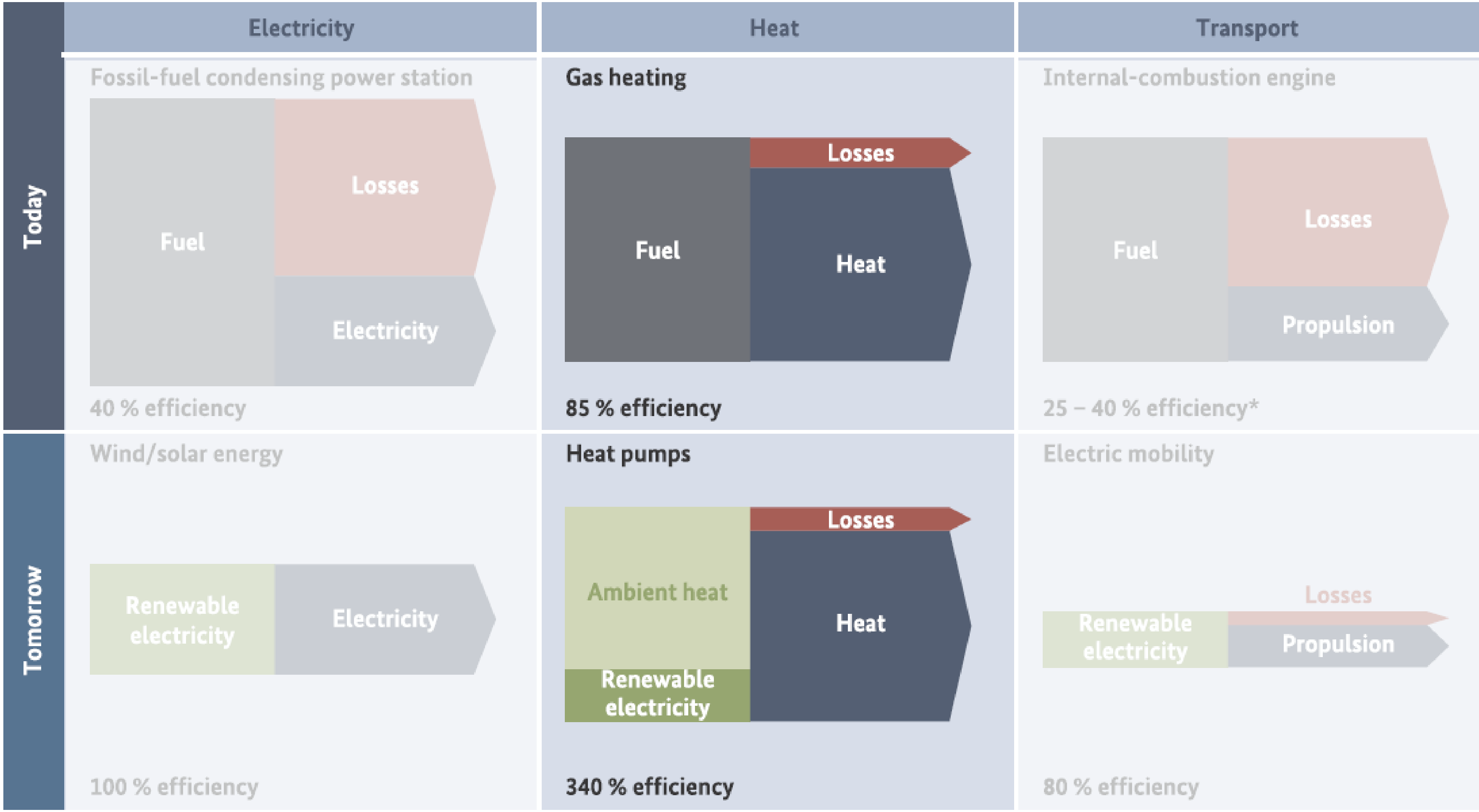






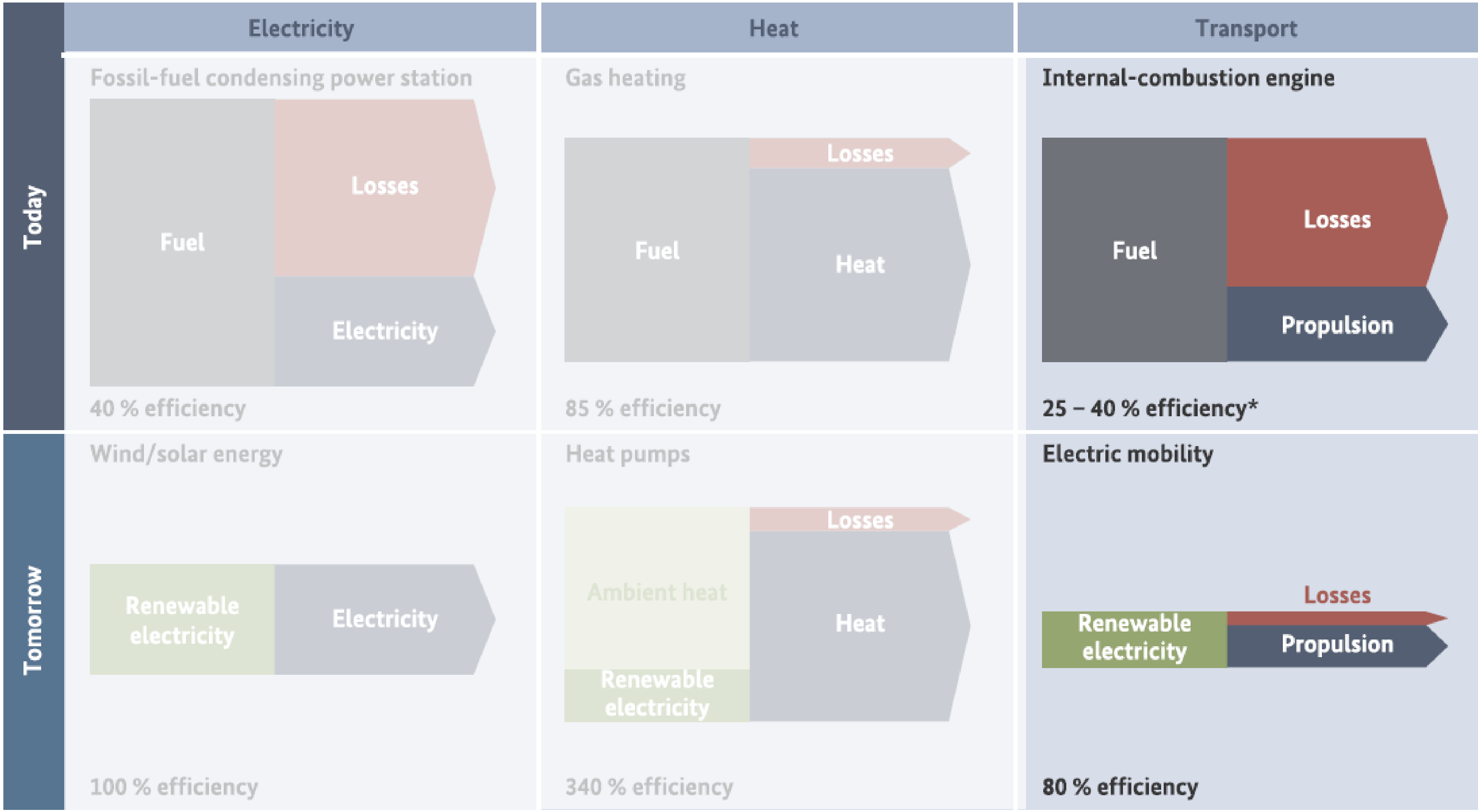
Zegeer M., Peer R., Haas J. "Can Residential Energy Systems Withstand the Heat? Quantifying Solar Photovoltaic and Heat Pump Yields for Future New Zealand Climate Conditions." Environmental Research: Infrastructure and Sustainability. 2025

3 Electrification



* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.

Brown. T (2018). Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'



* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.

Brown. T (2018). Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'

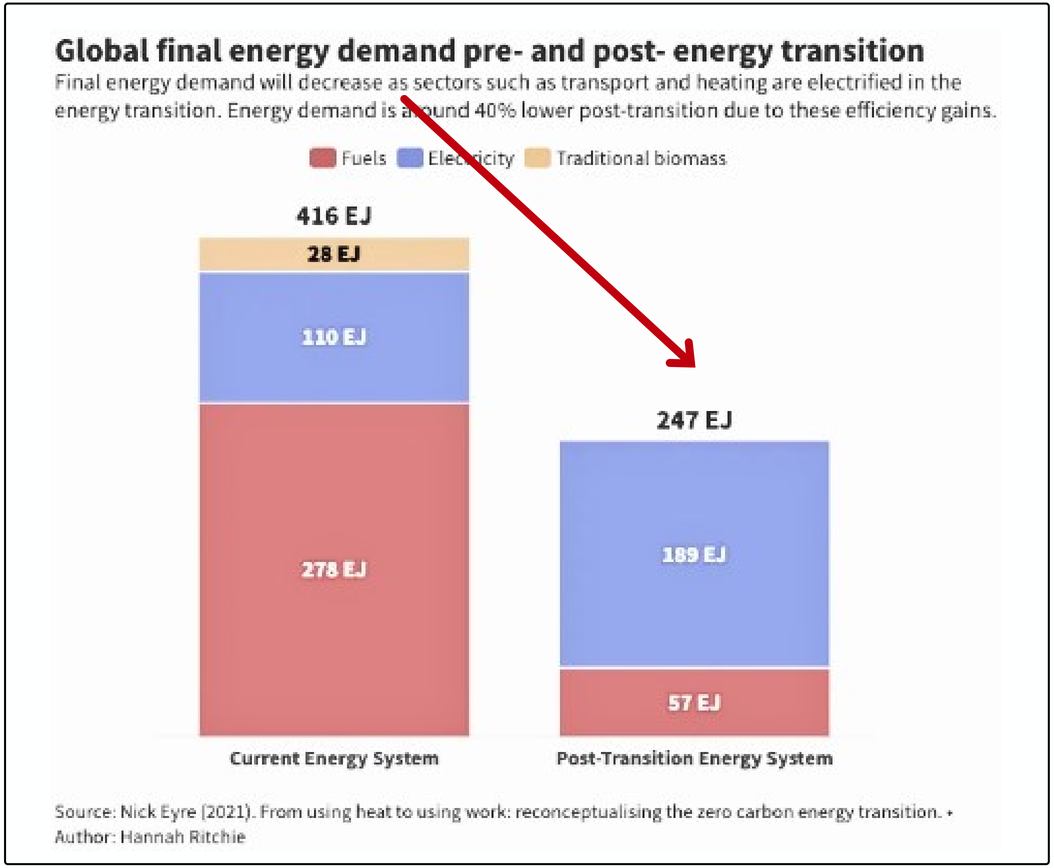
Electrification leads to 40% reductions in final energy

The "primary energy fallacy"

Critics of the energy transition often point to primary energy to demonstrate that the transition is going to be impossible.

But most consumed primary energy is lost after conversion

"The problem to solve is a lot smaller than primary energy suggests"
(Jan Rosenow 2024)

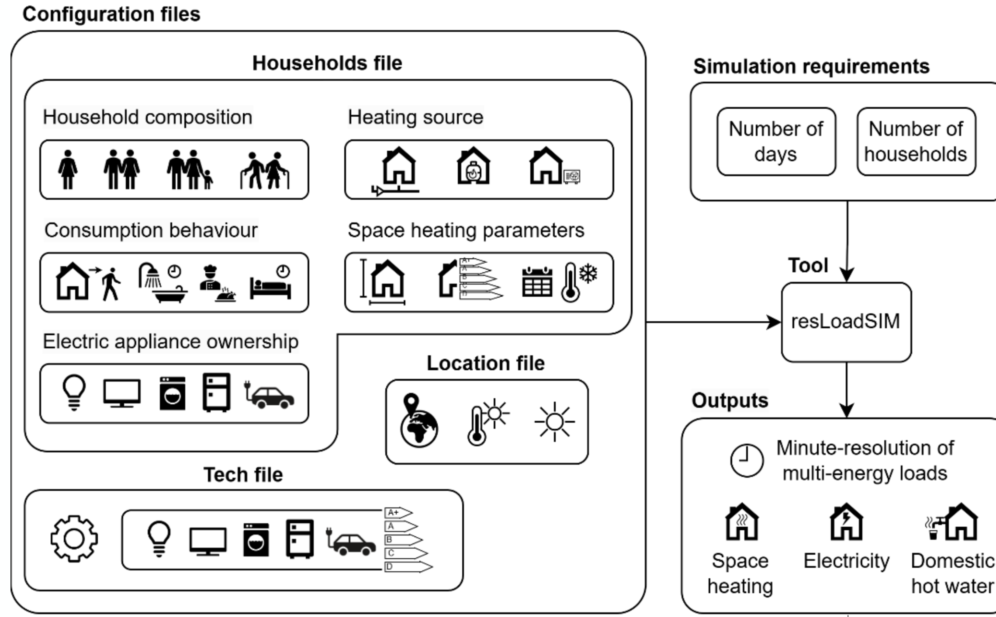


Eyre (2021) From using heat to using work: reconceptualising the zero carbon energy transition. Energy Efficiency.

Bottom-up modelling of households' energy demand as input for capacity planning

Tool: **resLoadSIM** - **R**esidential **Load SIM**ulator by the Joint Research Center - European Commision

- **Electrification scenarios** including varying adoption rates of **electric vehicles** and different **heating technologies**
- Outputs: high resolution **residential multi-energy load profiles** at neighbourhood or city level



Steidl et al. (2025). High-resolution residential energy load profiles under varying electrification scenarios for New Zealand and Germany using resLoadSIM [Data set]. Zenodo.

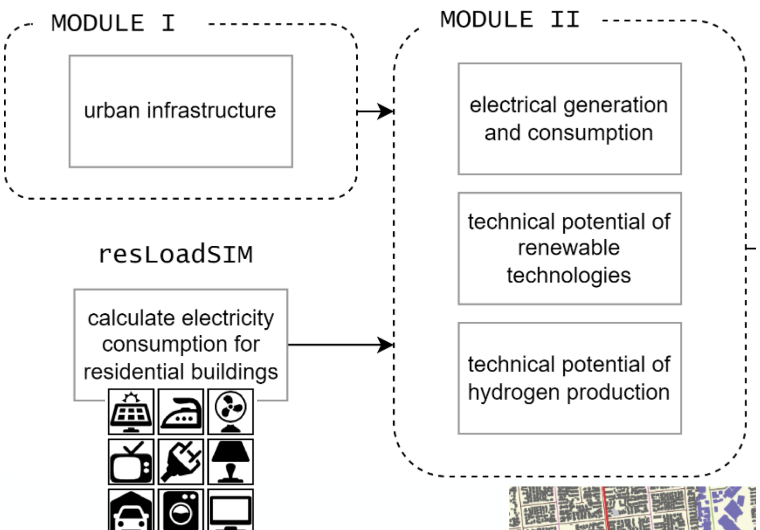
Steidl et al. (2025). High-resolution residential energy load profiles under electrification scenarios for New Zealand and Germany. Submitted.

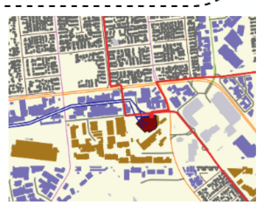
Bottom-up, GIS-based optimization of renewable energy technologies and hydrogen at city level

FLEXIGIS -H_2
developed in python

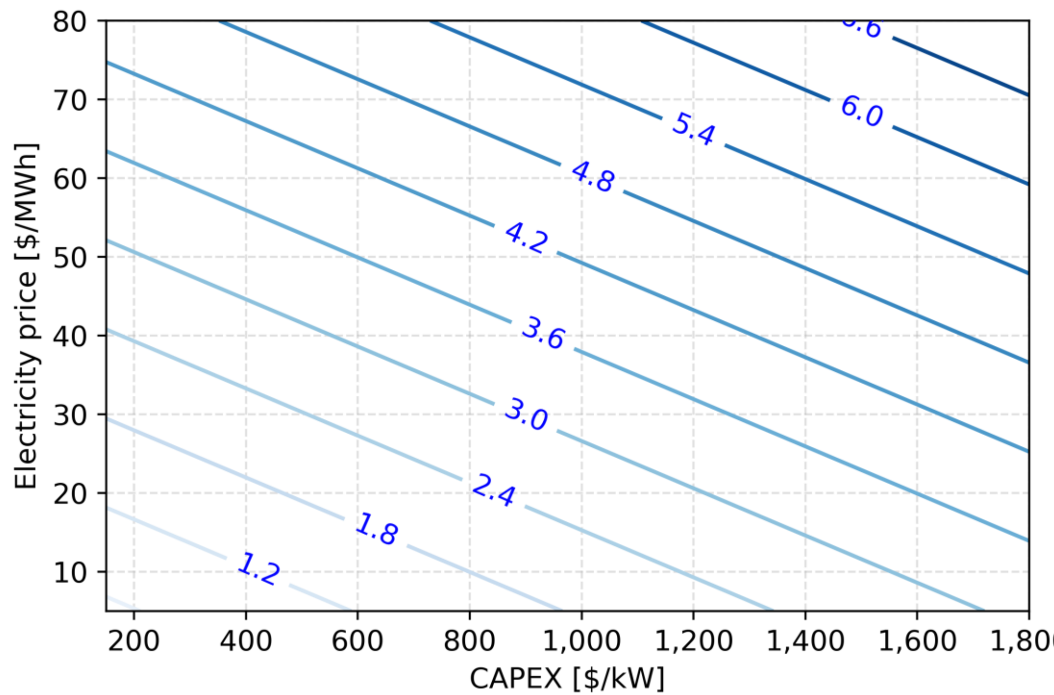
FLEXIbilisation technologies using **G**eographical **I**nformation **S**ystems for H_2 integration

- **GIS-based**
- **open-source**
- **high spatial and temporal resolution**





existing energy infrastructure



potential and demand

ideal integration of H_2

Steidl et al. (2025) Green hydrogen production potential in New Zealand cities: A bottom-up geospatial approach. Submitted.

UC

4 Hydrogen

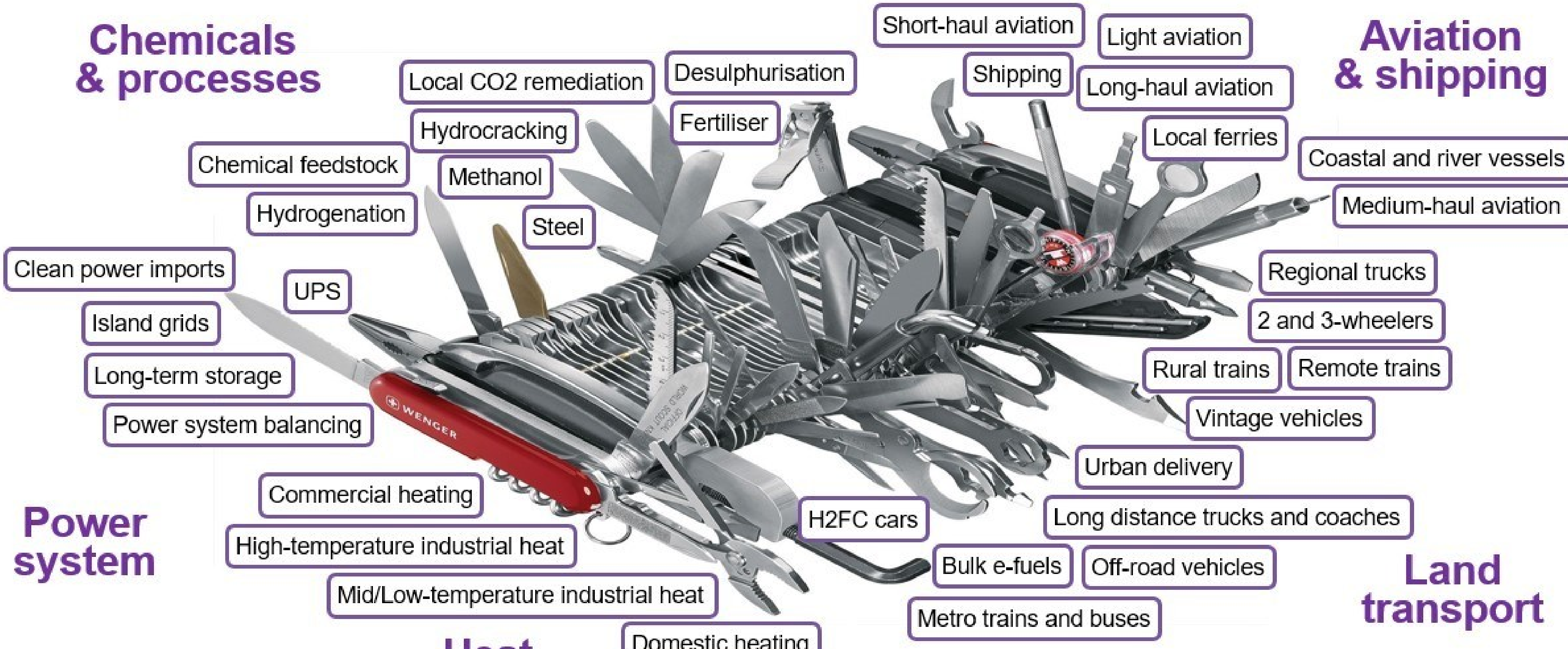


Image: Wenger (concept credit: Paul Martin)

2-million NZD (MBIE) + 0.5 million EUR (BMBF)

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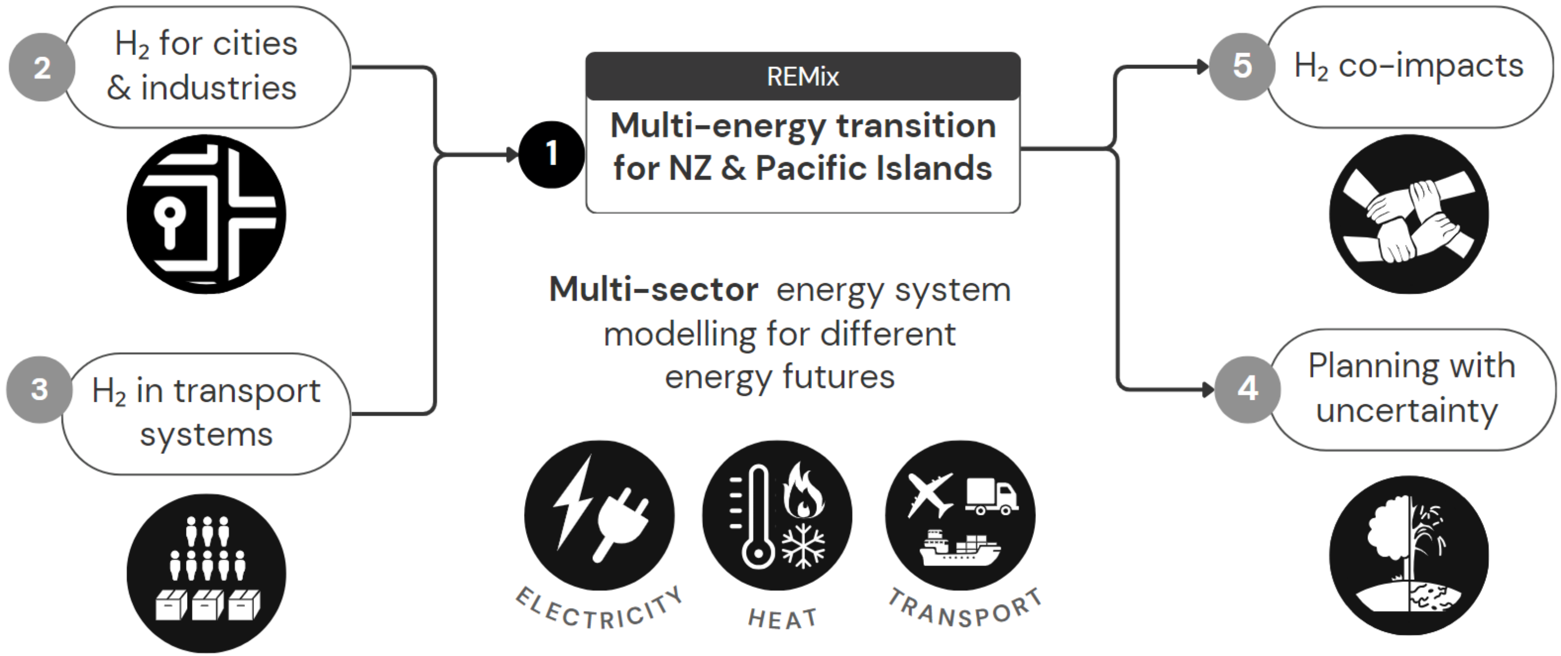
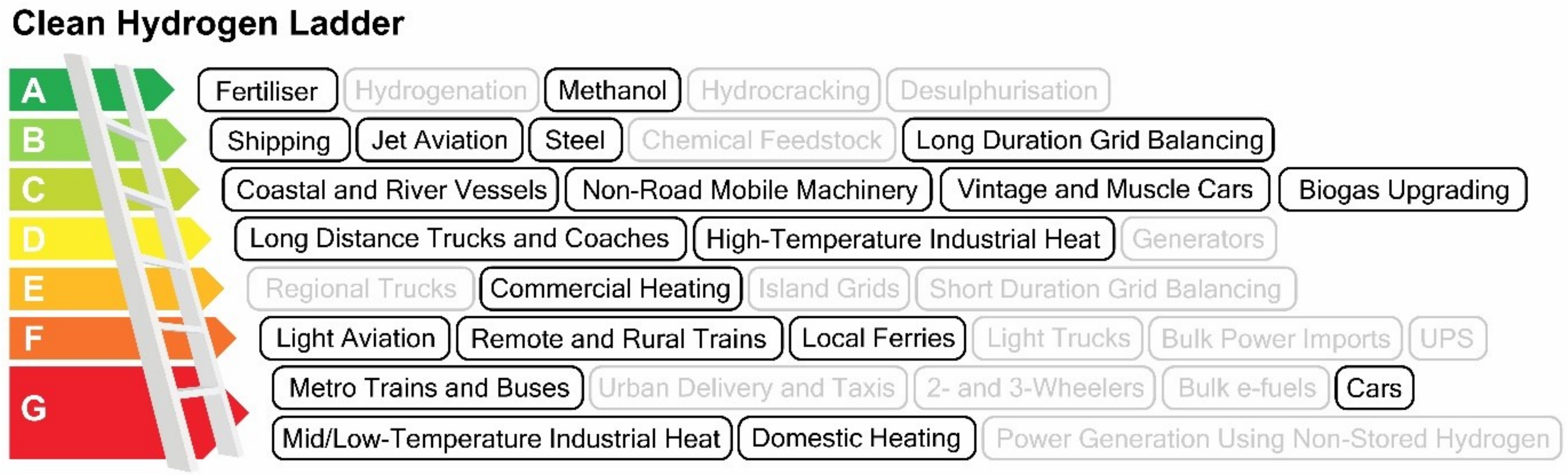
HINT: NZ-German platform for green hydrogen integration

Transition pathways for full decarbonisation of New Zealand, including H_2 derivatives and H_2 export options



Clean hydrogen demand scenarios for New Zealand

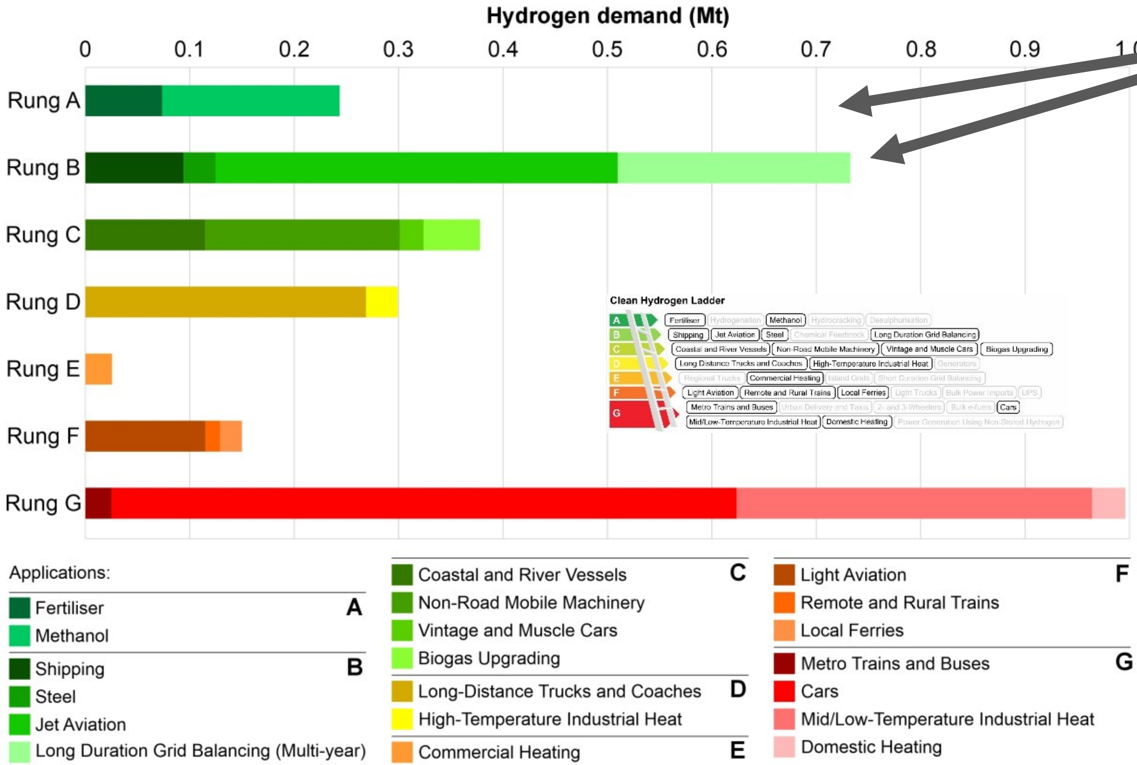
Applications relevant to New Zealand



Vatankhah Ghadim et al., How much hydrogen could we need in New Zealand? ..., Journal of the Royal Society of New Zealand, 2025
Liebreich M., Hydrogen Ladder Version 5.0, 2023, https://www.linkedin.com/pulse/hydrogen-ladder-version-50-michael-liebreich

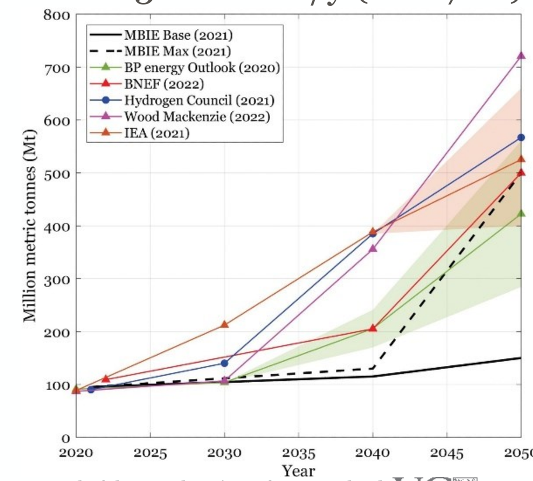
Potential hydrogen demand in New Zealand

By application



H_2 rule of thumb
1MTon/y=
10GW electrolyzers
20GW renewables
30B$ investments
40TWh

Exports? International hydrogen market ~300 MTon/y (100-700)

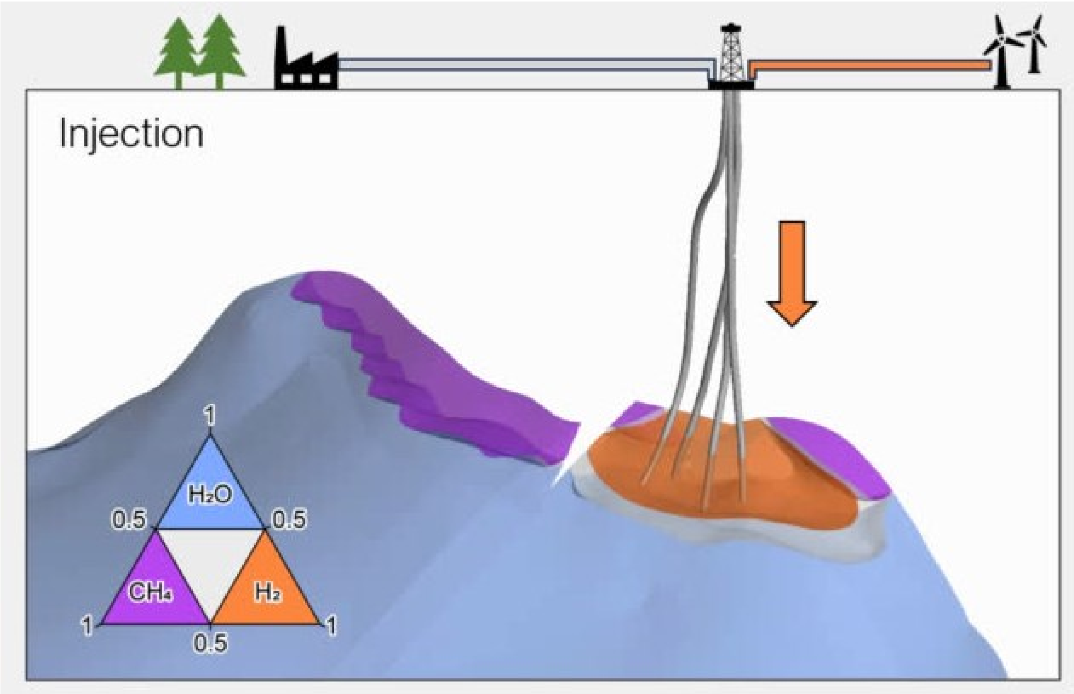


Vatankhah Ghadim et al., (2024) How much hydrogen could we need in New Zealand? ..., Journal of the Royal Society of New Zealand.
https://www.esmap.org/Hydrogen_Financing_for_Development

12-million NZD (MBIE)

Pūhiko Nukutū: a green hydrogen geostorage battery in Taranaki

Nicol A, Dempsey D, Adams M, Morgan K et al. (inc. Peer R).



Storage mechanisms

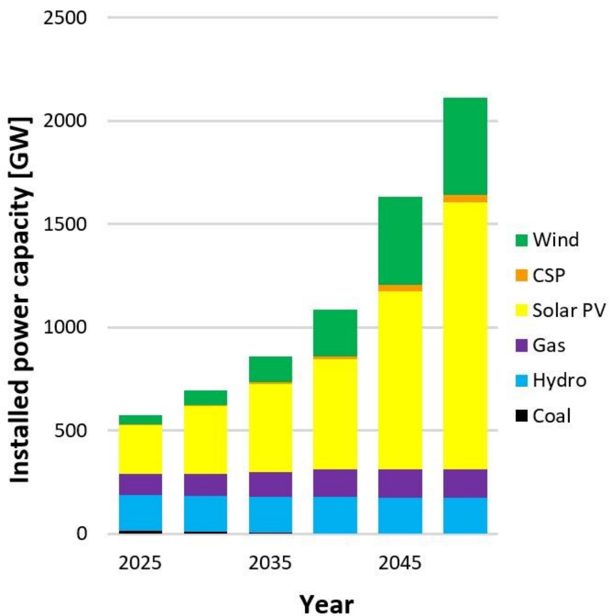
- Geologic
- On-site tanks
- Pipeline networks

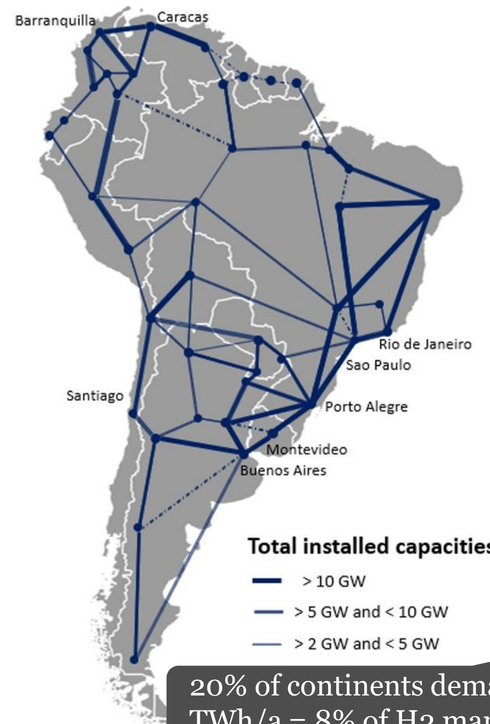
Spatial configurations

- Descentralised
- Centralised

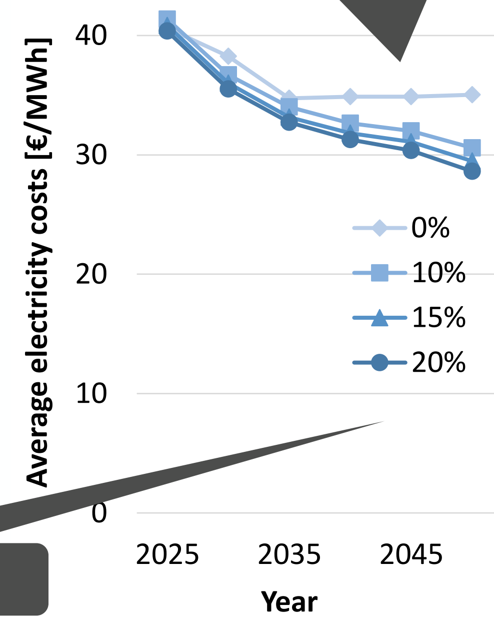
South America as a H2 continent with low risk of scale

Adding 20% of electricity demand to serve 8% of the hydrogen market





Hydrogen production can lower average electricity costs

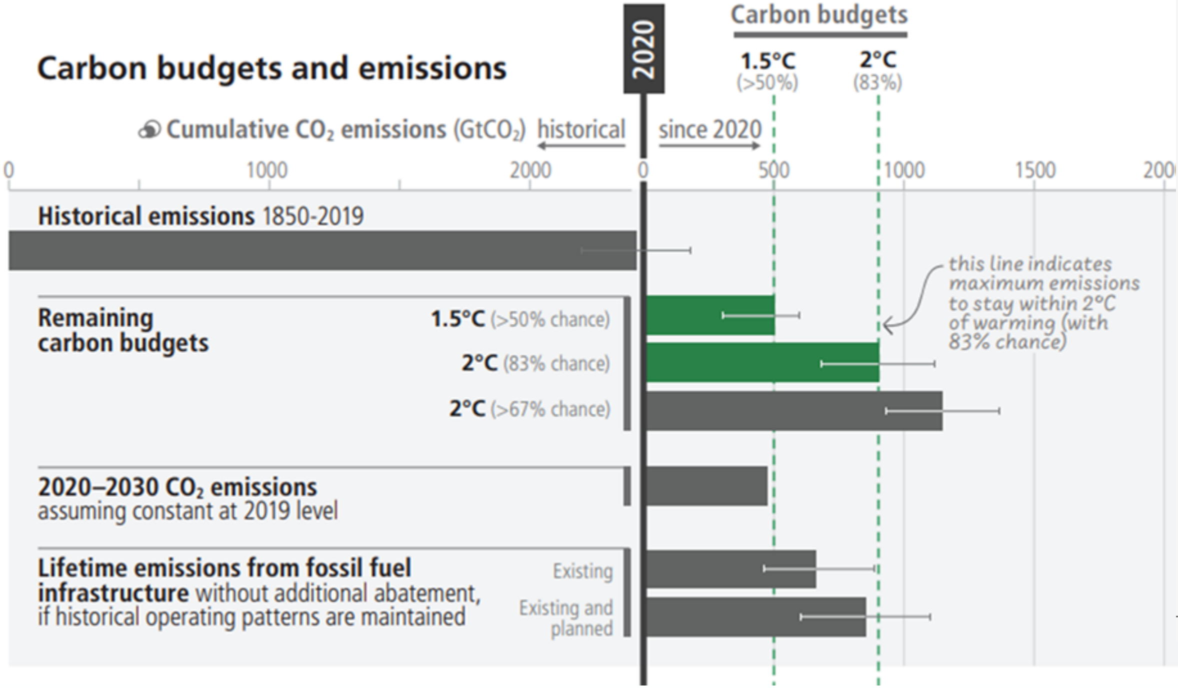


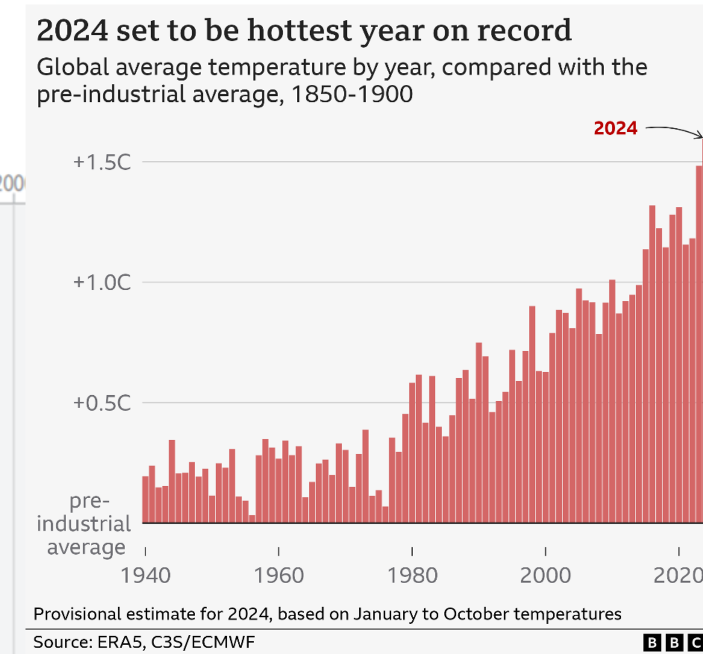
20% of continents demand ~1000 TWh/a = 8% of H2 market

Galvan, Haas et al. Exporting sunshine: Planning South America's electricity transition with green hydrogen. Applied Energy 2022

5 Carbon capture

Carbon capture to compensate for overshoot and for green molecules



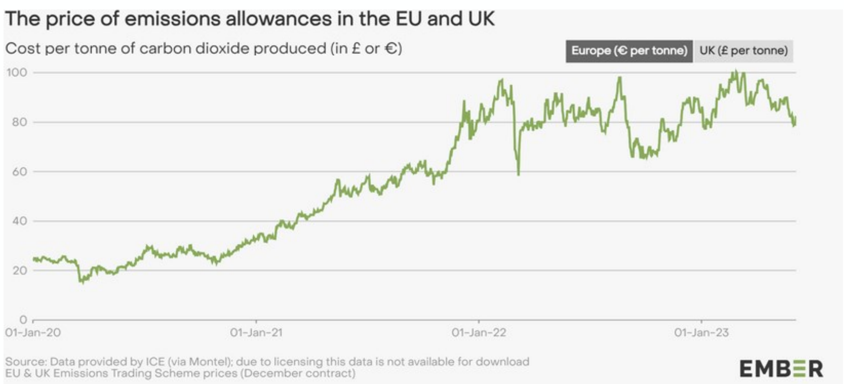


Afforestation: Planting trees, even in deserts

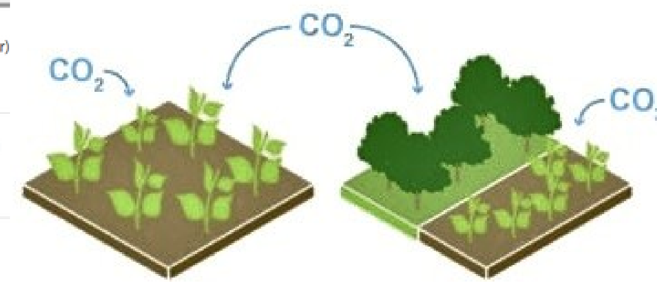
5. Carbon capture

		Afforestation with RE-desalination	DACCS (low-temperature DAC)	BECCS
Cumulative global potential	$GtCO_2$	92 (2050) 730 (2100)	no obvious limit	178–1,170 (sustainable potential is lower)
Average global CO_2 sequestration rate	$GtCO_2\ yr^{-1}$	7 (2050) 14 (2100)	8 (CDR demand in 2050) 37 (peak deployment in 2100)	sustainable deployment: 3–5 $GtCO_2\ yr^{-1}$
	$MtCO_2\ km^{-2}\ yr^{-1}$	0.002 (2050) 0.005 (2100)	2.5 (2050)	0.003–0.002 (2100) 0.0025–0.0004 (current)
Average cost (range)	€ per tCO_2	214 (2050) 99 (2100)	54 (2050; in regions with solar and wind conditions akin to the Maghreb region) for DACCS: CO_2 transport and storage may be €45 per tCO_2 (near-term) and €30 per tCO_2 (long-term)	100–200 (expected to increase after 2050 due to land and water limitation)

Like current EU carbon tax



Afforestation and reforestation



Afforestation (planting trees) and reforestation (replanting trees where they previously existed) enhance natural CO_2 "sinks"

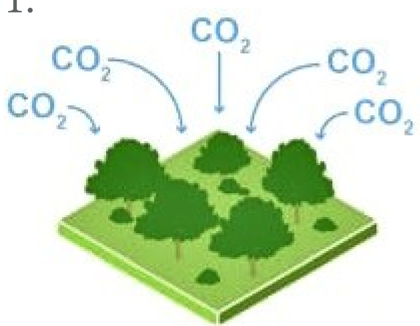
Fix CO2 in:
- timber (100y)
- afforestation with desalination in deserts

IPCC Report 2018. FAQ Chapter 4.
Caldera and Breyer: "Afforesting arid land with renewable electricity and desalination to mitigate climate change". Nature 2023

BECCS: Bio-energy with Carbon Capture and Storage

Bioenergy with Carbon Capture and Storage (BECCS)

1.



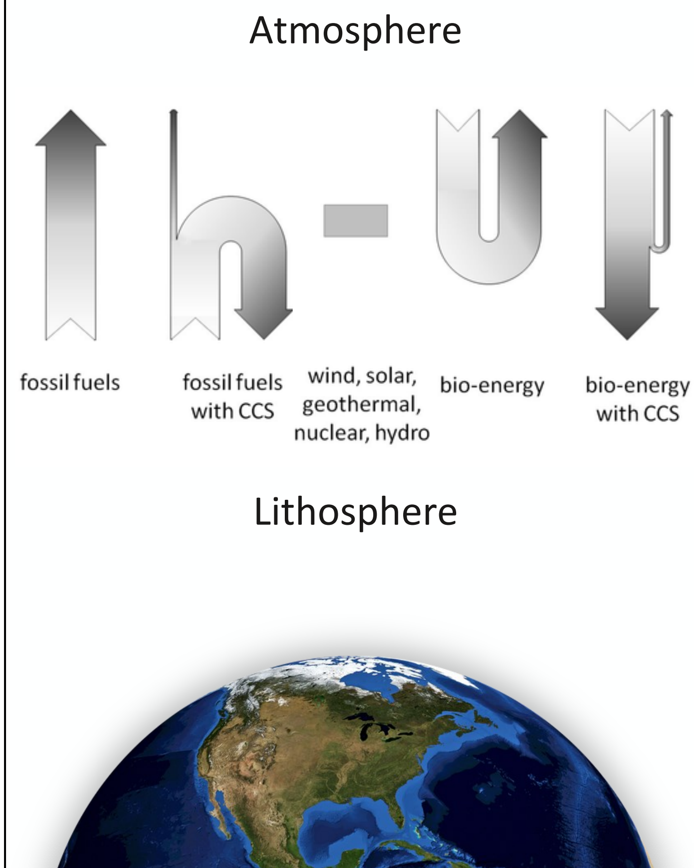
Atmospheric CO2 is absorbed by plants and trees as they grow and then the plant material (biomass) is urned into bioenergy

2.

The CO2 released in the production of bioenergy is captured before it reaches the atmosphere and stored underground

BECCS is combo-breaker:

- electricity
- heat
- seasonal storage
- negative CO2

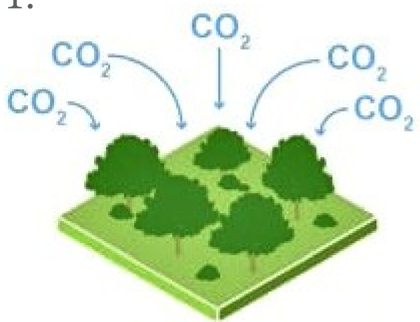


IPCC Report 2018. FAQ Chapter 4.

BECCS+Geothermal

Bioenergy with Carbon Capture and Storage (BECCS)

1.

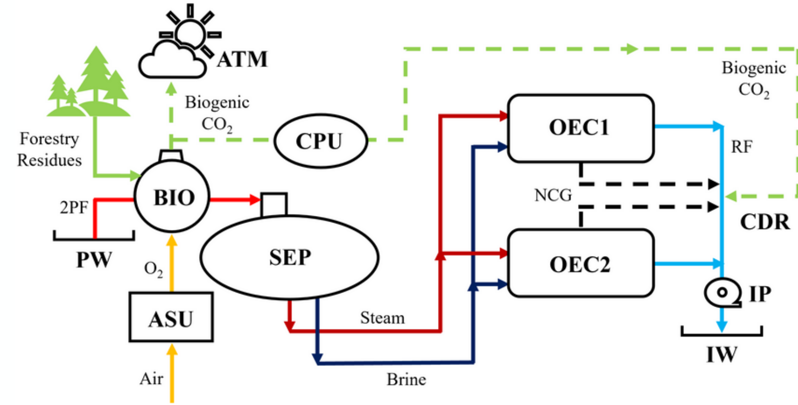


Atmospheric CO_2 is absorbed by plants and trees as they grow and then the plant material (biomass) is urned into bioenergy

2.

The CO_2 released in the production of bioenergy is captured before it reaches the atmosphere and stored underground

Bioenergy+CCS+Geothermal



- Enhance geothermal fluid with forestry residues
- Capture and dissolve CO_2 in aqueous dissolution
- Save costs on wells and transport
- NZ's geothermal fields 2-5 Mt/year

BECCS+Geothermal: ultimate combo-breaker

Building blocks of SAFSC for New Zealand

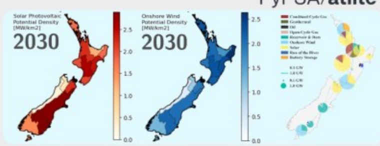
Resource potentials, techno-economic assumptions, and logistics parameters

RE potentials

Solar/onshore wind: PyPSA/Atlite

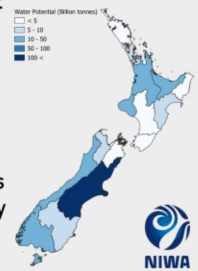
Hydro/Geothermal: PyPSA-NZ results

Possible additions:
- Offshore wind
- Trans-Tasman link



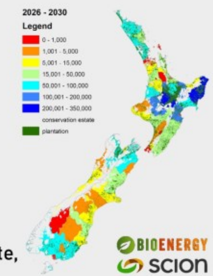
Water potential

Water potential data:
- Inland water: Accessible surface waters
- Sea water: Theoretically, infinite. Depends on the electricity capacity.



Biomass potentials

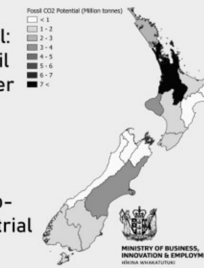
Biomass data:
- lignocellulosic (municipal wood, industrial wood processing waste, forest residue, etc.)
- Agricultural: corn, straws, etc.
- Animal: Dairy waste, pig farm effluents.



Carbon potentials

Carbon data:
- Existing potential: Aggregated fossil CO_2 emissions per region
- DACCS

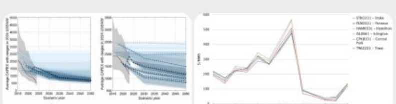
Possible additions:
- Separation of bio- -genic and industrial source points
- BECCS potential



Electricity costs

NREL ATB 2024:
- LCOE projections for solar PV, onshore wind, offshore wind, and geothermal

EECA:
- LCOE for hydro power (assumed constant for future)



Other costs

Biomass costs:
- SCION: Residual biomass fuel projection for New Zealand

Carbon price:
- NZ ETS

Technology costs:
- Danish Energy Agency, 2025
- Solomon Oyewo et al. 2024
- Farajiamiri et al. 2023

alpha/beta matrices

Alpha matrix:
- Consumption/production rates of technologies

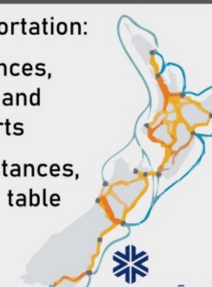
* Efficiency rates are included for all the conversion/production technologies.

Beta matrix:
- Input/output rates of resources

* Energy content-adjusted beta values for different biomass resources

Transport logic table

Freight transportation:
- Road: Distances, prod., stor., and demand ports
- Coastal: Distances, binary logic table for regions
- Rail: not included.



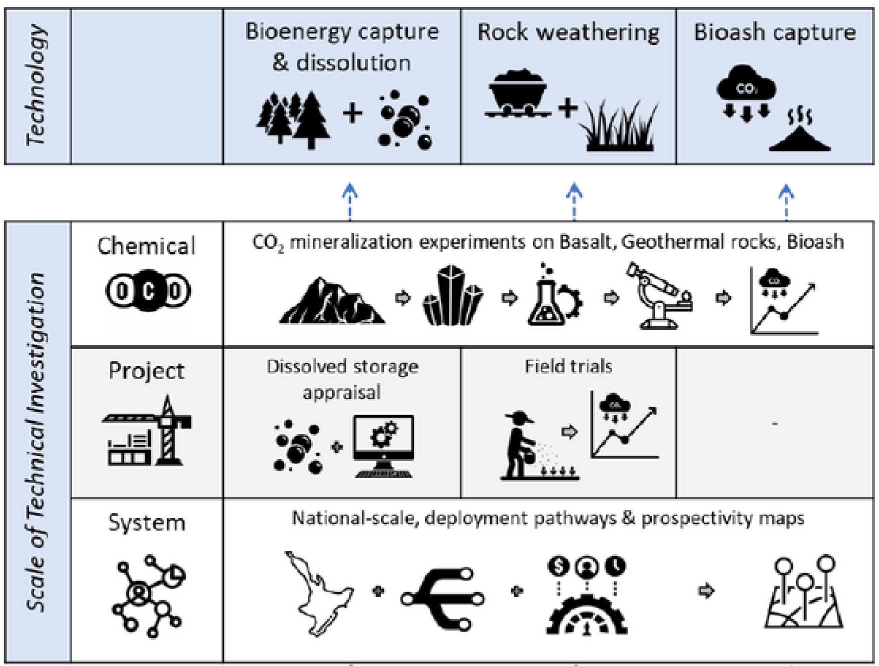
Vatankhah Ghadim H. et al., "What Will It Take to Fly Clean in New Zealand? A National Sustainable Aviation Fuel Value Chain Analysis". (Working paper)

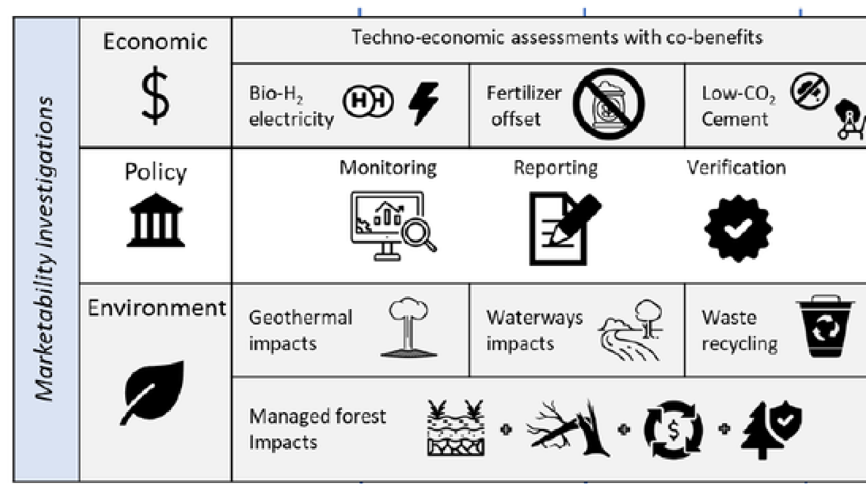
NIWA, SCION/BioEnergy, MfE, NREL ATB v2.0 2024, MBIE's levelized cost tool, DEA 2025, MoT

Derisking Carbon Dioxide Removal at Megatonne Scale in Aotearoa

Universities of Canterbury, Waikato & Auckland, Scion, GNS Science

David Dempsey, Mila Adam, Harry Barton, Jennifer Campion, Graham Coker, Jannik Haas, Matthew Hill, Terry Isson, Andrew La Croix, Andy Nicol, John O'Sullivan, Adrienne Paul, Rebecca Peer, John Reid, Allan Scott





ENDEAVOUR FUND

25 years of energy transition

1
Renewables
Build, build, build: Solar PV, wind, batteries, 10x!

2
Energy efficiency
New building designs, building thermal response. Timber!

3
Electrification
Primary energy fallacy. 3x-6x efficiency gain from HPs and EVs.

4
Hydrogen
Tackle hard-to-abate industry and efuels (shipping, aviation)

5
CO2 capture
As feedstock for efuels and to compensate overshoot. Bio-geo-CO_2 plants NZ.

Short-term: Energy stress +/- (e.g. bankruptcies Chile/Australia, spikes Texas)
Mid-term: Power-to-X (X=population, compute, electrification, H2, CO2 capture, precision fermentation)
Long-term: energy-unconstrained economy?

SERG Sustainable Energy Research Group

UC University of Canterbury
Te Whare Wānanga o Waitaha
Christchurch New Zealand

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Check-out the DAAD and NZ industry PhD scholarships

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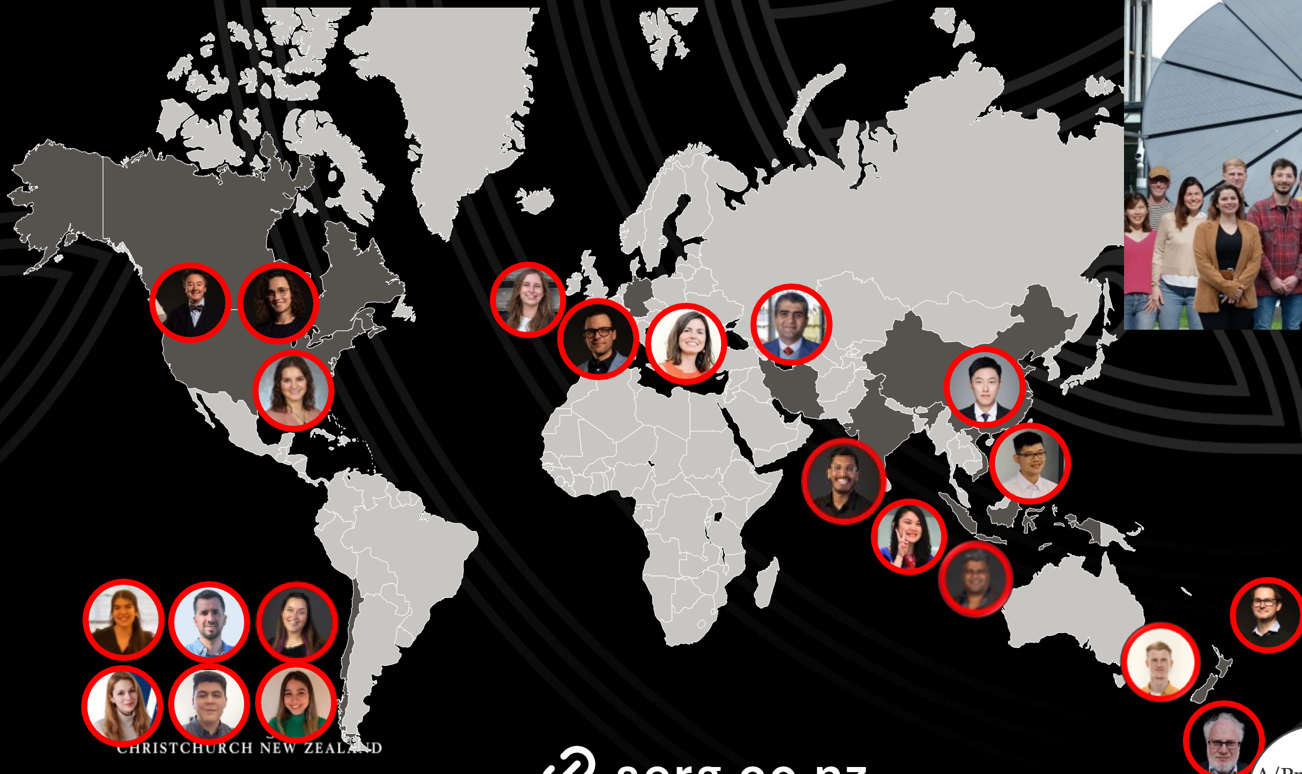

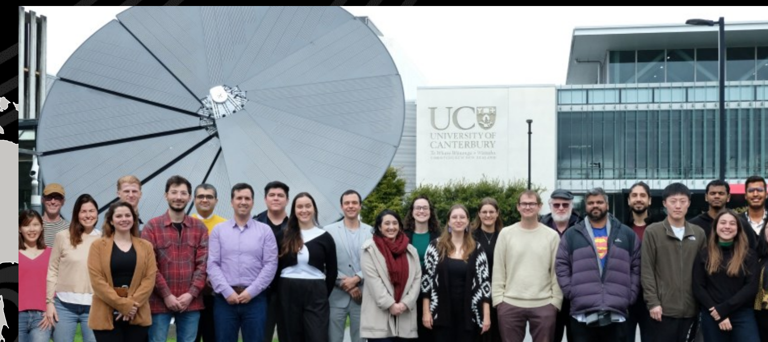

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