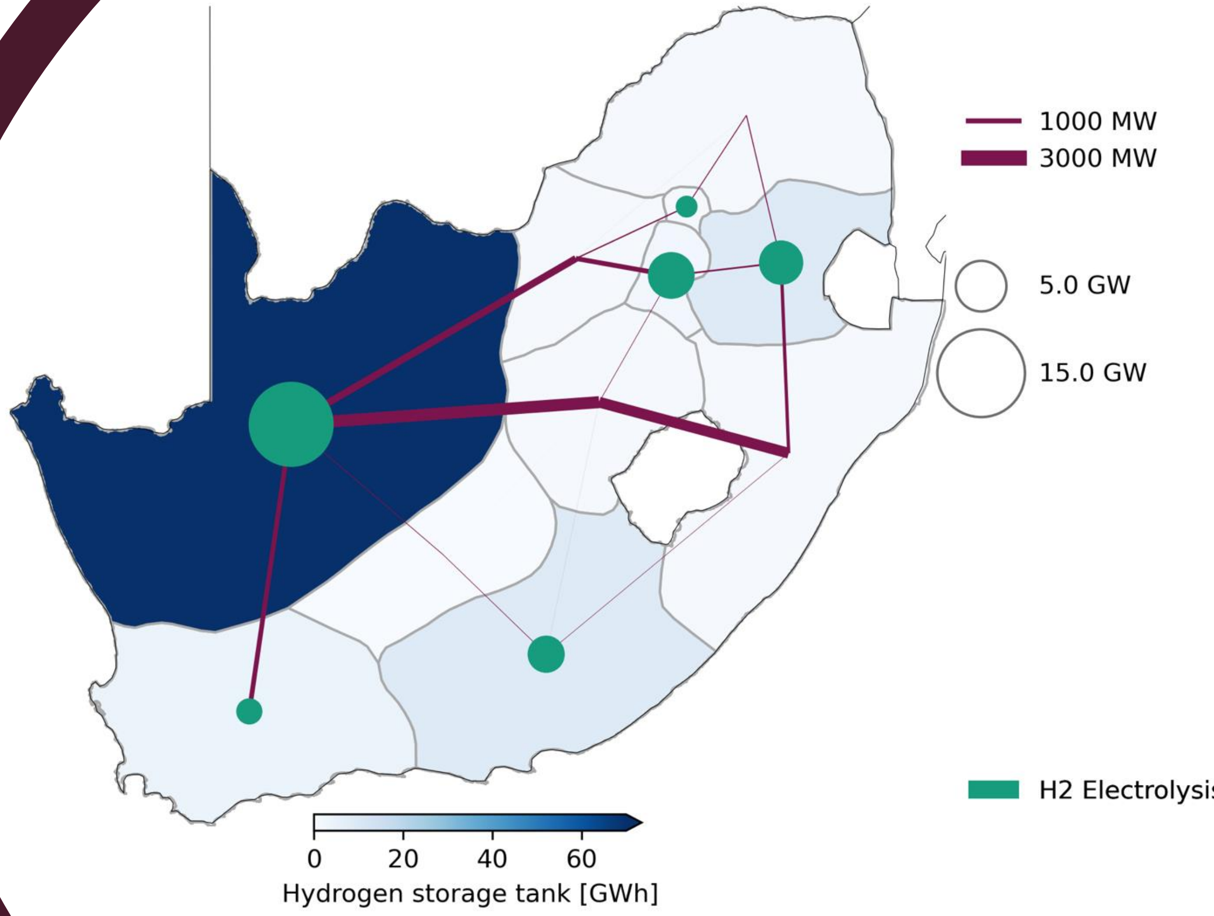
Long-term energy system modelling: Power-to-X scenario analysis for South Africa



Supported by:

Federal Ministry for Economic Affairs and Climate Action

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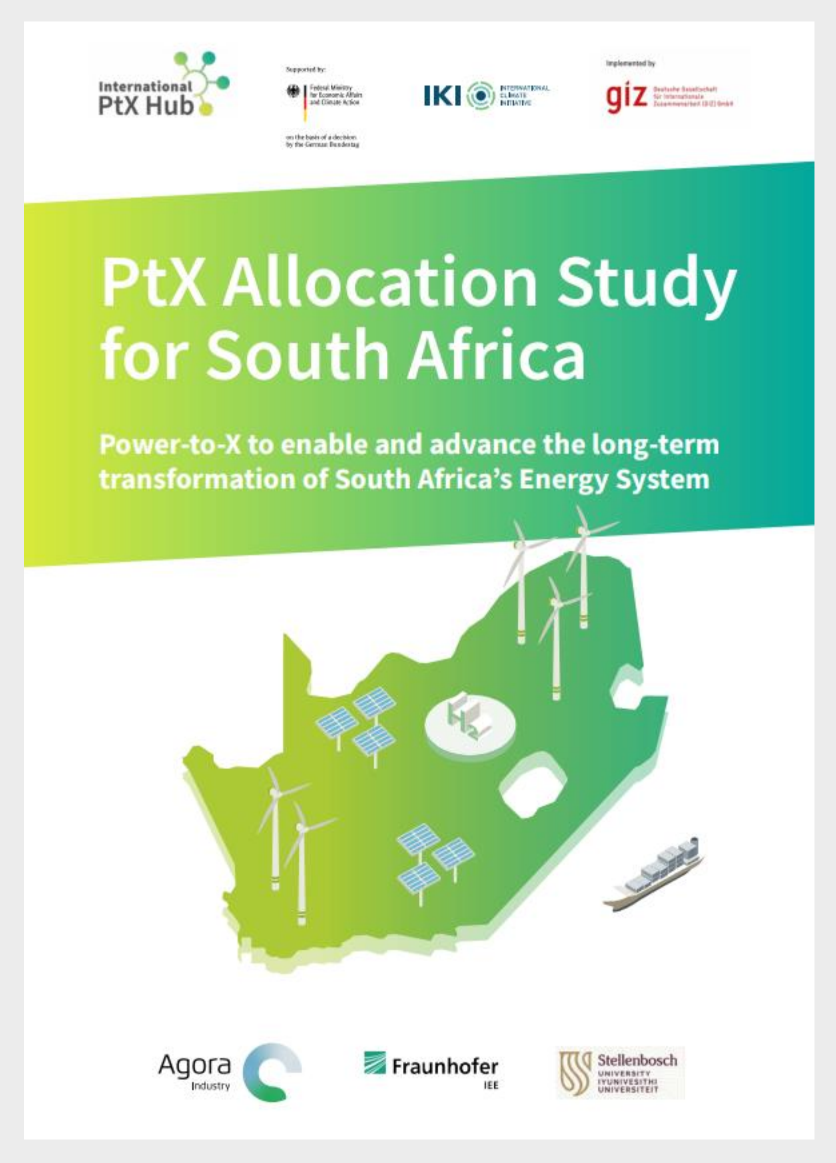
INTERNATIONAL CLIMATE INITIATIVE

Implemented by

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Power-to-X Allocation Study for SA

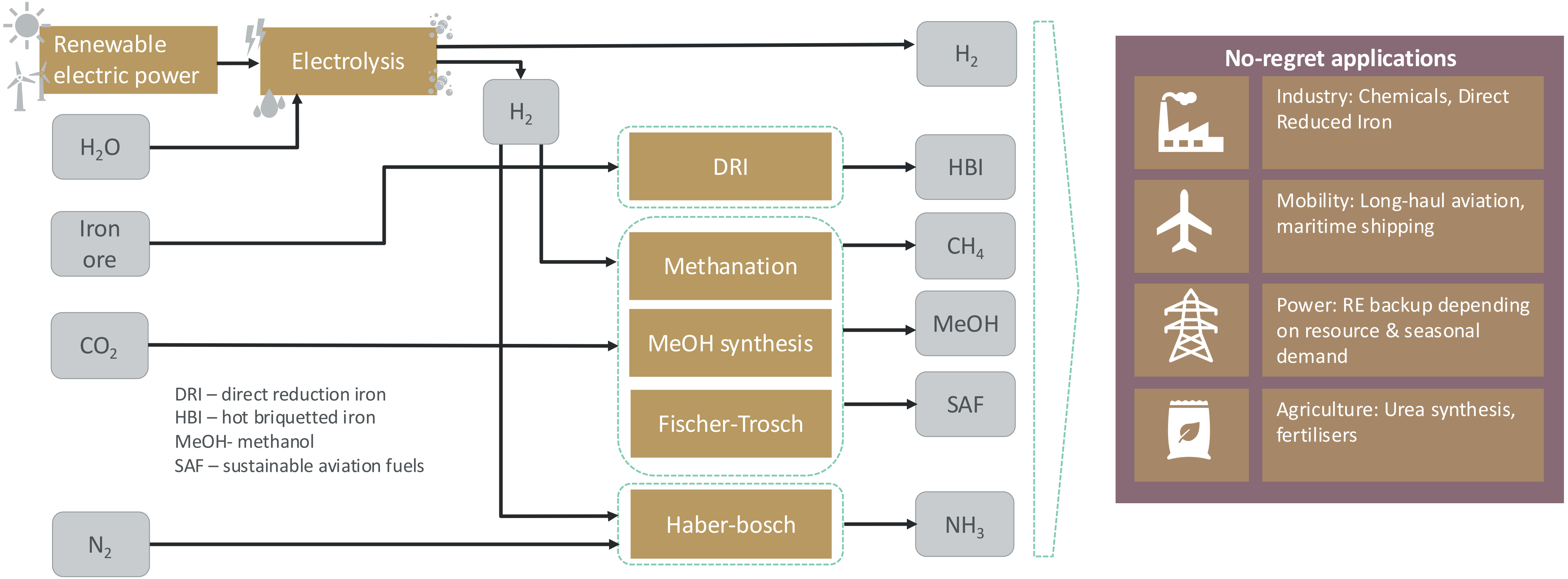


- CRSES contributed to a model-based study of defossilisation and Power-to-X (PtX) development scenarios for South Africa (SA), in collaboration with **Fraunhofer IEE, Agora Industry and the PtX Hub**, which was implemented by the **GIZ**.
- While most emission reductions are anticipated from renewable energy (RE) deployment, energy efficiency, and direct electrification, both green electrons (RE electricity) and green molecules (renewable fuels and chemicals) will be required to decarbonise hard-to-abate sectors.
- The study identified cost-efficient PtX pathways, aligning RE expansion and the growing demand (local and export) for green electricity, hydrogen, ammonia, and synthetic fuels.
- Access the full publication here[1].
- Explore the model here[2]. Required datasets can be made available on request and are described in the installation instructions.

1 https://ptx-hub.org/publication/ptx-allocation-study-south-africa/
2 https://github.com/ljansen-iee/pypsa-rsa-sec

What is PtX?

- RE powers electrolysers to split water into green hydrogen (GH_2) and oxygen. GH_2 is combined with renewable carbon or nitrogen sources to produce various PtX products.
- SA is potentially well-positioned for emerging PtX markets given its natural and industrial strengths (abundant land area, solar and wind resources, Fischer-Tropsch expertise and assets, mature iron and platinum sectors, etc).
- The study considered GH_2, synthetic green Fischer-Tropsch and methanol fuels, green methane, and green ammonia (with desalinated seawater, nitrogen, and usable carbon dioxide feedstocks).



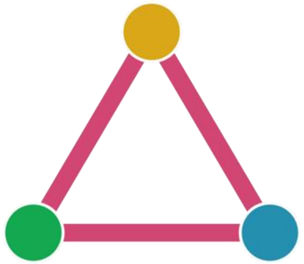
Adapted from Agora Energiewende PtX Training (2024)

Models leveraged to develop PyPSA-RSA-Sec

- Building on PyPSA-RSA (developed and maintained by Meridian Economics[1]) and integrating features from PyPSA-Eur[2] (F. Neumann *et al*, 2022) and PyPSA-Earth-Sec[3] (H.Abdel-Khalek *et al*, 2025), a cross sector model of SA's energy system, PyPSA-RSA-Sec was developed.
- This is the first open-source multisector, multi-regional, and hourly-resolved energy system model for SA.
- PyPSA-RSA-Sec optimises operational and investment decisions for generation, storage, transport and conversion technologies to meet projected hourly demands for 2030, 2040 and 2050.

PyPSA

A python software toolbox for simulating and optimising modern power systems



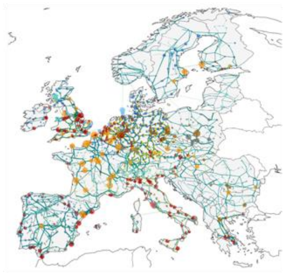
Framework

https://pypsa.readthedocs.io/

T. Brown, et al. (2018)

PyPSA-Eur

A sector-coupled open optimisation model of the European energy system



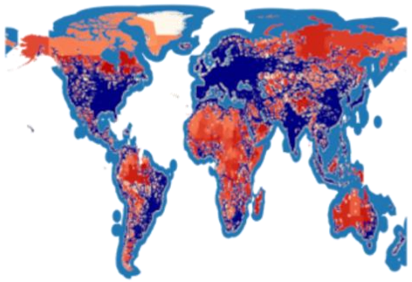
Model

https://pypsa-eur.readthedocs.io/

F. Neumann, et al.(2022)

PyPSA-Earth

A flexible open sector-coupled optimisation model of the global energy system.



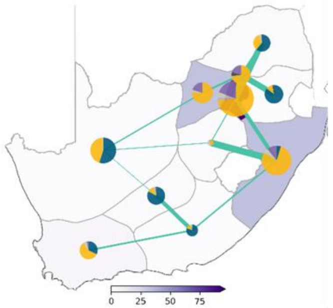
Model

https://pypsa-earth.readthedocs.io/

H. Abdel-Khalek, et al.(2024)

PyPSA-RSA

An optimisation model for the South African power system



Model

https://pypsa-za.readthedocs.io/

Meridian Economics (2024)

1 https://github.com/MeridianEconomics 2 https://pypsa-eur.readthedocs.io/en/latest/ 3 https://pypsa-earth.readthedocs.io/en/latest/

- H. Abdel-Khalek et al. "PyPSA-Earth sector-coupled: A global open-source multi-energy system model showcased for hydrogen applications in countries of the Global South", Applied Energy, 2025
- Fabian Neumann et al "The potential role of a hydrogen network in Europe", Joule, 2023

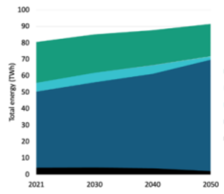
Inputs and methodology

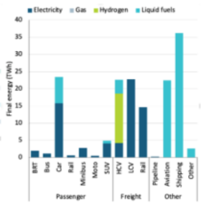
- The future energy demand is based on South Africa's Just Energy Transition Investment Plan[1] (JET-IP), a report commissioned by presidency which sets out the scale of investments required to achieve decarbonisation commitments in our Nationally Determined Contribution, based on the South African Times (SATIM) model (developed and maintained by the University of Cape Town).
- Spatio-temporal models were applied to identify potential sites for renewable energy deployment and to generate corresponding solar and wind production profiles using Fraunhofer's specialised energy system tools (energyANTS ans regioANTS)[2].

Final Energy Demands from SATIMGE (JET-IP)

Projection and calibration of socio-economic factors and final energy demands

- per sub-sector and application for residential, industry, transport, commercial and agriculture
- per commodity electricity, coal, liquid fuel, methane, biomass, hydrogen



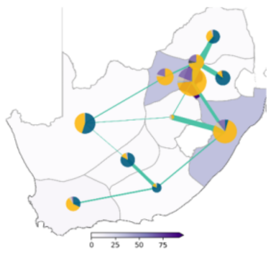


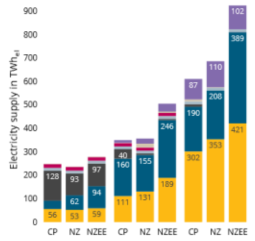
Minor modification of demands and spatial disaggregation based on geospatial information

Energy System Optimisation with PyPSA-RSA-Sec

For each region, time step and scenario

- Cost-optimised capacities, generation mix, PtG/PtL synthesis, imports and exports, and system costs





Techno-economic assumptions, Policy constraints, …

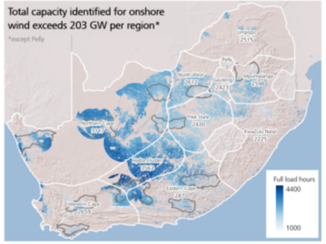
energy ANTS

Simulation of profiles for each cell and aggregation to model regions

Area Potentials for Wind & Solar

regio ANTS

Suitable areas considering built-up areas, croplands, forests, protected areas, critical habitats, slope, available infrastructure (grid, cities, water)



1 https://www.climatecommission.org.za/publications/sa-jet-ip
2 https://www.iee.fraunhofer.de/de/anwendungsfelder/energieprognosen/energiesystemsimulation.html

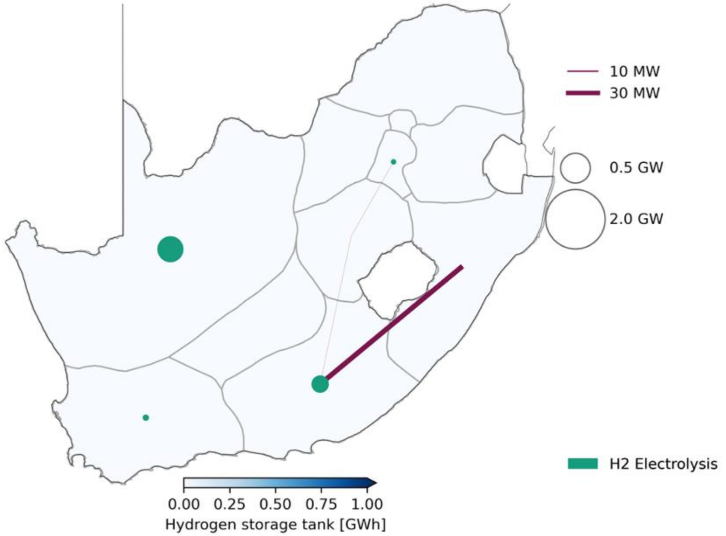
Scenario pathways considered

- The study tested three different future pathways, including the current policy (CP), resilient net-zero (NZ) and net zero early export (NZEE).
- The scenarios have varying levels of RE and PtX adoption, using inputs from national plans (JET-IP, Transmission Development Plan (TDP), Green Hydrogen Commercialisation Strategy (GHCS)), industry reports, and global hydrogen trade studies.
- The results are shaped by assumptions for 2030–2050, and should be seen as modelled scenarios rather than forecasts - as they depend on changing economic, policy, and technical conditions.

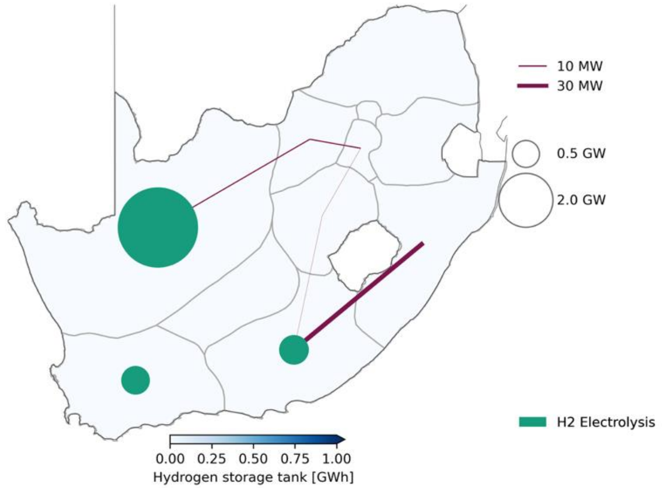
Key drivers	Current Policy (CP)	Resilient Net-Zero (NZ)	NZ + Early Export (NZEE)
CO_2 Policy	No budget limits, CO_2-price, ESKOM plans for coal phase-out	50MtCO_2 in 2050, 8.3 GtCO_2 budget, CO_2 price, Coal phase-out by 2040	=NZ
PtX export	Delayed and low exports (10% of High), Products: Ammonia, Fischer-Tropsch fuels	=CP	High exports for Ammonia and FT fuels, all projects go online as announced
Wind, PV expansion	**2030** Â Limits for four western regions, otherwise free expansion	=CP	Free expansion, assuming on- & off-grid generation
Grid expansion	Limit of +10% existing inter-regional transmission capacities up to 2050	=CP	=CP
Transport sector	Delayed transition to efficiency, modal shift, and new electric vehicles	Ambitious transition to efficiency, modal shift, and new electric vehicles	=NZ
Industry sector	Delayed transition to innovative technologies (e.g. DRI) and efficiency	Ambitious transition to innovative techs & higher domestic fertilizer production	=NZ

Large potential for GH_2 production

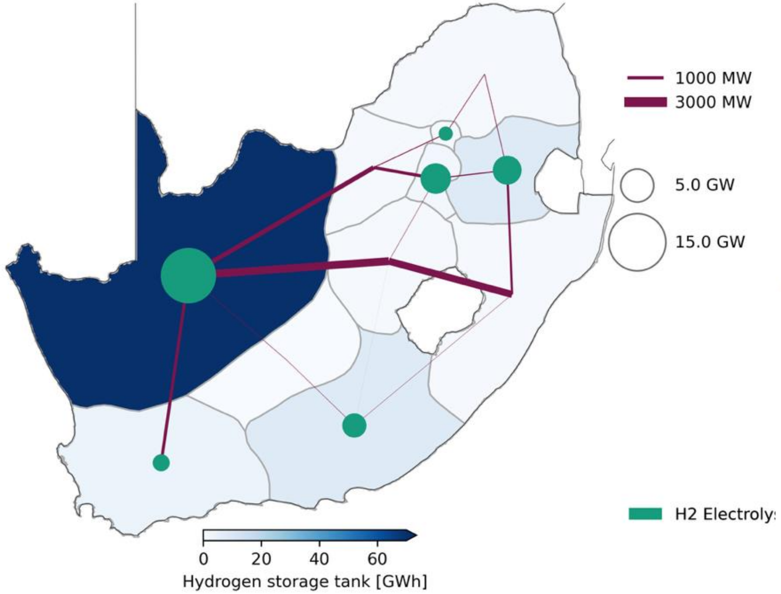
- GH_2 capacity is projected to grow substantially across all scenarios, from under 6 GW electrolyser capacity in 2030 to 17–70 GW by 2050, with higher levels under net-zero pathways.
- Transportation and storage of GH_2 from Northern Cape production sites to industrial hubs and population centres will be key considerations for meeting future demand.
- South Africa has strong potential for GH_2 and could emerge as a major producer, but only if **large-scale investment in green electricity occurs in parallel with GH_2 transport and storage infrastructure development.**



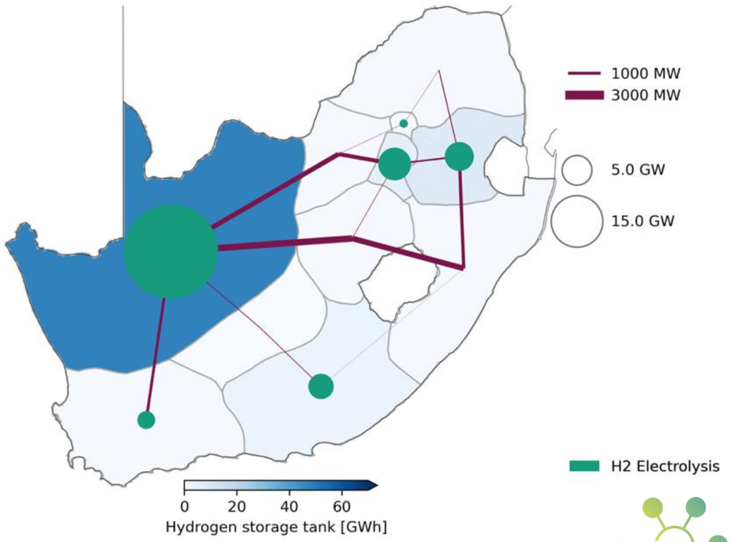
Hydrogen generation, storage and transport capacities by 2030 for NZ.



Hydrogen generation, storage and transport capacities by 2030 for NZEE.



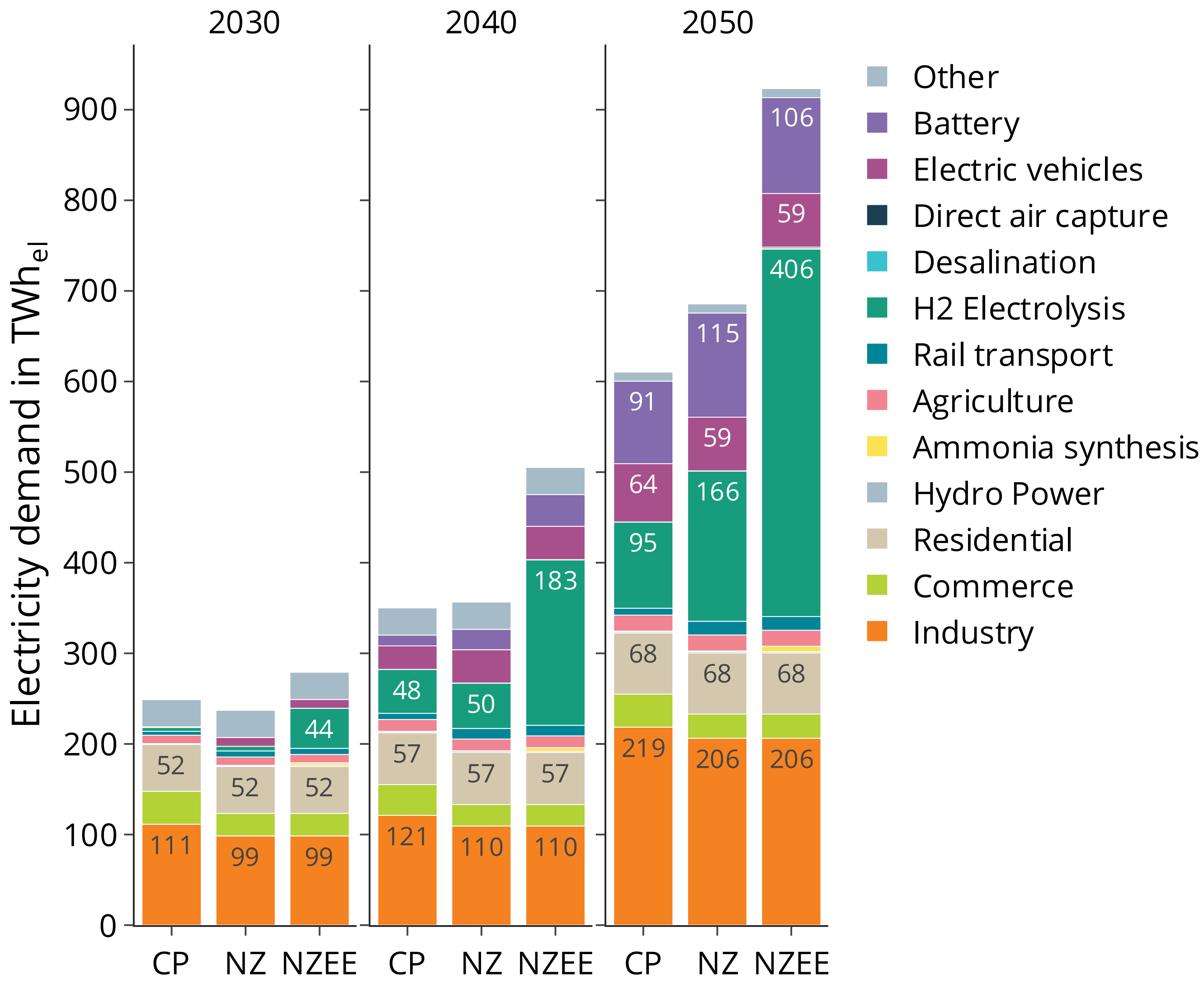
Hydrogen generation, storage and transport capacities by 2050 for NZ.



Hydrogen generation, storage and transport capacities by 2050 for NZEE.

PtX could reshape electricity demand

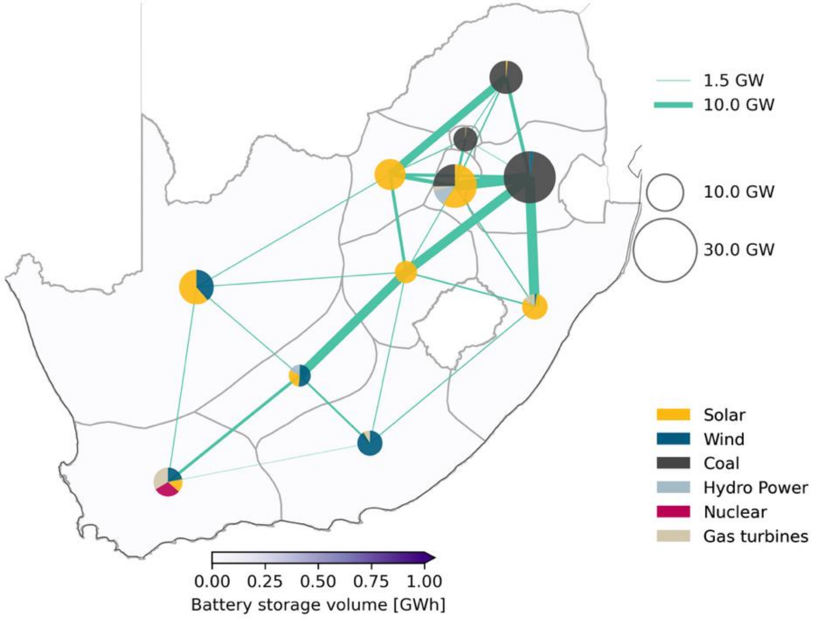
- **By 2050 half the electricity consumption could be attributed to GH_2 production** in the ambitious NZEE scenario.
- Electricity use for electrolysis in this scenario is consistently two to four times higher than the CP and NZ scenarios.
- Meeting this demand will require an **unprecedented scale-up of wind and solar power.**



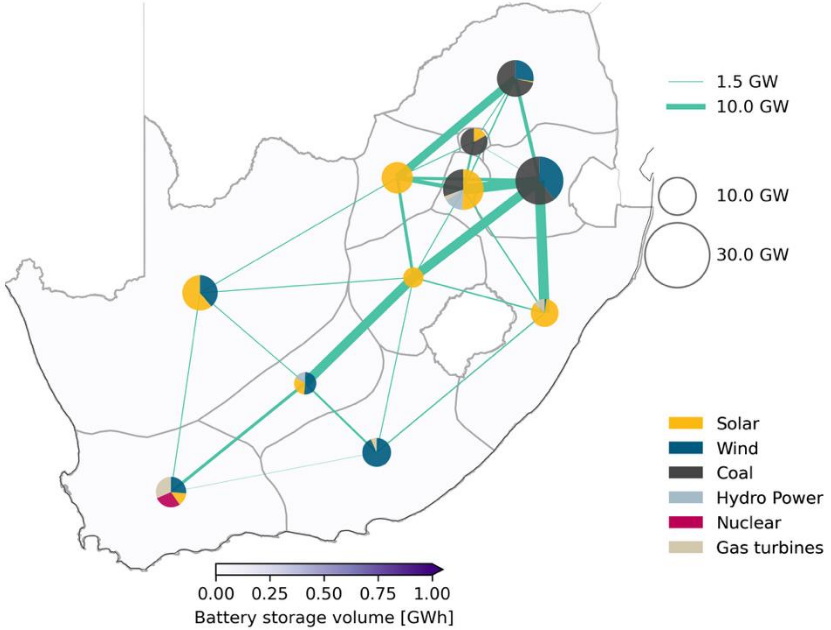
Annualised system expenses (+) and revenues via export (-)

Rapid RE expansion required

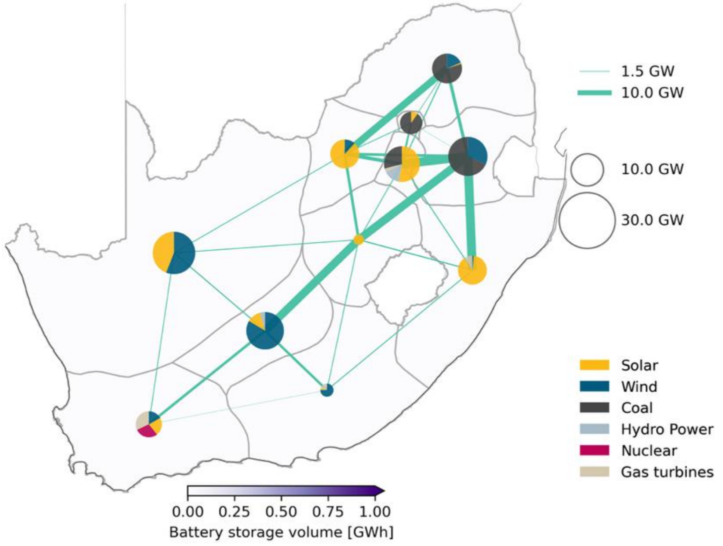
- By 2050, wind and solar capacity are expected to be **seven to ten times larger** than today's coal fleet to meet **domestic demand** and **PtX export ambitions across different scenarios**.
- **Net-zero scenarios require significantly more capacity compared to the CP case, necessitating 20-50% more renewables by 2030.** Furthermore, NZEE requires a further 30% more renewables than NZ by 2050.
- **Transmission is a key enabler.** In NZEE, expanded grid or off-grid PtX allows more growth in Cape-region renewables. Sensitivity analyses show that without any grid expansion total energy system costs would be 10% higher compared to a scenario with a 20% increase in current transmission capacity.
- **Coordinated expansion is essential.** Power generation, transmission, and the PtX value chain must grow **together** to avoid bottlenecks.



Installed electricity generation, storage and transmission capacities by 2030 in CP.



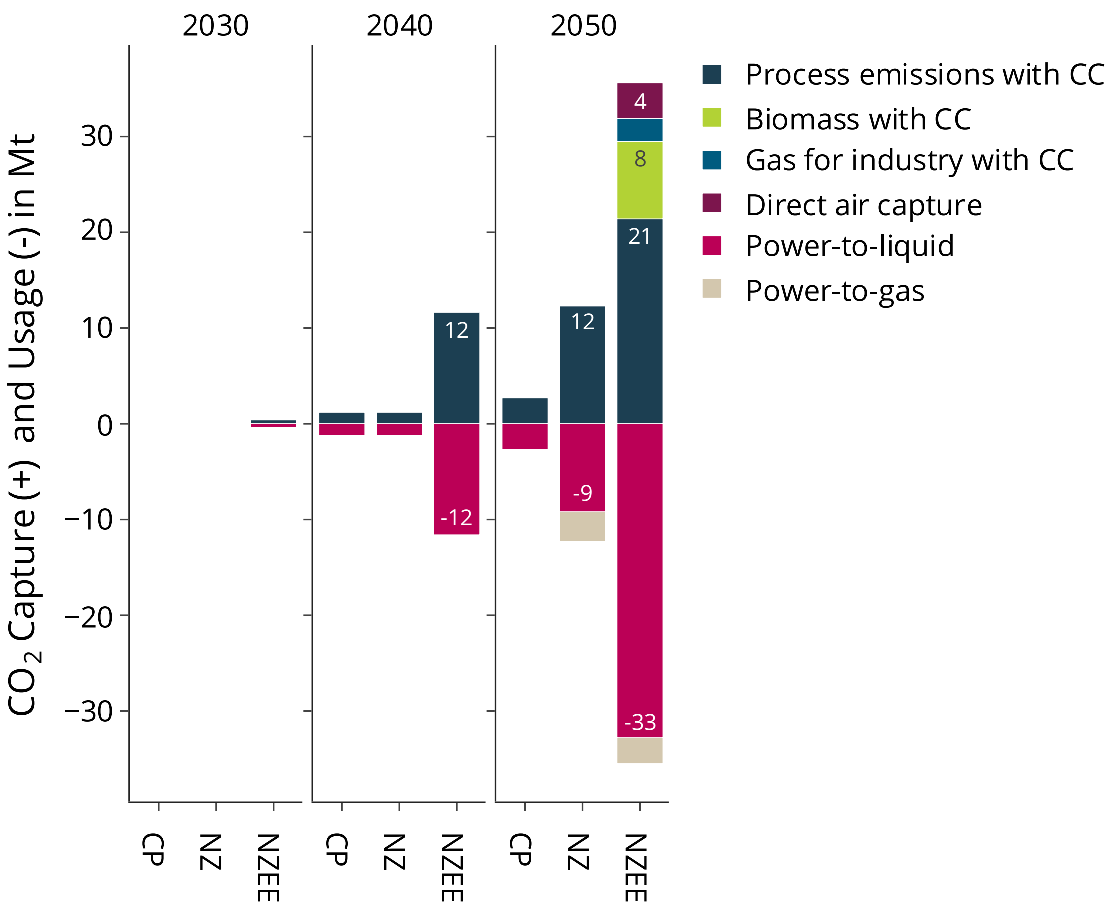
Installed electricity generation, storage and transmission capacities by 2030 in NZ.



Installed electricity generation, storage and transmission capacities by 2030 in NZEE.

Sustainable & viable carbon sources

- Sustainable sources of CO_2 are needed to produce synthetic liquid fuels and gases.
- The scale of this demand is huge, with net-zero pathways requiring much more sustainable CO_2.
- By 2050 more than 30 million tonnes of CO_2 will be needed for the ambitious NZEE, capturing CO_2 from process emissions, biomass, industry and eventually direct air capture (DAC) to supply PtX fuels.
- DAC is unlikely to be widely available before 2040, making it a last-resort option in NZEE. This underscores the high costs and technical challenges of deep decarbonisation.

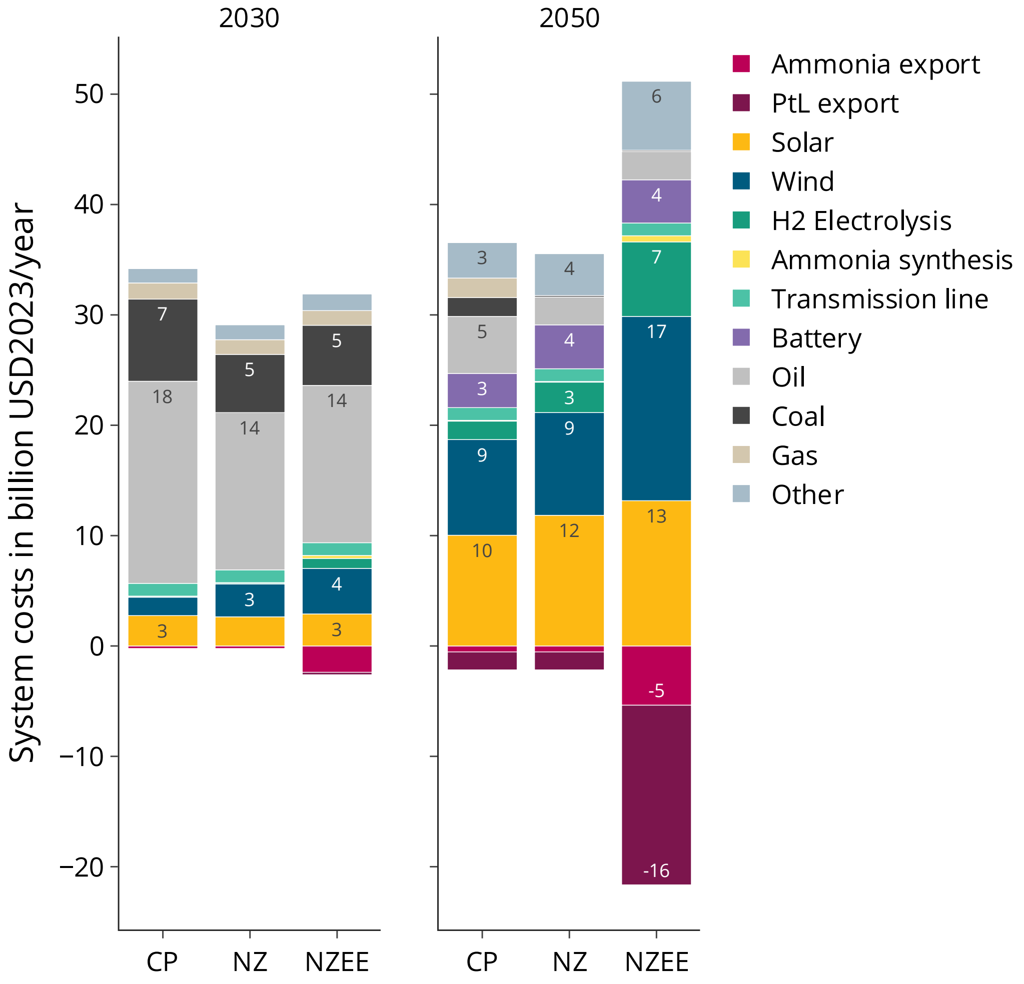


CO2 feedstock balance with capture volumes (+) and usage volumes (-)

This study draws on the NBI report titled "Decarbonising South Africa's petrochemicals and chemicals sector", and the most recent study on Carbon Sources for the Production of PtX Products and Synthetic Fuels in South Africa, to establish the basis for available quantities and associated prices of CO2 from alternative sources.

Export revenue potential coupled with expenses

- The energy system shifts from a **fuel-dominated cost structure in 2030** (oil and coal) to a **capital-intensive structure in 2050** (wind, solar, battery, hydrogen electrolysis).
- PtX fuels are expected to be more profitable than ammonia due to South Africa's local advantages, with Fischer-Tropsch expertise, lower-cost CO_2 sources, long coastlines for desalination, and well-positioned ports.
- While the early export scenario has the highest export revenue potential, it also requires the largest investments and carries significant risks.
- Explore a further analysis here[1], where McGregor and Young unpack the risks and infrastructure challenges behind South Africa's GH_2 ambitions.



Electricity demand, battery storage charging, self-consumption and exports (other)

1 http://wits.ac.za/news/latest-news/opinion/2025/2025-02/why-sa-is-not-ready-to-produce-green-hydrogen.html

Future research recommendations

CENTRE FOR RENEWABLE & SUSTAINABLE ENERGY STUDIES | Stellenbosch University | Fraunhofer IEE | Agora Industry

System Modelling & Data

- Explore higher spatial resolutions with improved mapping of transport routes and infrastructure for hydrogen, methane, liquid fuels, water, ammonia, CO_2, and biomass.
- Focus on short-term horizons with realistic RE expansion, integrating unit commitment constraints.

Technology & Products

- Improve modelling of technology limits, such as the Fischer-Tropsch process.
- Expand analysis to other PtX products, including green Direct Reduced Iron (DRI).

Regional & Socio-Economic Dimensions

- Explore synergies with neighbouring SADC countries through a regional, multi-national model.
- Carry out detailed socio-economic assessments of transport and industrial demand developments at both national and regional levels.

Policy & Planning Integration

- Integrate PtX scenarios into the next Integrated Resource Plan (IRP) and Transmission Development Plan (TDP).
- Update South Africa's hydrogen roadmaps on a regular basis.
- Continuously track global PtX markets, regulations, and technology trends to adapt strategies.

International PtX Hub

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