Energy Consumption in Higher Education Buildings: Bridging the Performance Gap Using Digital Twin Technology

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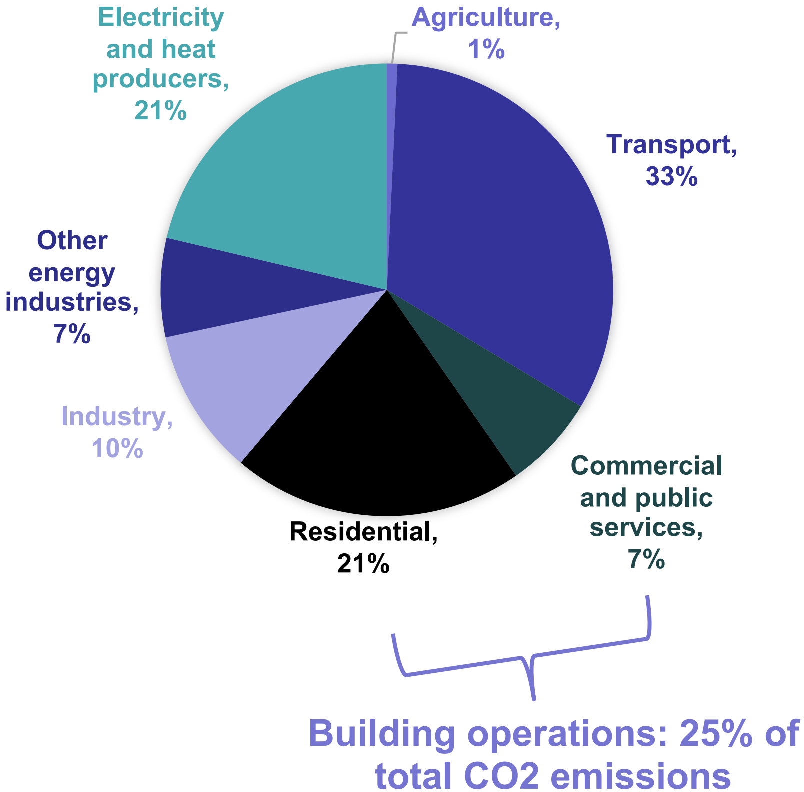
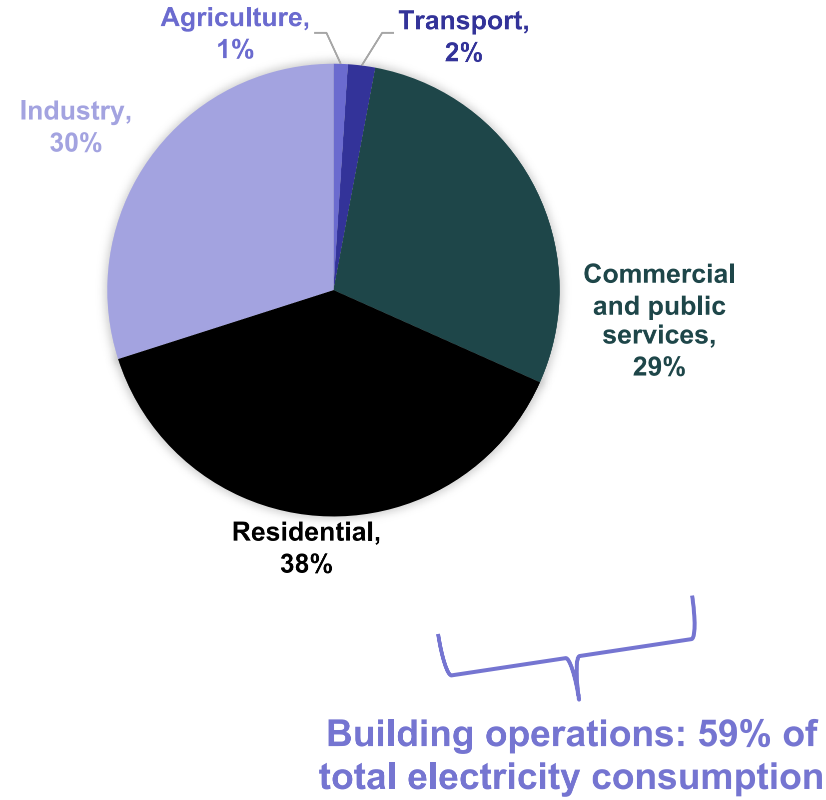
MSc Energy Systems 2022-2023
DPhil Engineering Science

Background



UK CO2 emissions by sector – 2021



UK electricity consumption by sector – 2021

HEIs: 2% of total building stock, yet 2nd highest energy-intensive sector

Graphs source: IEA, https://www.iea.org/data-and-statistics

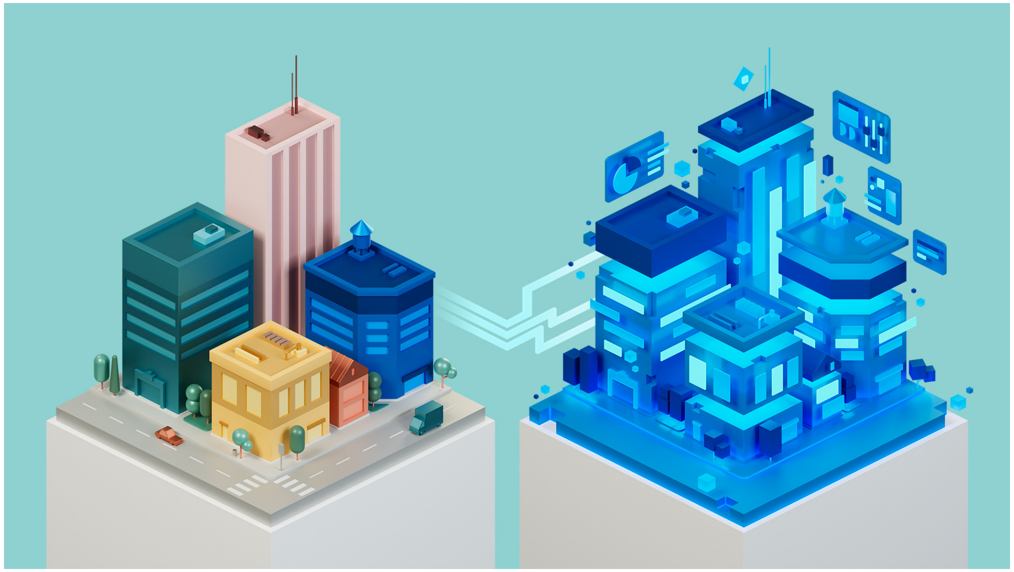
Digital Twin Technology

Digital twin (DT): virtual model representing the operations and system configurations of a building's physical object

Building energy simulation

Performance gaps identification

Energy efficiency and conservation measures testing



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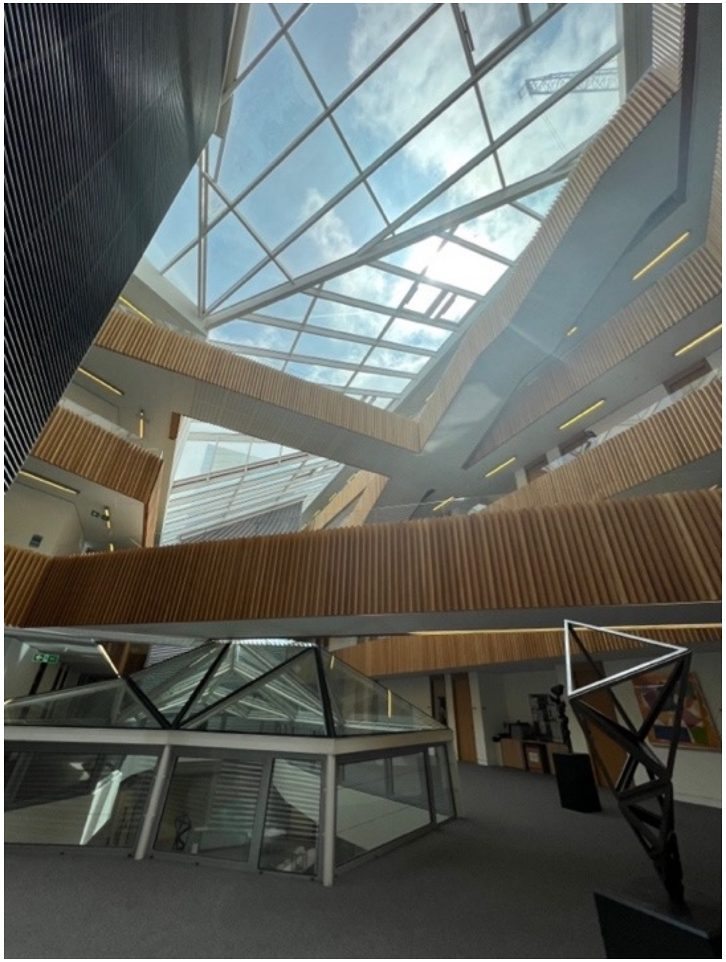
Oxford e-Research Centre

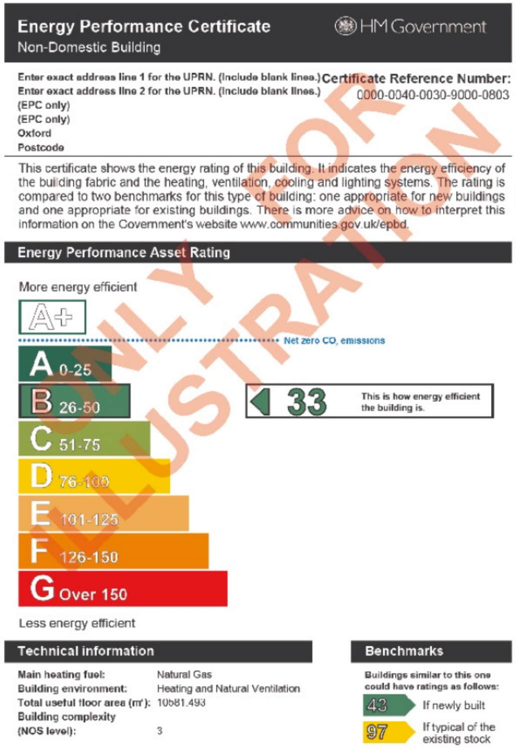
The Andrew Wiles Building

DEPARTMENT OF ENGINEERING SCIENCE

ENERGY SYSTEMS



The Andrew Wiles Building



Energy Performance Certificate
HM Government
Non-Domestic Building

Enter exact address line 1 for the UPRN. (Include blank lines.)
Enter exact address line 2 for the UPRN. (Include blank lines.)
(EPC only)
(EPC only)
Oxford
Postcode

Certificate Reference Number:
0000-0040-0030-9000-0803

ONLY FOR ILLUSTRATION

This certificate shows the energy rating of this building. It indicates the energy efficiency of the building fabric and the heating, ventilation, cooling and lighting systems. The rating is compared to two benchmarks for this type of building: one appropriate for new buildings and one appropriate for existing buildings. There is more advice on how to interpret this information on the Government's website www.communities.gov.uk/epbd.

Energy Performance Asset Rating

More energy efficient

A+

Net zero CO_2 emissions

A 0-25
B 26-50
C 51-75
D 76-100
E 101-125
F 126-150
G Over 150

Less energy efficient

33 This is how energy efficient the building is.

Technical information

Main heating fuel:	Natural Gas
Building environment:	Heating and Natural Ventilation
Total useful floor area (m²):	10581.493
Building complexity (NOS level):	3

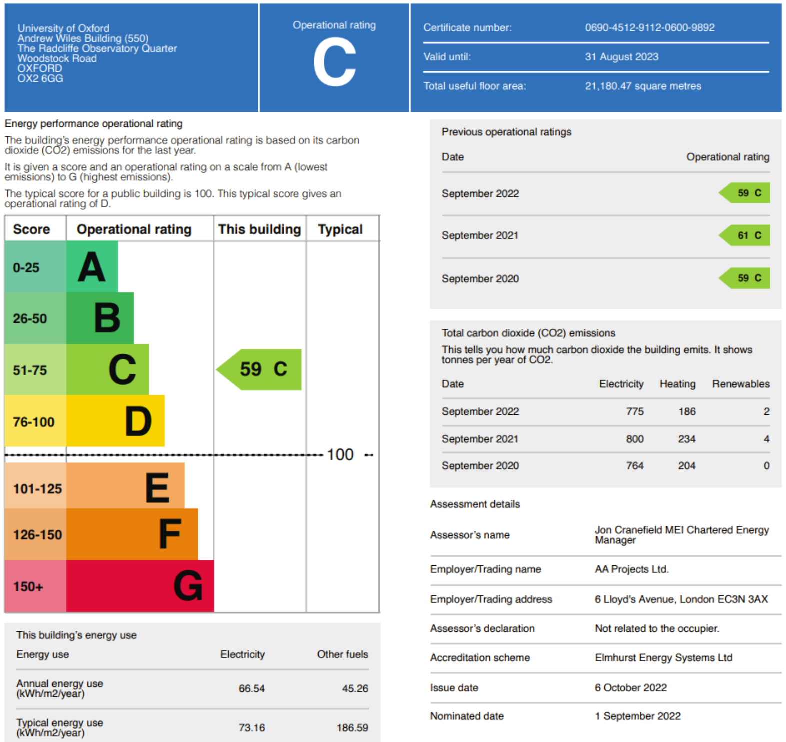
Benchmarks

Buildings similar to this one could have ratings as follows:

43 If newly built

97 If typical of the existing stock

EPC before construction



University of Oxford
Andrew Wiles Building (550)
The Radcliffe Observatory Quarter
Woodstock Road
OXFORD
OX2 6GG

Operational rating
C

Certificate number:	0690-4512-9112-0600-9892
Valid until:	31 August 2023
Total useful floor area:	21,180.47 square metres

Energy performance operational rating

The building's energy performance operational rating is based on its carbon dioxide (CO_2) emissions for the last year.

It is given a score and an operational rating on a scale from A (lowest emissions) to G (highest emissions).

The typical score for a public building is 100. This typical score gives an operational rating of D.

Score	Operational rating	This building	Typical
0-25	A		
26-50	B		
51-75	C	59 C	
76-100	D		100
101-125	E		
126-150	F		
150+	G		

This building's energy use

Energy use	Electricity	Other fuels
Annual energy use (kWh/m2/year)	66.54	45.26
Typical energy use (kWh/m2/year)	73.16	186.59

Previous operational ratings

Date	Operational rating
September 2022	59 C
September 2021	61 C
September 2020	59 C

Total carbon dioxide (CO2) emissions

This tells you how much carbon dioxide the building emits. It shows tonnes per year of CO2.

Date	Electricity	Heating	Renewables
September 2022	775	186	2
September 2021	800	234	4
September 2020	764	204	0

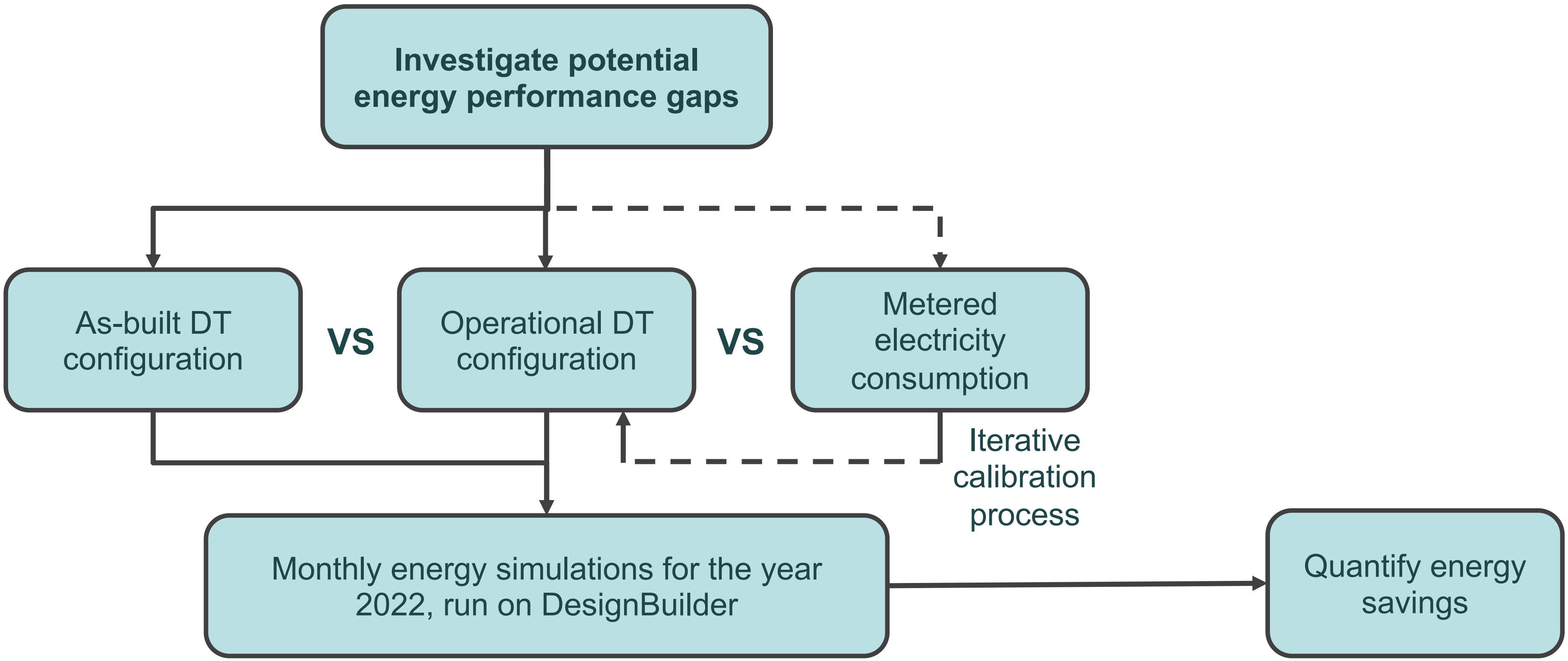
Assessment details

Assessor's name	Jon Cranefield MEI Chartered Energy Manager
Employer/Trading name	AA Projects Ltd.
Employer/Trading address	6 Lloyd's Avenue, London EC3N 3AX
Assessor's declaration	Not related to the occupier.
Accreditation scheme	Elmhurst Energy Systems Ltd
Issue date	6 October 2022
Nominated date	1 September 2022

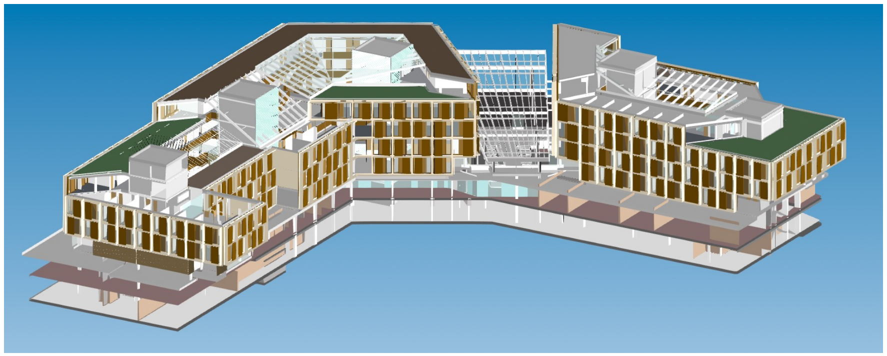
DEC for 2022

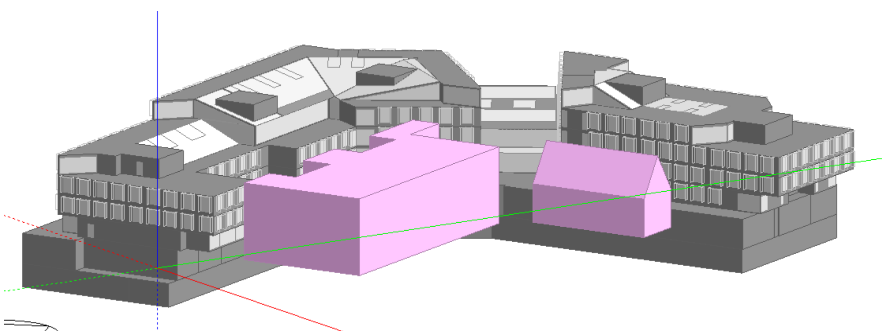
~ 30.5 kgCO2/m2/year ≠ **~ 45 kgCO2/m2/year**

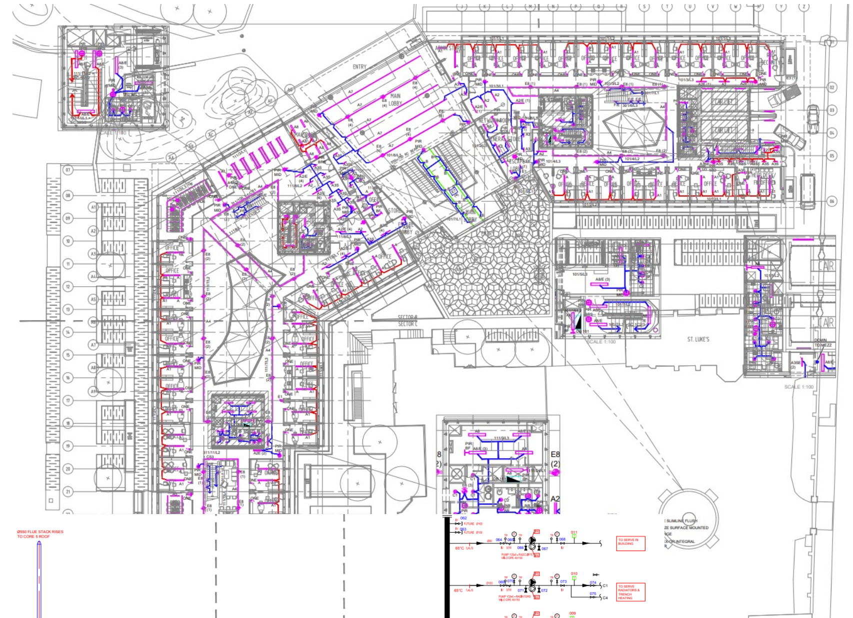
Objectives

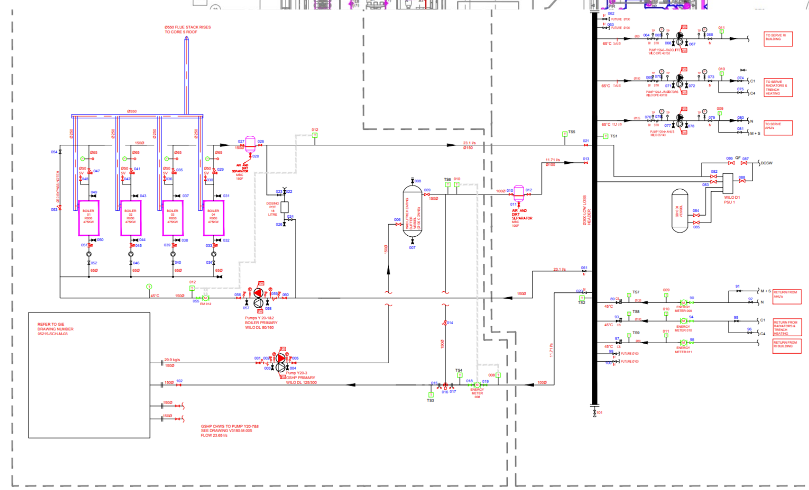

Investigate potential energy performance gaps
As-built DT configuration
VS
Operational DT configuration
VS
Metered electricity consumption
Iterative calibration process
Monthly energy simulations for the year 2022, run on DesignBuilder
Quantify energy savings

As-Built DT Configuration

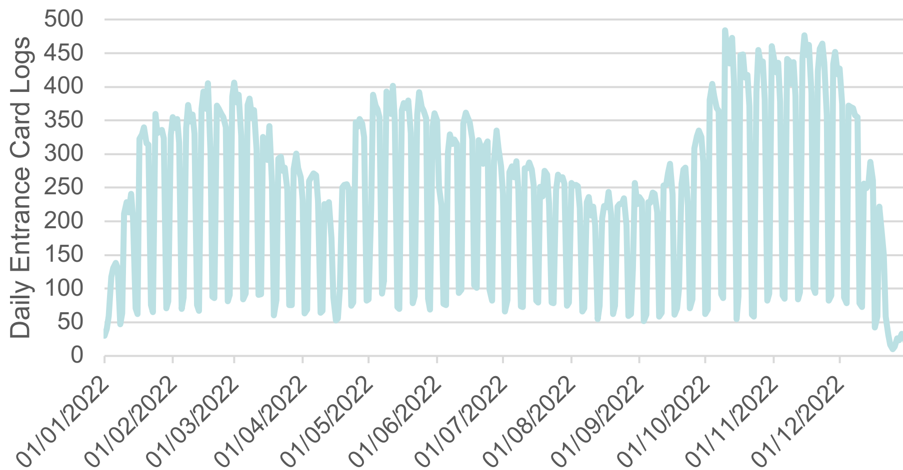




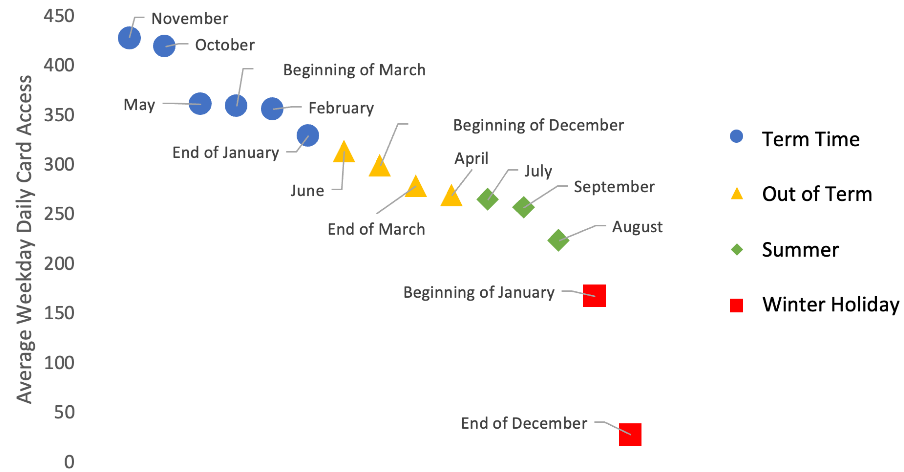




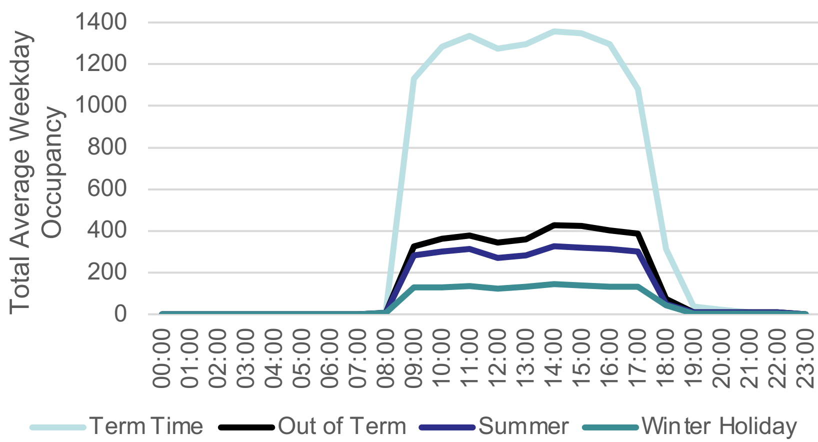
As-Built DT Configuration



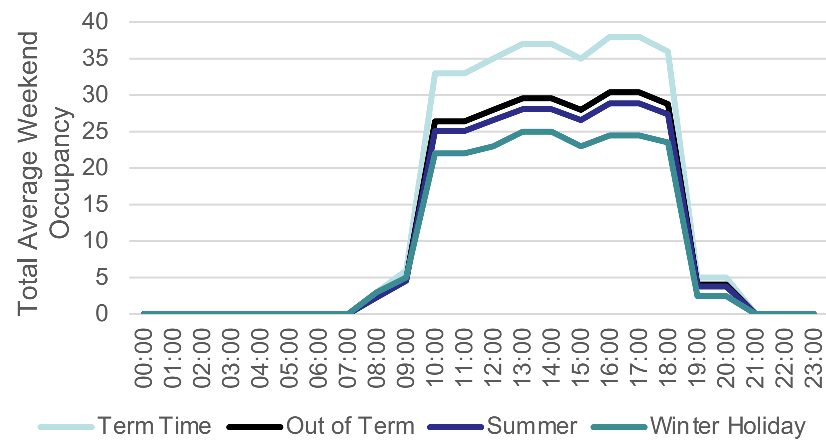
Card Access Data



Occupancy Rate Clusters



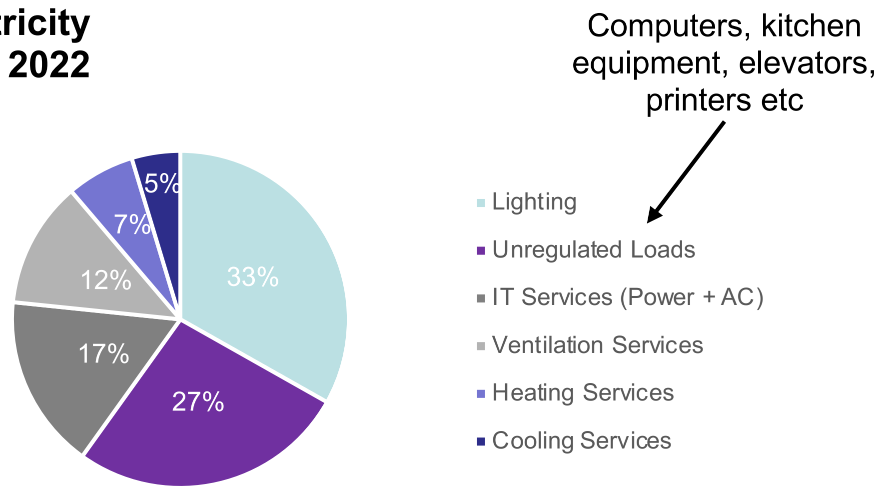
Occupancy Profile - Weekday

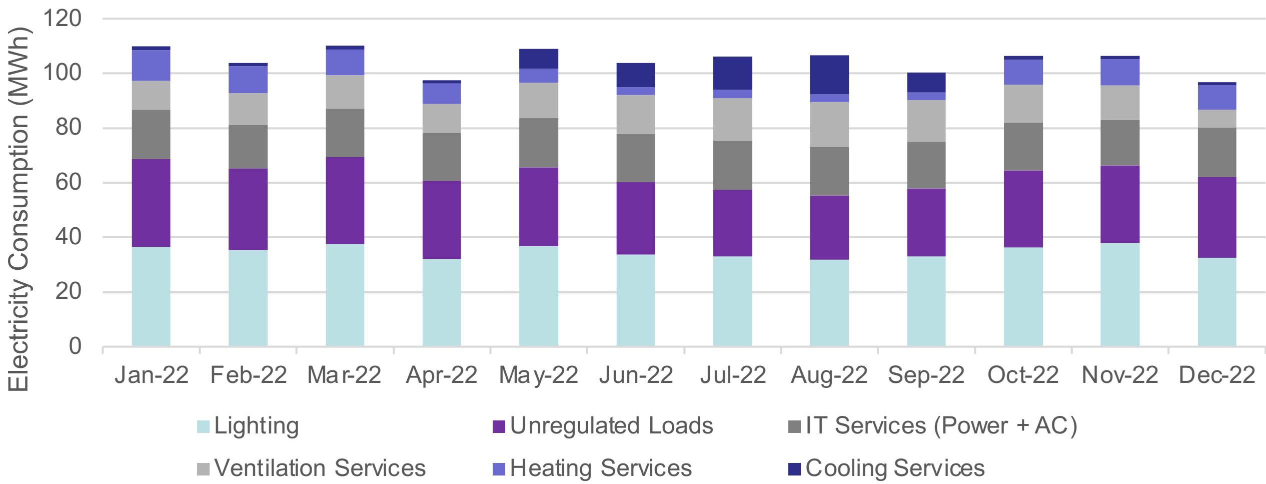


Occupancy Profile - Weekend

Operational DT Configuration

Metered electricity consumption 2022





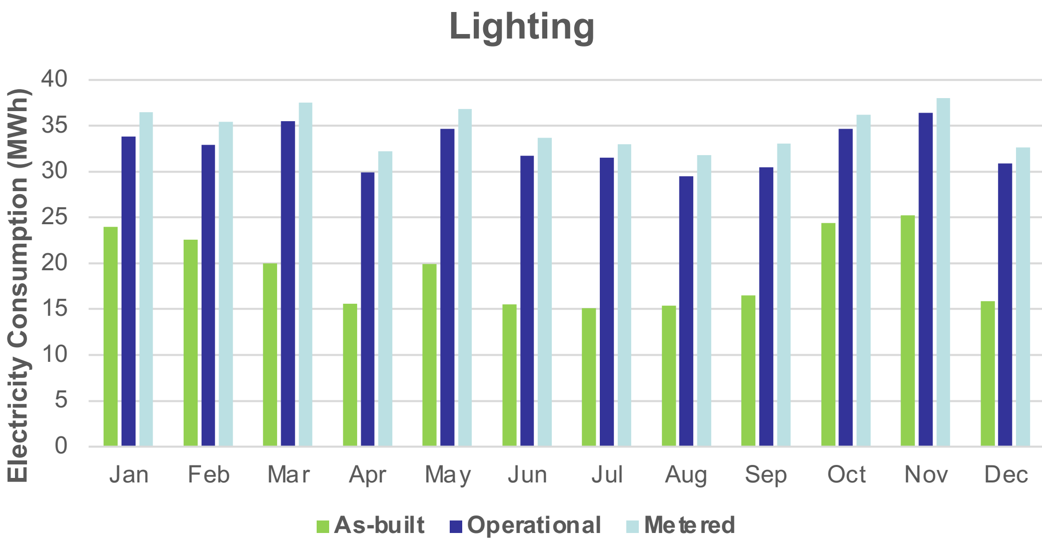
Identified equipment and control failures:

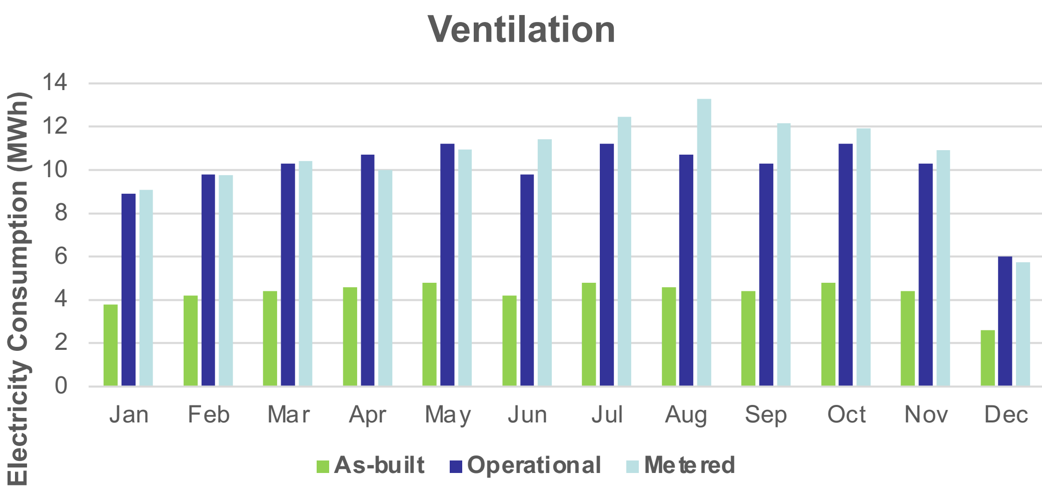
- Photocell sensors
- VAV boxes
- Heating water pumps running during summer
- Louvred panels

Challenges:

- Heating and cooling services shared with neighbouring building

Simulation Results – Lighting & Ventilation



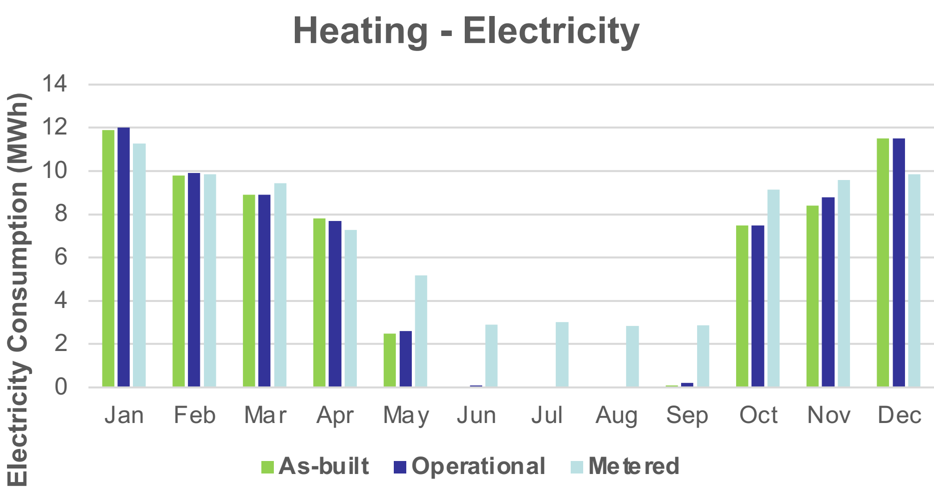


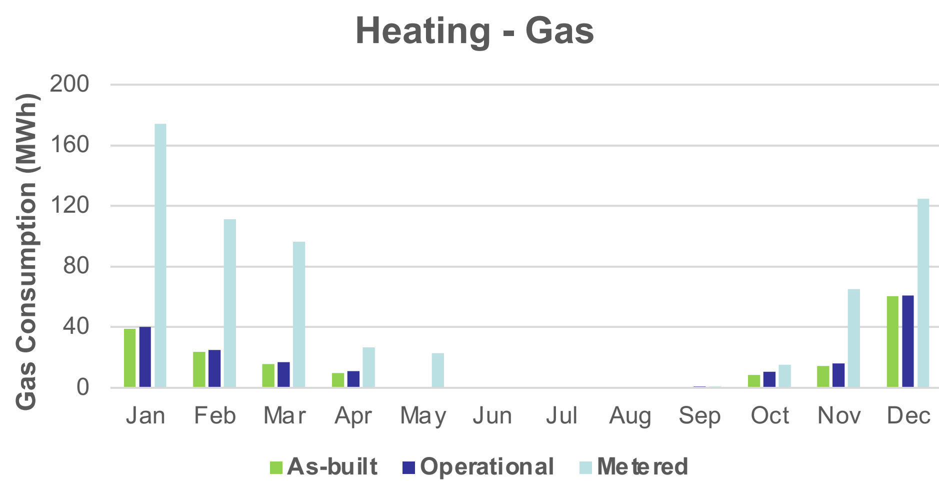
Potential savings: 229 MWh/year or £69,700/year

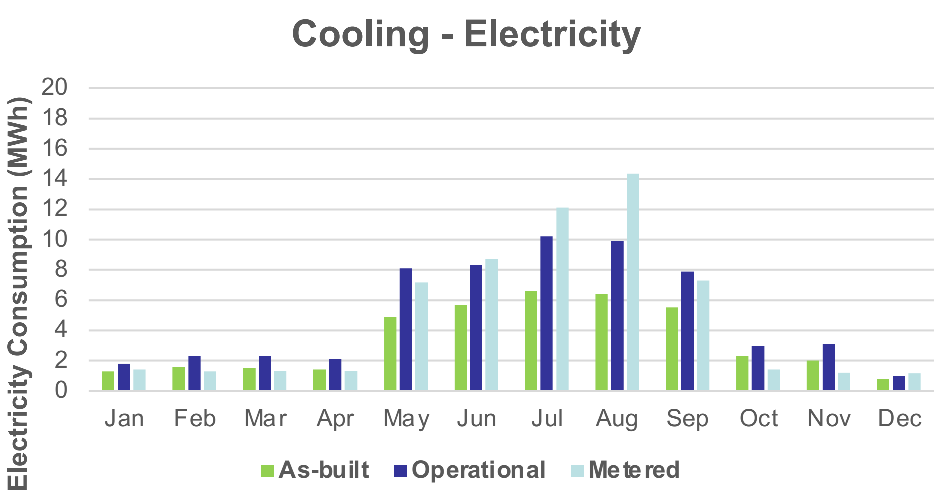
Recommendations:

- Ensure photocell sensors are working as they should
- Repair VAV boxes

Simulation Results – Heating & Cooling





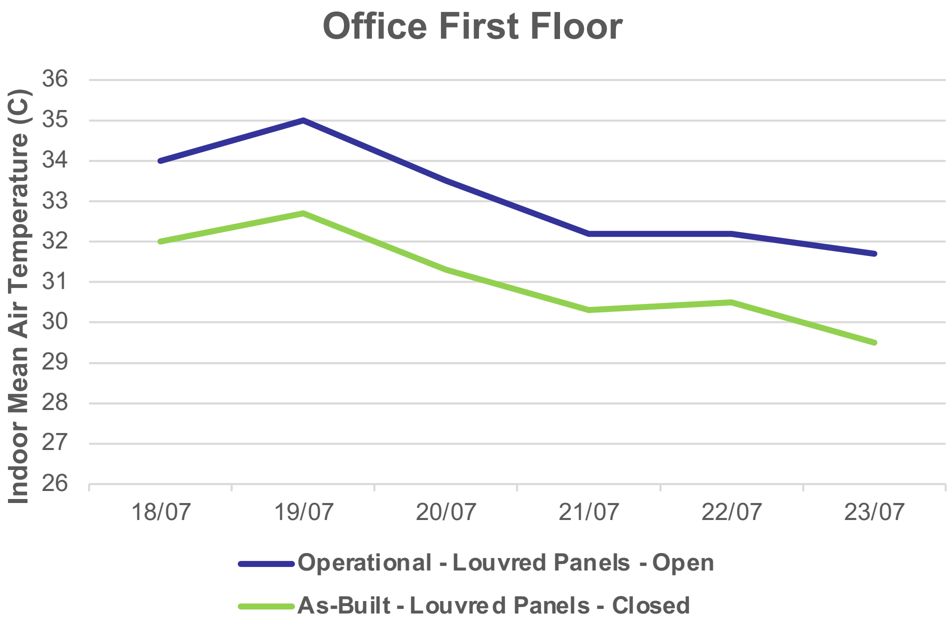


Potential savings: 35 MWh/year or £10,660/year

Recommendations:

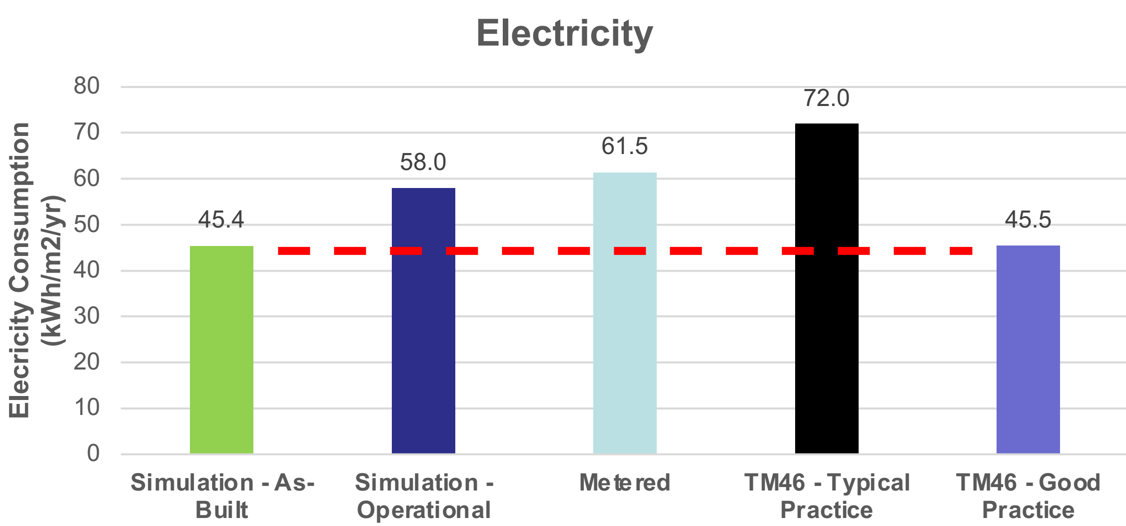
- Shut down GSHP heating water pumps during summer
- Install additional gas submeter in neighbouring building

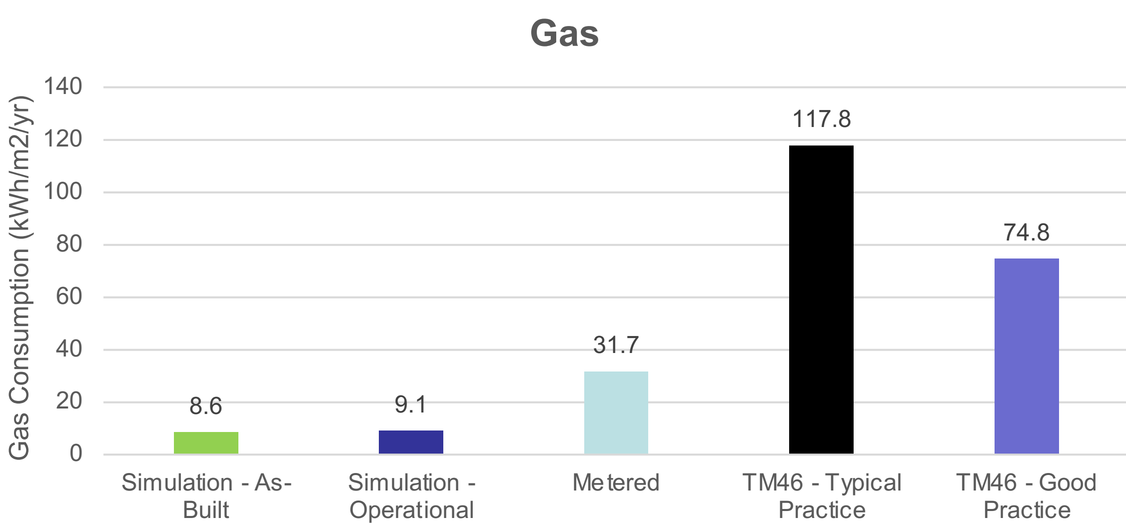
Simulation Results – Louvred Panels



Decrease of 2℃ in indoor office temperature during summer

Comparison with Benchmarks





FINAL RECOMMENDATIONS:
- Repair photocell sensors
- Repair VAV boxes
- Shut down heating water pumps running during summer
- Repair louvred panels

TOTAL POTENTIAL SAVINGS:

£ 80,360 / year

Conclusion

- DT energy simulations are a valuable tool to identify energy performance gaps in operational university buildings

- Building managers can assess the performance of their building and quantify energy savings associated to energy-efficient intervention measures

- Trade-off between simulation results accuracy and input data granularity

Thank you!

Questions?

Techno-economic optimisation of the green H_2 and green NH_3 production and distribution ecosystem for the steel and ammonia industries in South Africa and Namibia (2022-2050)

Colin Kinghorn
(Researcher/Author)

- MSc Energy Systems (University of Oxford)
- BCG (2 years; focused on decarbonisation)
- Completing MSc in Digital & Social Change (University of Oxford) as a Rhodes Scholar and running cleantech financing startup

Professor Rene Bañares-Alcántara
(Supervisor)

- Reader in Department of Engineering Sciences (University of Oxford)
- Leads Oxford Green Ammonia Technology Group (OXGATE)

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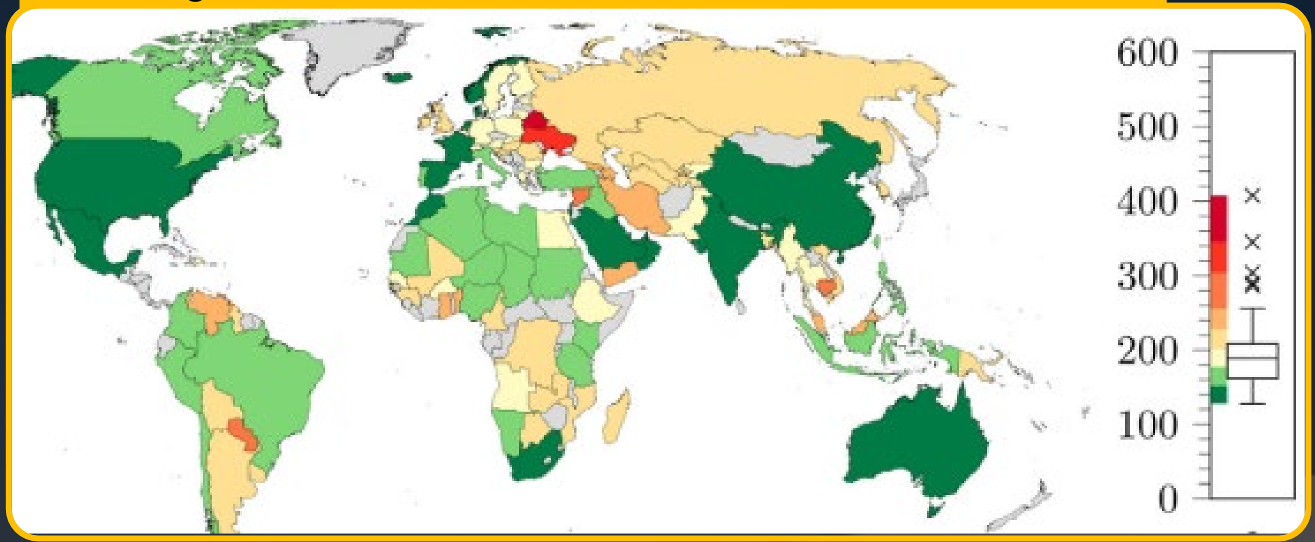
1. Why?

Southern Africa's green e-fuels play matters for global energy security, affordability and sustainability…

1

Southern Africa as a globally relevant Green e-fuels producer

GNH_3 production cost (USD/MWh - 2030)



- Clean energy is driving a **shift away from centralised global energy supply** towards regional energy hubs
- Chile, South Africa, and Namibia likely to form a **2nd tier of globally competitive supply** (behind Australia, Saudi Arabia, & Morocco) given their strong RE cost potential & land availability but higher WACC (Moritz, et al., 2023)
- RWE has announced plans for a \$9.7 Bn GNH_3 investment in Namibia – how can benefits be captured locally?

2

Southern Africa as a 'developing economy decarbonisation blueprint'


South Africa to get \$8.5 bln from U.S., EU and UK to speed up shift from coal

By Jeff Mason, Andrea Shalal and Emma Rumney

November 2, 2021 3:53 PM GMT · Updated 2 years ago

Aa

President Cyril Ramaphosa said that the agreement marked a "watershed moment" for South Africa and the world, while von der Leyen that the "just energy transition partnership" could provide a blueprint for work with other countries.

- South Africa is the 14th highest emitting country, is arguably the most industrialised country in sub-Saharan Africa & possesses significant 'hard-to-abate' steel and chemicals assets that are likely viable GH_2/GNH_3 use-cases (this makes it a strategic 'testing ground' for developing-nation decarbonisation funding approaches)
- If SA industry fails to decarbonise, 32% of export earnings & 18 000 local jobs at risk of CBTs (BCG, 2021) & the surrounding SADC region contains 4 of the 11 poorest countries, making its integration into the green economy a developmental priority

…however, lack of a rigorous least-cost optimisation at an integrated system level may limit sophistication of planning

No integrated, technically rigorous GH_2 / GNH_3 production & delivery ecosystem ramp-up optimisation that addresses *SA National GH_2 Commercialisation Strategy* calls for "analysis of the optimal mix of electricity and molecules for transportation between production and load centres aligned to export, decarbonisation and energy uses of GH_2"

Green H_2 & NH_3 production cost studies (SA)

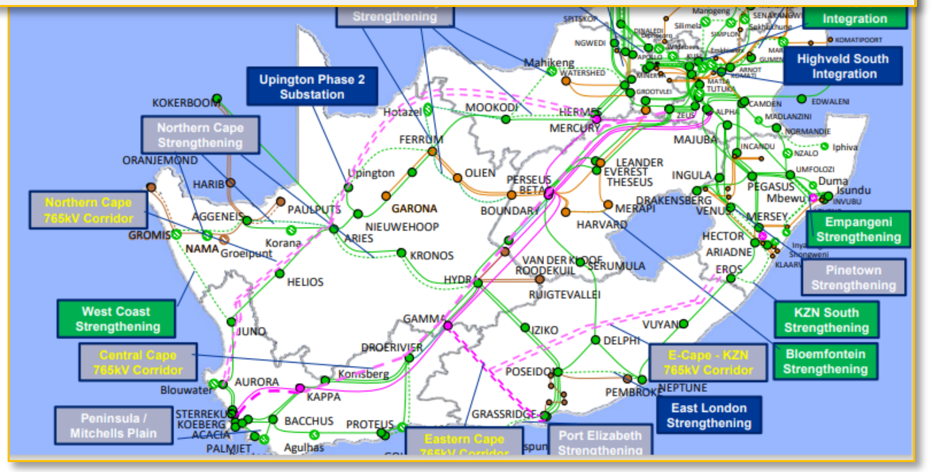
Paper	Key findings	Strengths	Weaknesses
"Potential of green H2 production by water electrolysis with wind energy in RSA", Ayodele & Munda, 2019	• LCOH for 15 sites (assuming all RE supply from wind) • RE potential (irradiance levels & wind speeds) • Priority GH2 use cases in SA socio-economic context - benchmark	• Uses range of direct wind mast measurements and gives detailed sensitivities • Considers political factors	• H2 produced on wind mast site (no demand outlook) • Only current production cost with wind calculated and no demand outlooks considered
"Green H2: a potential export commodity in a new global marketplace", TIPS, 2020	• Key export destinations for SA GH2 are EU, SK, and Japan • Infrastructure lock-in a risk without sufficient technical analysis - gap	• Considers political factors • Considers potential risks & incentives - consider	• No calculation of LCOH or LCOA (production or delivered) • Limited demand outlooks
"The cost of production and storage of renewable H2 in RSA and transport to Japan and EU up to 2050 under different scenarios", Roos, 2021	• South Africa can meet 2030 green H2 import cost targets in Japan at a 6% WACC - test • Ammonia is the lowest cost carrier for H2 delivered to export markets	• Techno-economic analysis with detailed costing of H2 and NH3 production and shipping	• No optimisation of production and delivered cost (scenario testing used) • Only Rotterdam & Japan demand considered (no local study)
"Stimulating domestic hydrogen consumption opportunities in South Africa", Roos et al, 2022	• For selected local applications, AEC electrolysers are lowest cost vs PEM and SOEC - test • Roughly equal ratios of wind and PV are lowest cost - test • Bunkering fuel seen as greatest opportunity- benchmark	• Techno-economic analysis with detailed costing of H2 and NH3 production and shipping • Detailed costing and analysis of adjacent use-cases to Saldanha and Nqura sites	• No optimisation of production and delivered cost (scenario testing used) - gap • Only Rotterdam & Japan demand considered (no local study & no inland supply considered) - gap
"How green iron production in RSA could help global decarbonization", Trollip et al., 2022	• Optimal PV, electrolyser, and storage ratios to supply major steel plant in SA and costs - benchmark	• Specific to local context & optimisation performed	• Only considers PV and doesn't optimise transportation or consider ecosystem of steel - gap
"Techno-economic optimisation within an integrated energy system", Bellocchi et. Al, 2023	• GH2 is more beneficial (from a cost & emissions perspective) when used in FCEVs rather than powerfuels • Islanded systems have higher embodied carbon	• Uses EnergyPLAN model to perform integrated energy system modelling • Multi-objective optimisation – consider?	• Least cost solutions appear to be non-net zero aligned & no consideration of relative return of different use cases (only a cost minimisation between use cases)
[Global GNH3 & GH2 production cost optimisations] – incl. Fasihi et al (2021), Brandle et al. (2021), Campion et al (2023)	• All identify same cohort of 10-15 countries as high potential	• Global, allowing for development of international trade 'pecking order'	• Little or no specificity to South African context or attempts to optimise scale-up of local supply networks over time
"Green H2 production and use in low-inome countries: A least-cost geospatial approach applied to Kenya", Muller et al, 2023	• Granular selection of production sites by use case using a geospatial approach – interesting approach	• Higher resolution location optimisation • Relevant in low infrastructure cases (in developing countries where significant e.g., new-build required	• Simplified ammonia inclusion (limited optimisation), not relevant to SA case • Only looks to 2030 & few sensitivities

Key gaps

- Production cost studies estimate LCOH/LCOA for specific sites but **do not use sophisticated optimisation techniques across region**
- **No national-scale production site scale-up optimisation** (considering multiple time scales and demand scenarios)

Green H_2 & NH_3 delivery cost studies (SA)

Paper	Key findings	Strengths	Weaknesses
"Long-distance renewable hydrogen transmission via cables and pipelines", Miao et al., 2019	• Generally pipeline produces lower delivered H2 cost than wheeling for long ranges (>1 000 km) • But results highly sensitive to scale of energy transmitted & plant capacity factor (larger scale & capacity factor = pipeline more cost effective	• Many sensitivities tested • Real project benchmark data used (but may also be limitation)	• Only considers long ranges and a few energy transmission volumes • No plant optimisation
"Cost of long-distance energy transmission by different carriers", DeSantis et al., 2021	• HVDC lines generally much more expensive than hydrogen pipelines over long distances (>1000 miles) • But results sensitive (but not as much as Miao et al.)	• Detailed comparison with other studies	• Only considers long ranges and a few energy transmission volumes • No plant optimisation



Key gaps

- **No SA-specific delivery costings** that trade-off molecule versus electricity transmission at a system-level and consider issues of competitiveness, lock-in and pathway dependence for varying WACC, demand, and technology cost scenarios

2. How?

This study presents a 2050 net-zero, least-cost ramp-up optimisation for regional green H_2/NH_3 production & delivery across 12 scenarios

Three key questions answered for 2022-2050 period

1
How will Southern African and global GH_2/GNH_3 **demand** evolve?

2
What is the least-cost way to **scale** local GH_2/GNH_3 **production and delivery infrastructure**?

3
How does the least-cost system configuration change in **different demand, technology cost, and cost of capital scenarios?**

		Technology cost scenarios					
		Low learning rate (NREL)			High learning rate (Way et al)		
	WACC	4%	7%	11%	4%	7%	11%
Demand Scenarios	'NZ Base'			**'Pessimistic'**			
	'Green Hub'				**'Optimistic'**	**'Moderate'**	

2. How?

The energy system was modelled hourly to meet temporal and volumetric supply requirements and optimised using a MILP approach

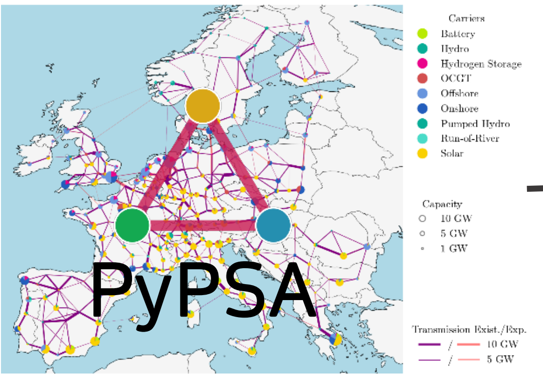
System optimised for lowest total delivered cost between supply, intermediate port, and demand nodes (2022-2050)

$$\boldsymbol{NPV}_{N_s N_p N_d} = CAPEX_{s,p,d} + G_{EY} OPEX_{s,p,d}$$

$$\boldsymbol{LCOP/S}_{N_s N_p N_d} = \frac{\boldsymbol{NPV}_{N_s N_p N_d}}{G_{EY} \sum_{s \in N_s p \in N_p d \in N_d} F_{s,p,d}}$$

$\boldsymbol{LCOT}_{N_s N_p N_d}$ *determined through interpolation of empiral values*

Used to construct hourly energy flows



Optimisation function

$$DLCO\ A/H_{N_s, N_p, N_d} = \sum_{s,p,d \in N_s, N_p, N_d} [\mathbf{LCO\ P/S + LCOT}]_{s,p,d}$$

GUROBI OPTIMIZATION

Used to perform MILP optimisation

Three constraints applied to optimisation to improve validity of model

1. In each year, the incremental demand of each demand node is met in full and supply-demand node pairs maintained over period
2. Ports supply as much as they are supplied, thereby not acting as either supply node or demand node
3. Supply node capacity only added if supply node exceeds minimum capacity allowed by linearisation to avoid linearisation errors

Optimisation inputs

1. Local steel, ammonia, & marine fuel demand outlooks
2. Global import demand outlooks
3. Potential local supply node locations
4. Technology cost outlooks

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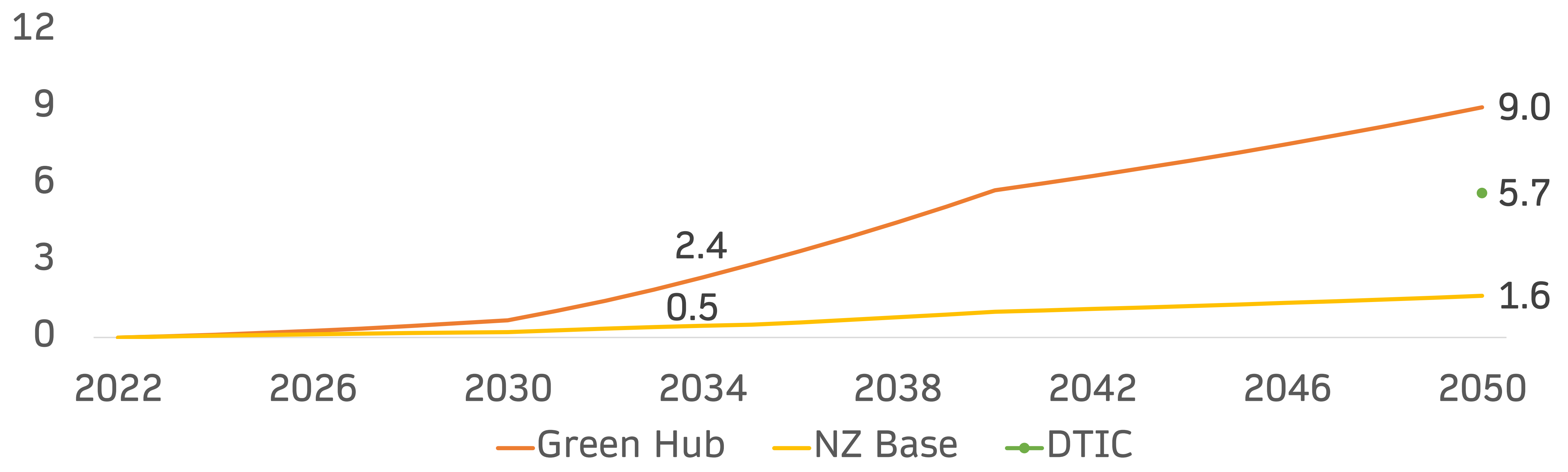
2. How?

Local demand outlooks for each scenario include steel, marine fuel oil, and fertiliser applications

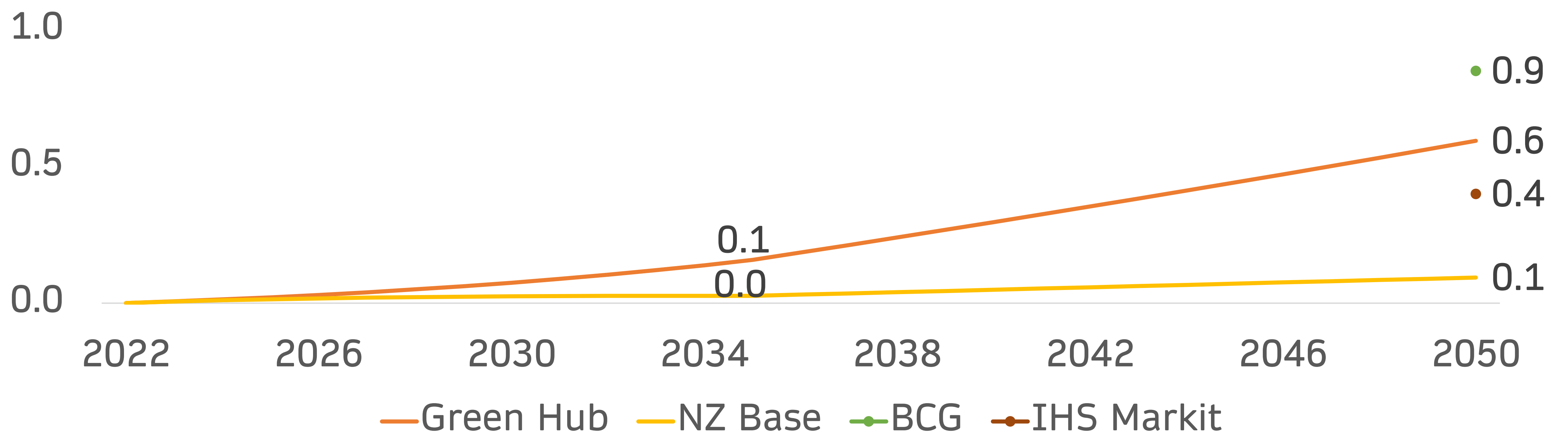
Local GNH_3 demand for marine and fertiliser applications (MMtpa)



Key drivers:

- South African fertiliser/marine fuel local production ratio outlook (either remains same or fully localised given GNH_3 cost advantage)
- Penetration of green production methods in line with IEA SDS global projection

Local GH_2 demand for steel application (MMtpa)

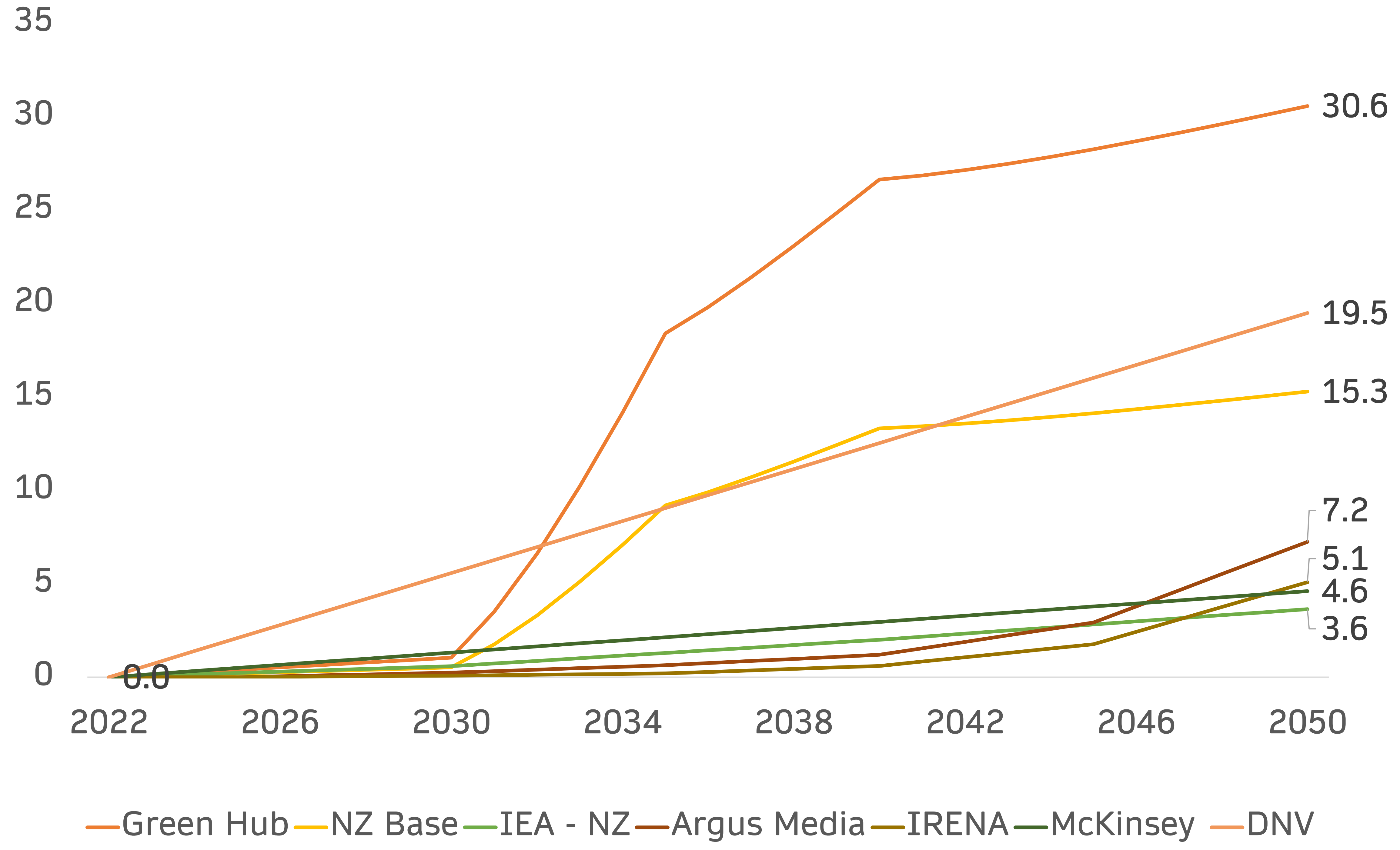


Key drivers:

- South African steel production outlook (either remains in structural decline or revitalised given 'green steel' cost advantage)
- Penetration of green production methods in line with IEA SDS global projection

Export demand outlooks for each scenario include export to countries with announced import targets with NH_3 as carrier

Southern Africa GNH_3 export demand (MMtpa) – only countries with announced import targets included

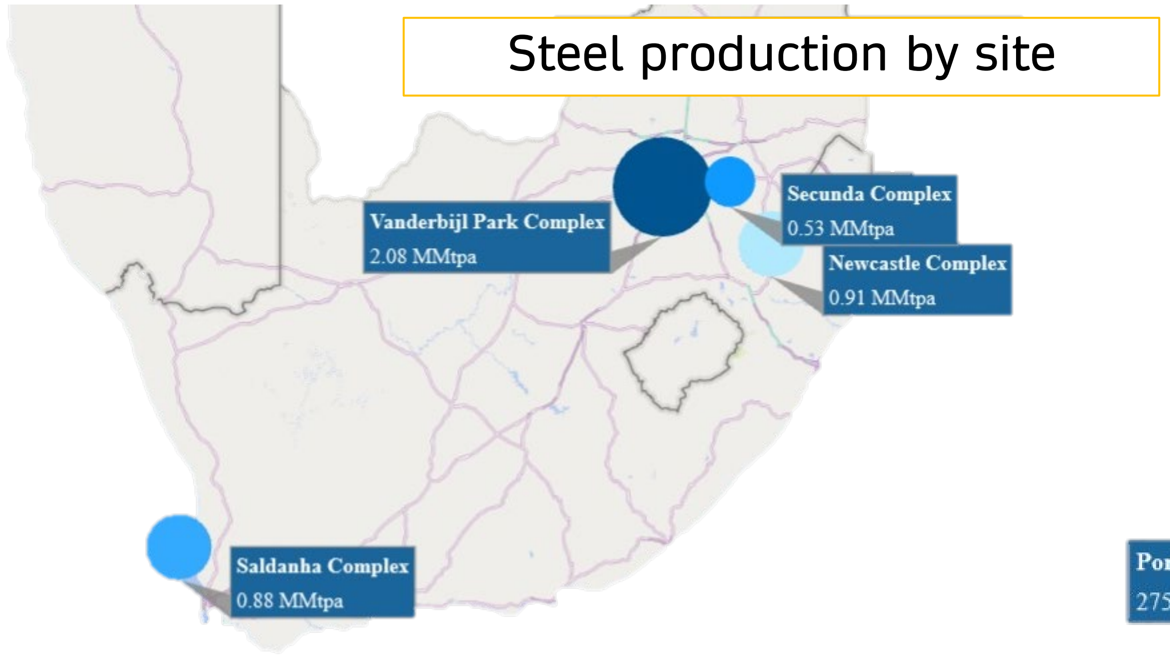


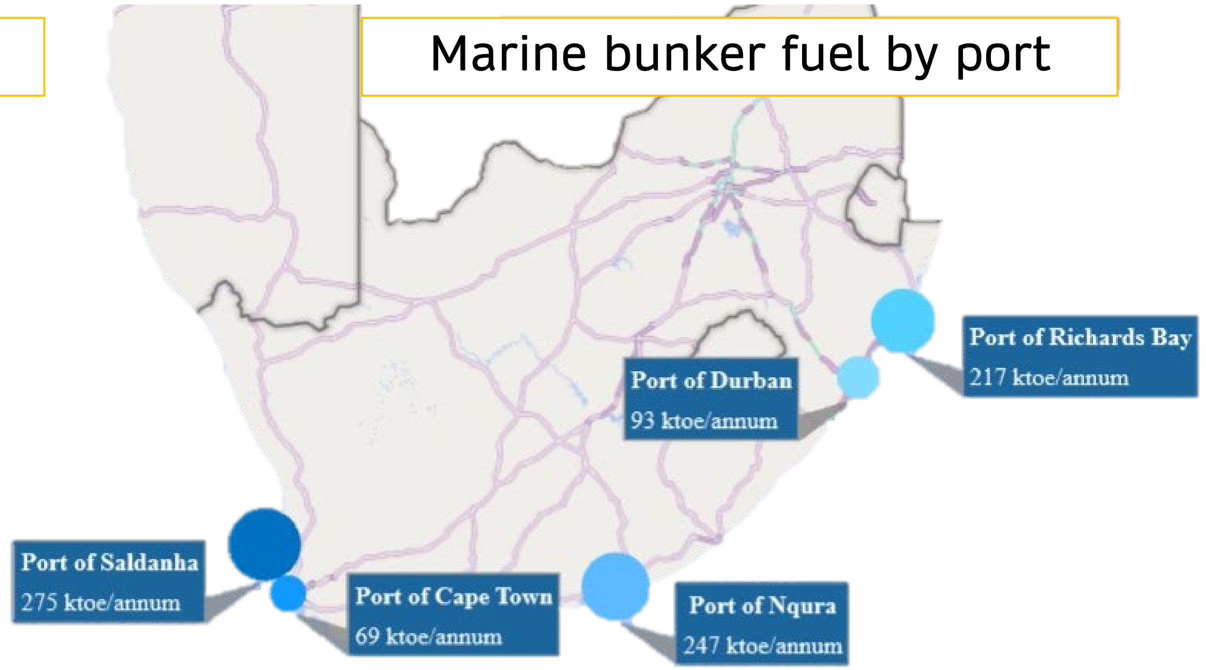
Key drivers:

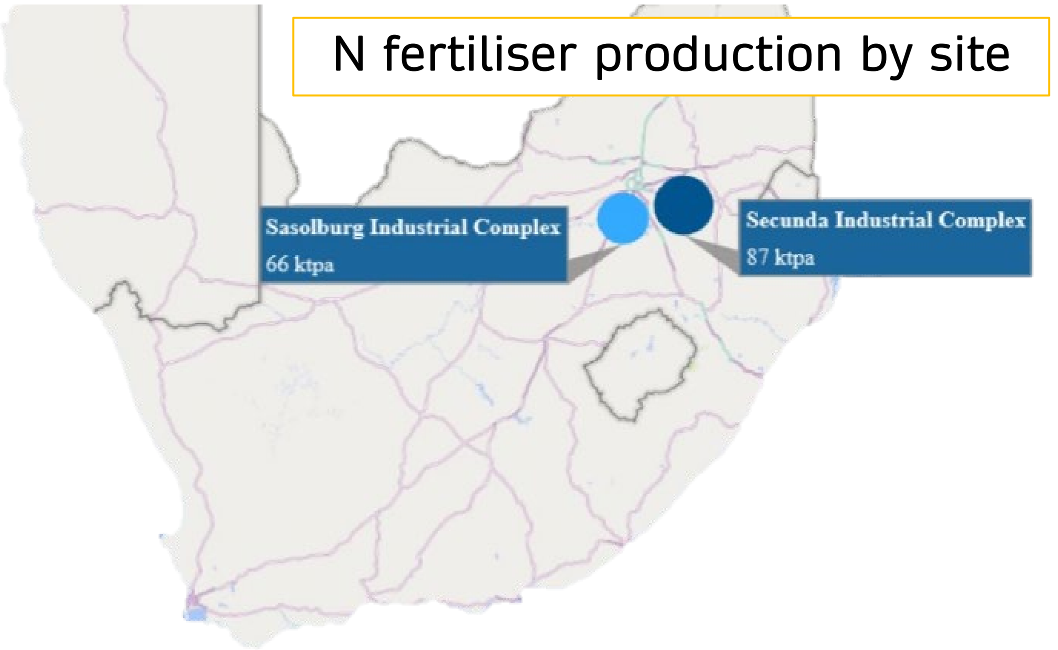
- Import targets set by South Korea, Japan, Germany, and the UK
- Southern African capture of global import demand (2.5%-5% and dependent on geographic proximity, availability of other low-cost supply, and historical energy trade ties between Southern Africa and importing countries)

Locations of demand nodes allocated based on existing and planned local assets and import port locations

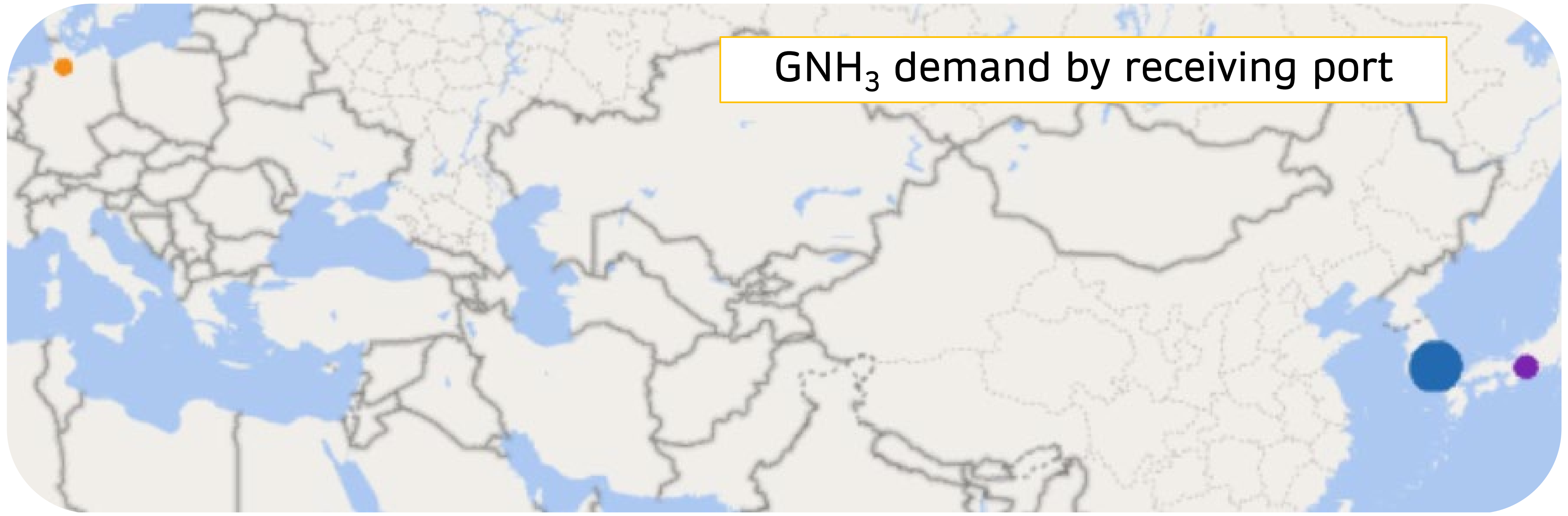
Local GH_2 & GNH_3 demand node locations for steel, marine and fertiliser applications (MMtpa)







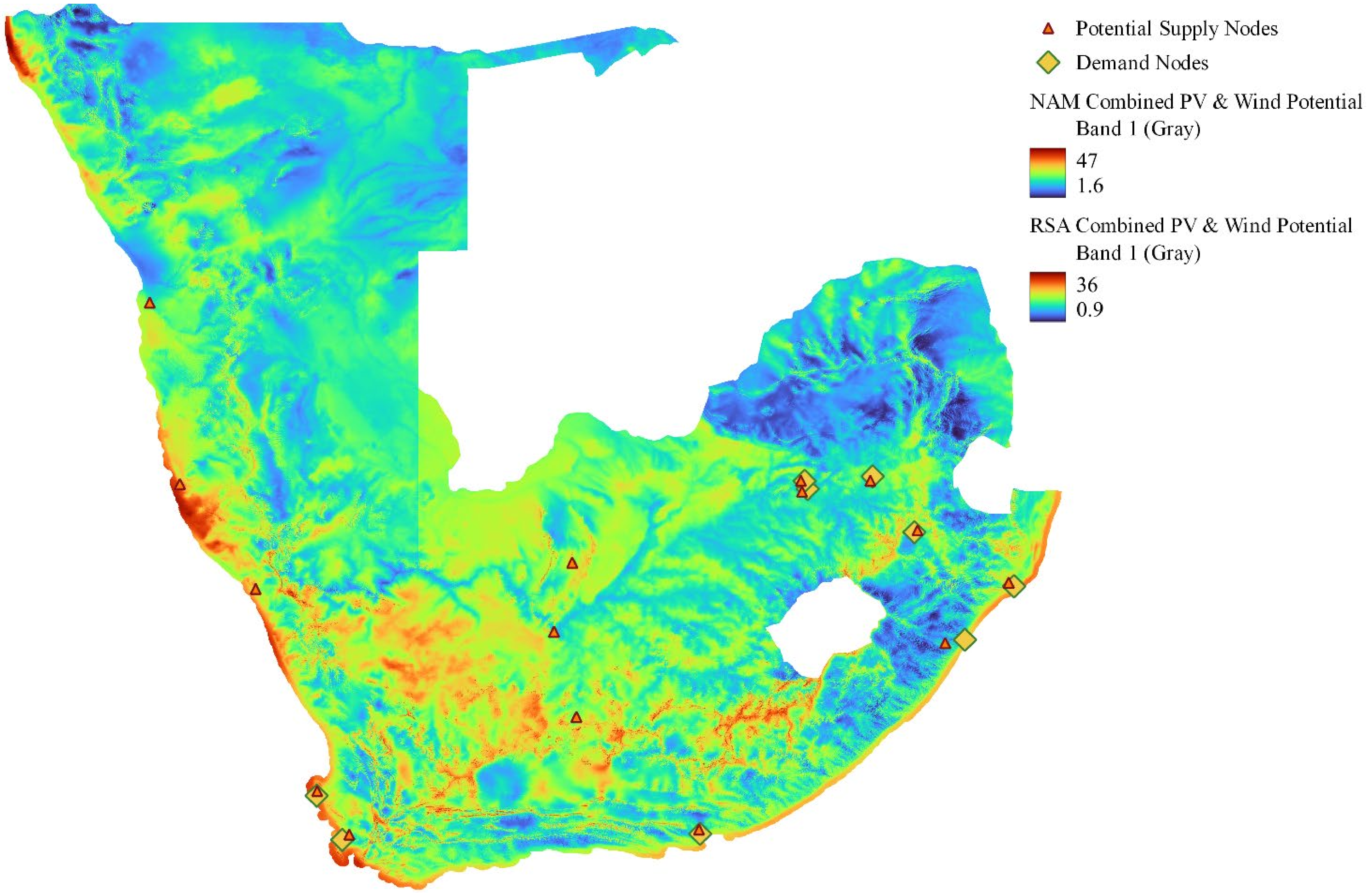
Export GNH_3 demand to countries with announced import targets (MMtpa)



2. How?

Potential supply nodes included based on existing/planned projects and renewable energy potential

Local GH_2 & GNH_3 potential supply node locations (to be considered in optimisation) layered onto GIS analysis of combined solar PV and wind capacity factors at 5km² resolution to select promising locations



Three criteria for potential supply node inclusion:

- Potential supply nodes included for each green GH_2/GNH_3 production project planned and listed in the latest Government Gazette

OR

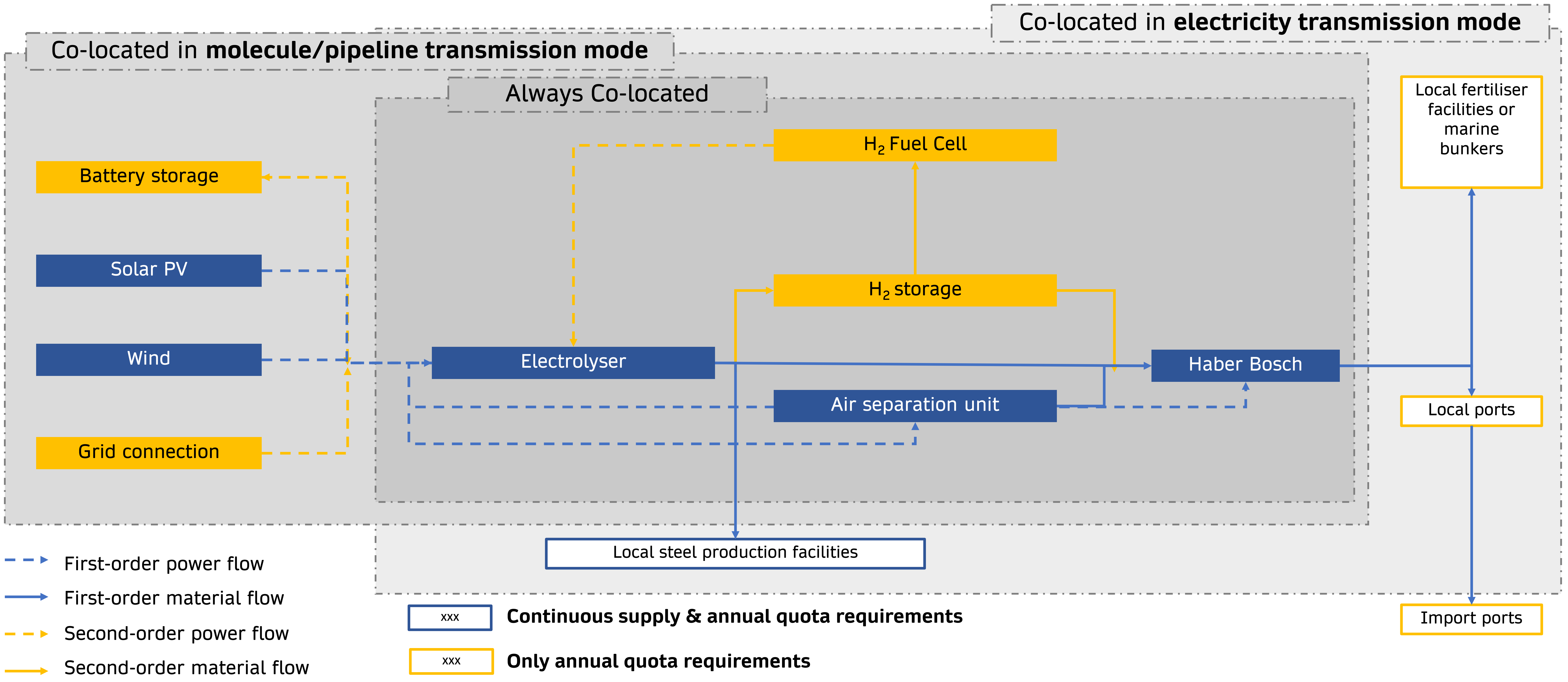
- Potential supply nodes included near each demand node (such as ports and industrial production facilities) to simulate 'on-site' production

OR

- Potential supply nodes placed in locations possessing extraordinarily strong renewables potential – based on GIS raster calculation

Two delivery modes considered in the optimisation model to connect supply and demand nodes

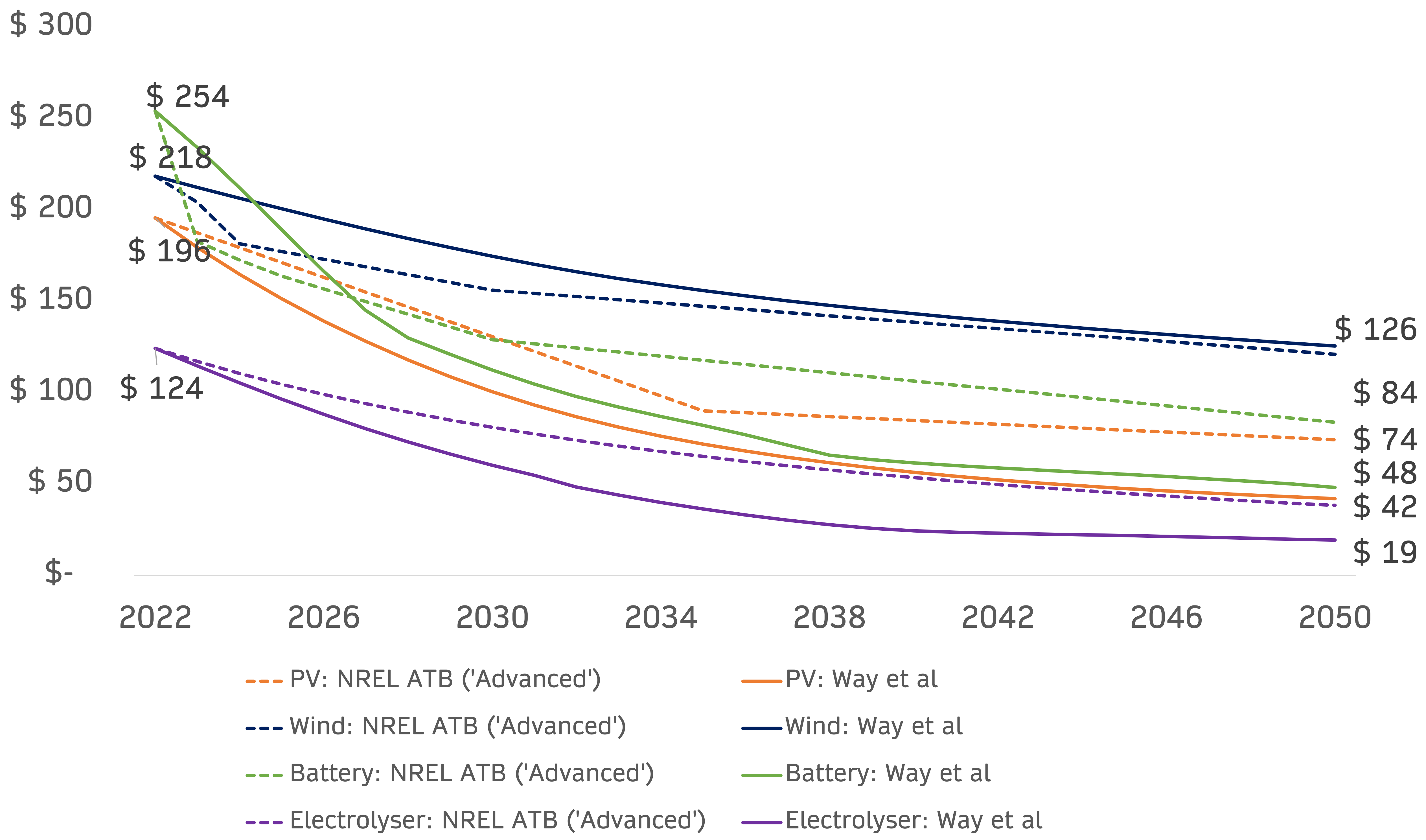
Energy delivery by new-build electricity transmission & pipeline compared



2. How?

Production and storage input costs developed for different WACC scenarios and using two learning rate benchmarks

Total annualised cost projection of production and storage technologies for GH_2/GNH_3 (USD/kW installed)

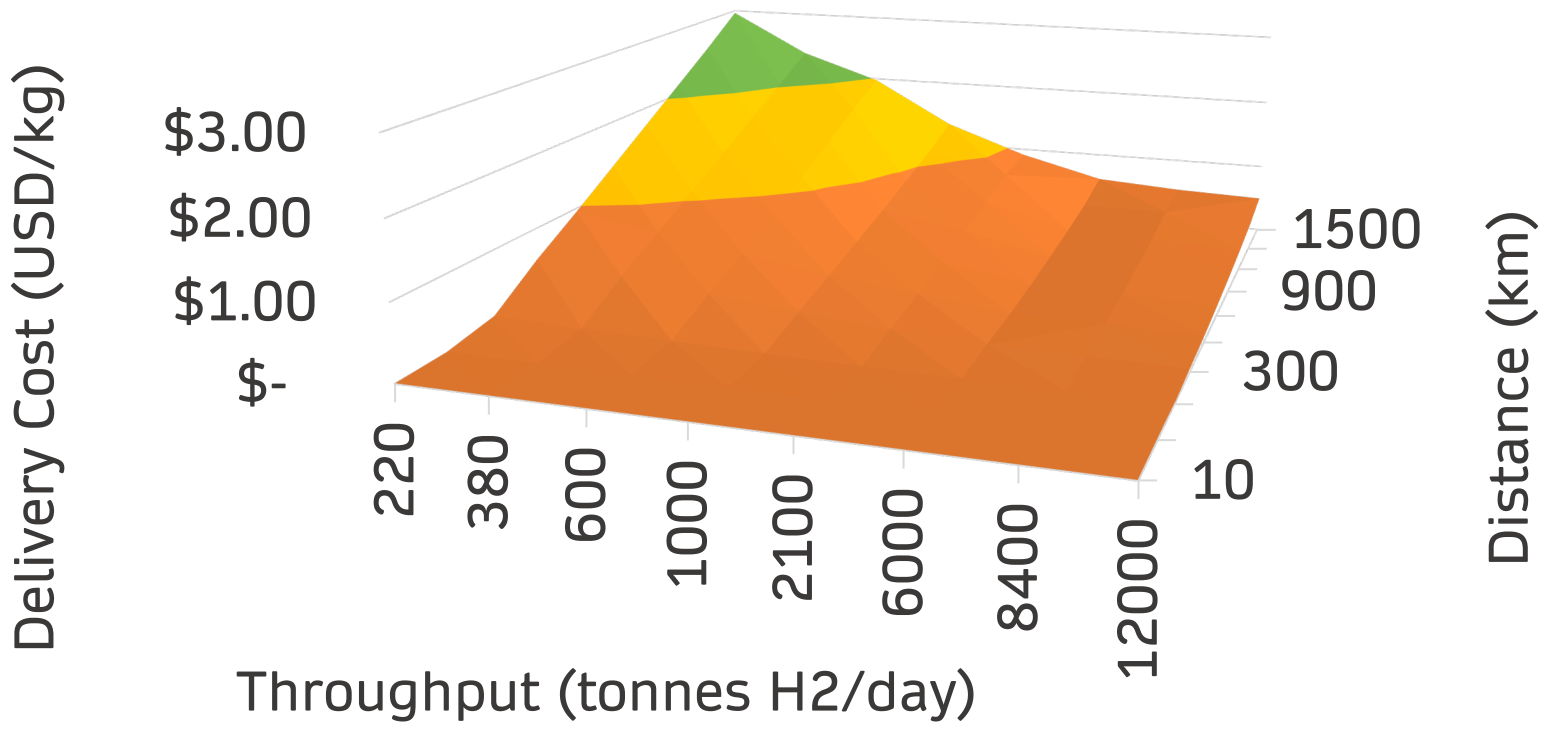


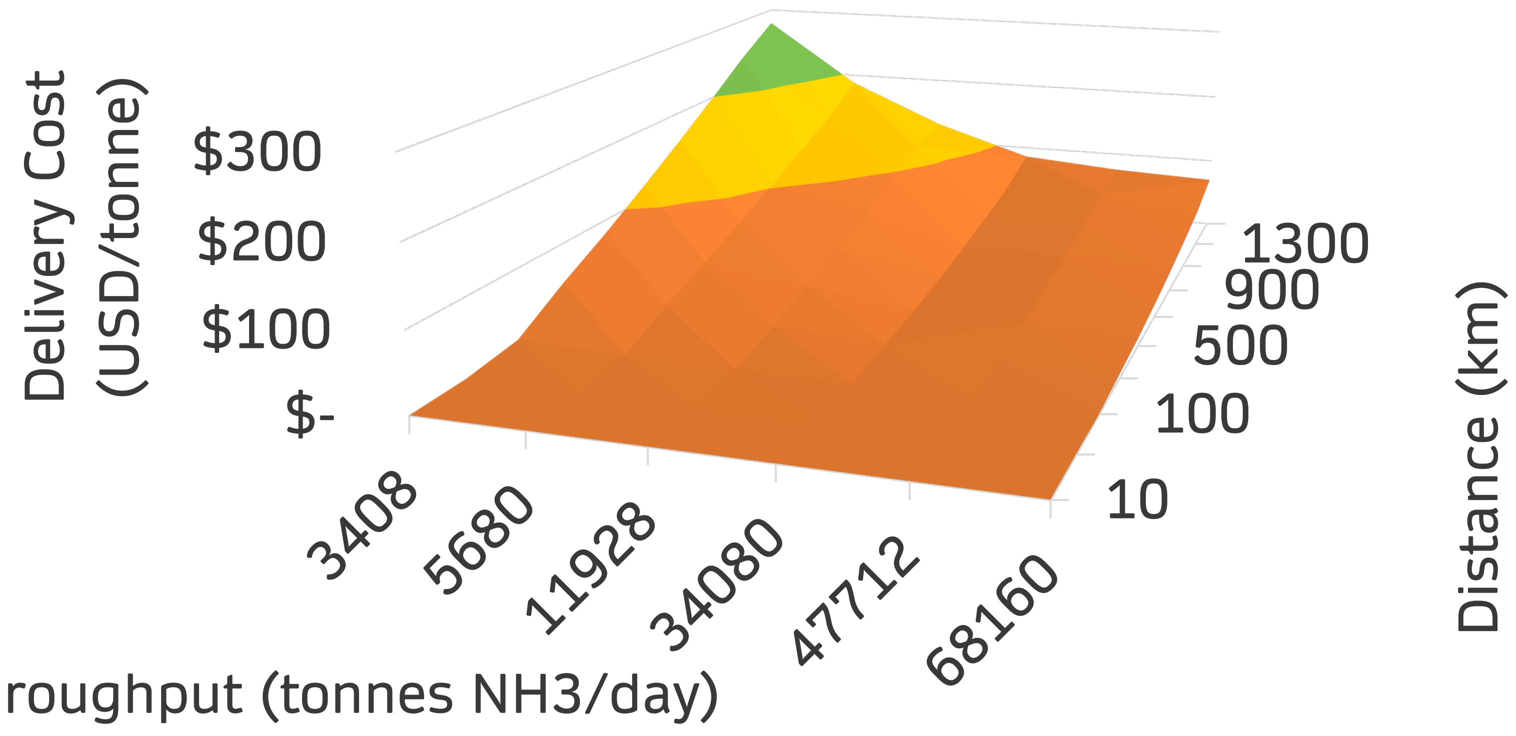
- 2022 'starting costs' based on NREL empirical baseline
- **NREL Annual Technology Baseline (Advanced Scenario)** learning rates considered pessimistic given consistent under-estimation of learning rates in the past
- ***Way et al*** provides more 'optimistic' outlook that attempts to correct for previous IEA and IRENA learning rate underestimations through an empirically grounded approach

2. How?

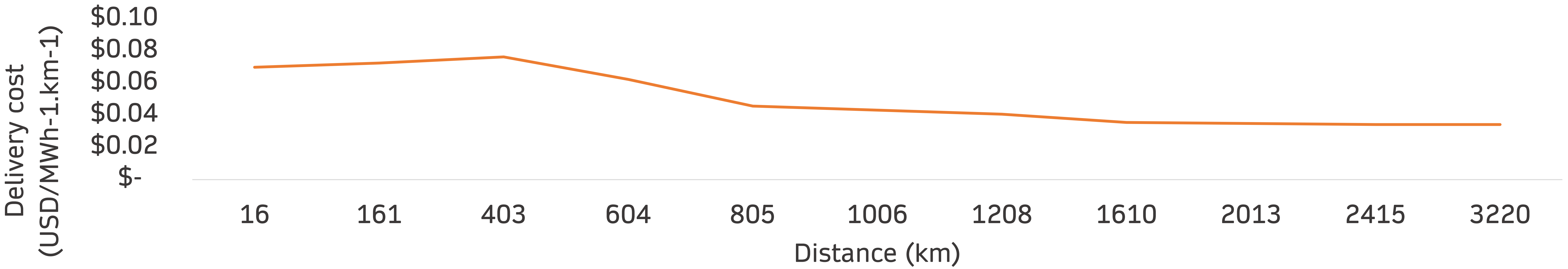
Input delivery costs developed by interpolating empirical studies

Total annualised cost of delivery for GH_2/GNH_3 pipeline transmission





Total annualised cost of delivery for electricity transmission



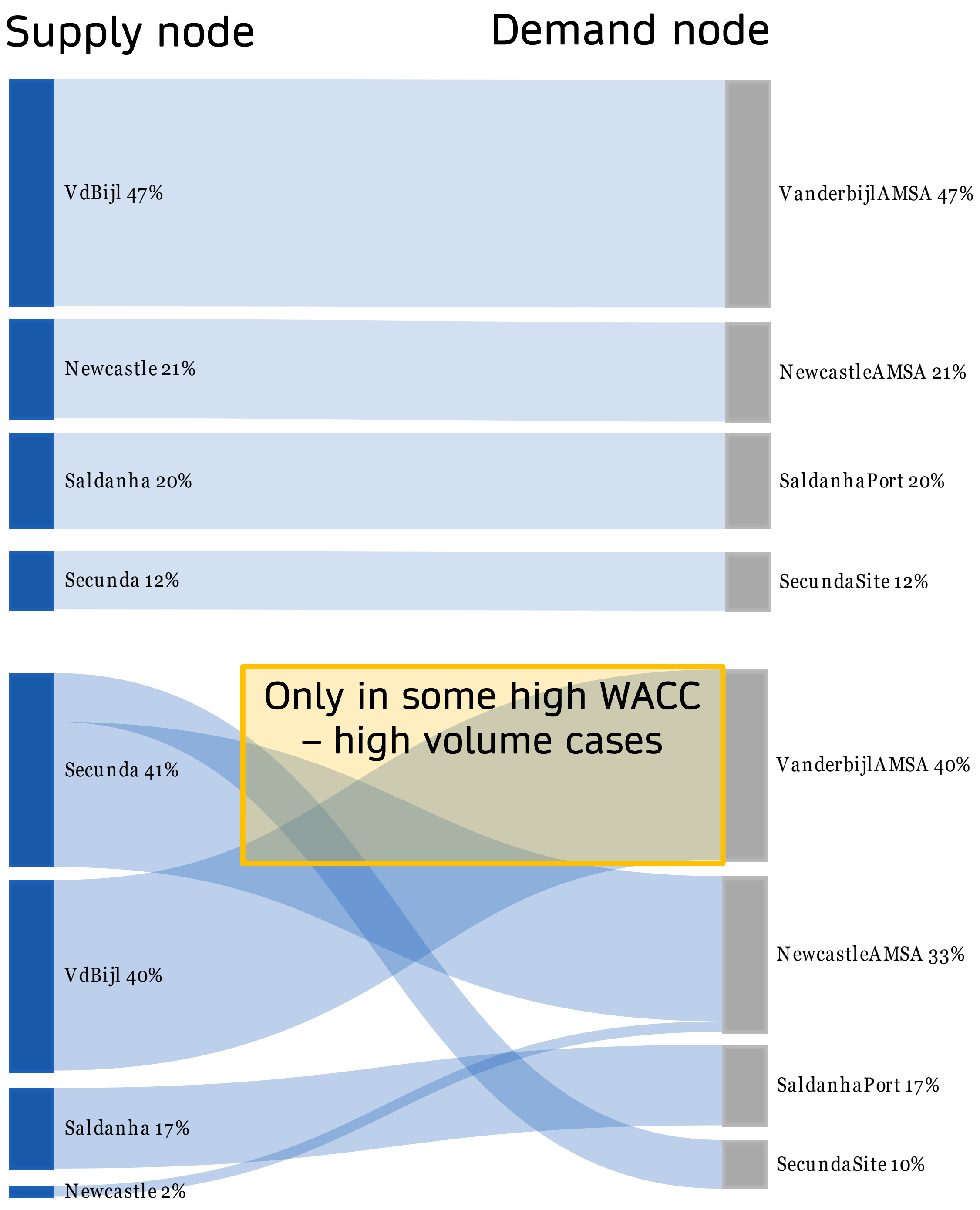
On-site supply is dominant least-cost configuration, but offsite viable in high WACC & pessimistic learning rate scenarios

'Likely' and 'fringe' optimal supply-demand node matching by use case (2050 view)

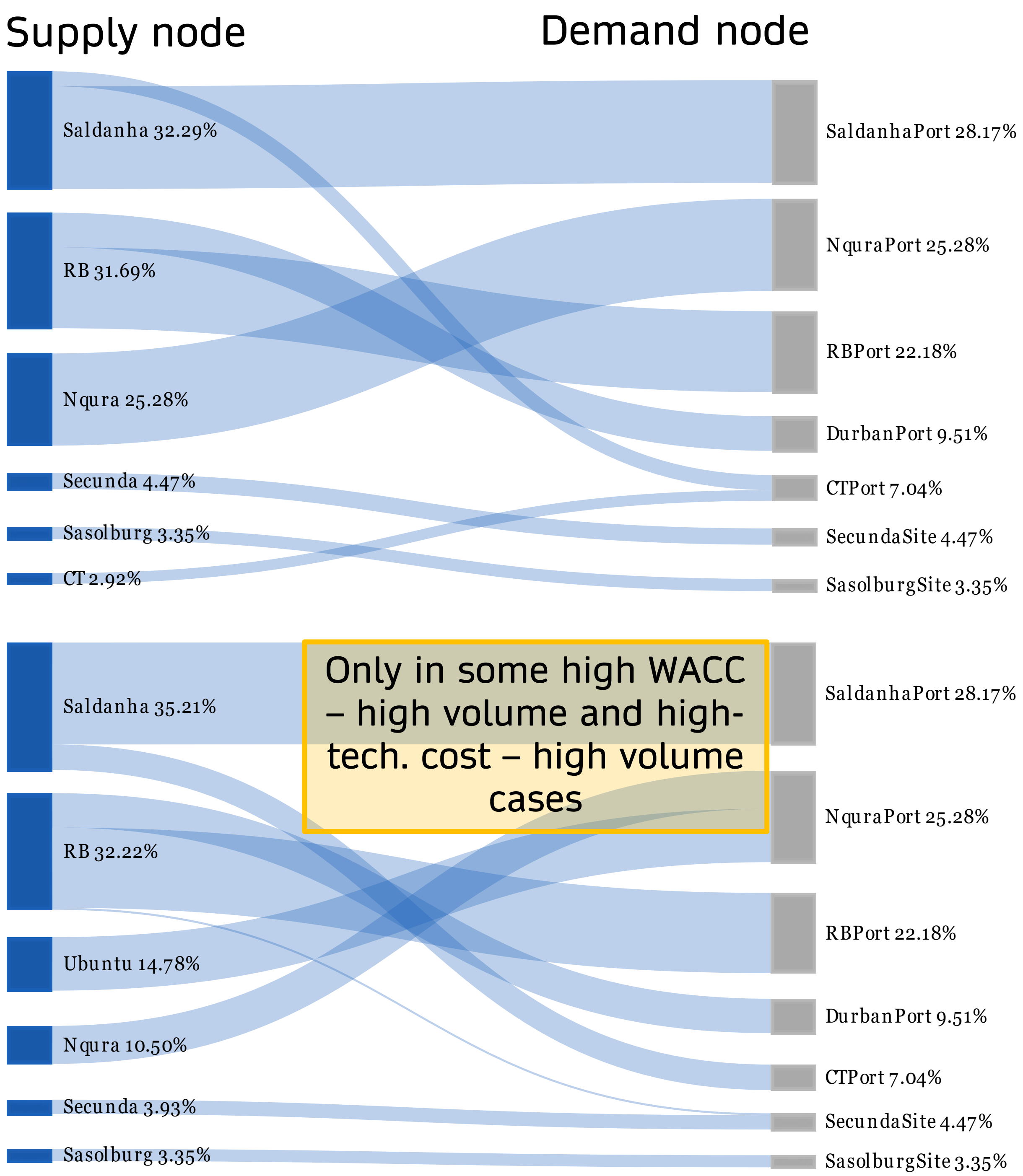
'Likely' matching (optimal in >70% of scenarios)

'Fringe' matching (optimal in <30% of scenarios)

Local GH_2



Local NH_3



Export NH_3

Walvis Bay, northern Namibia selected as least-cost supply option to all import demand nodes across scenarios

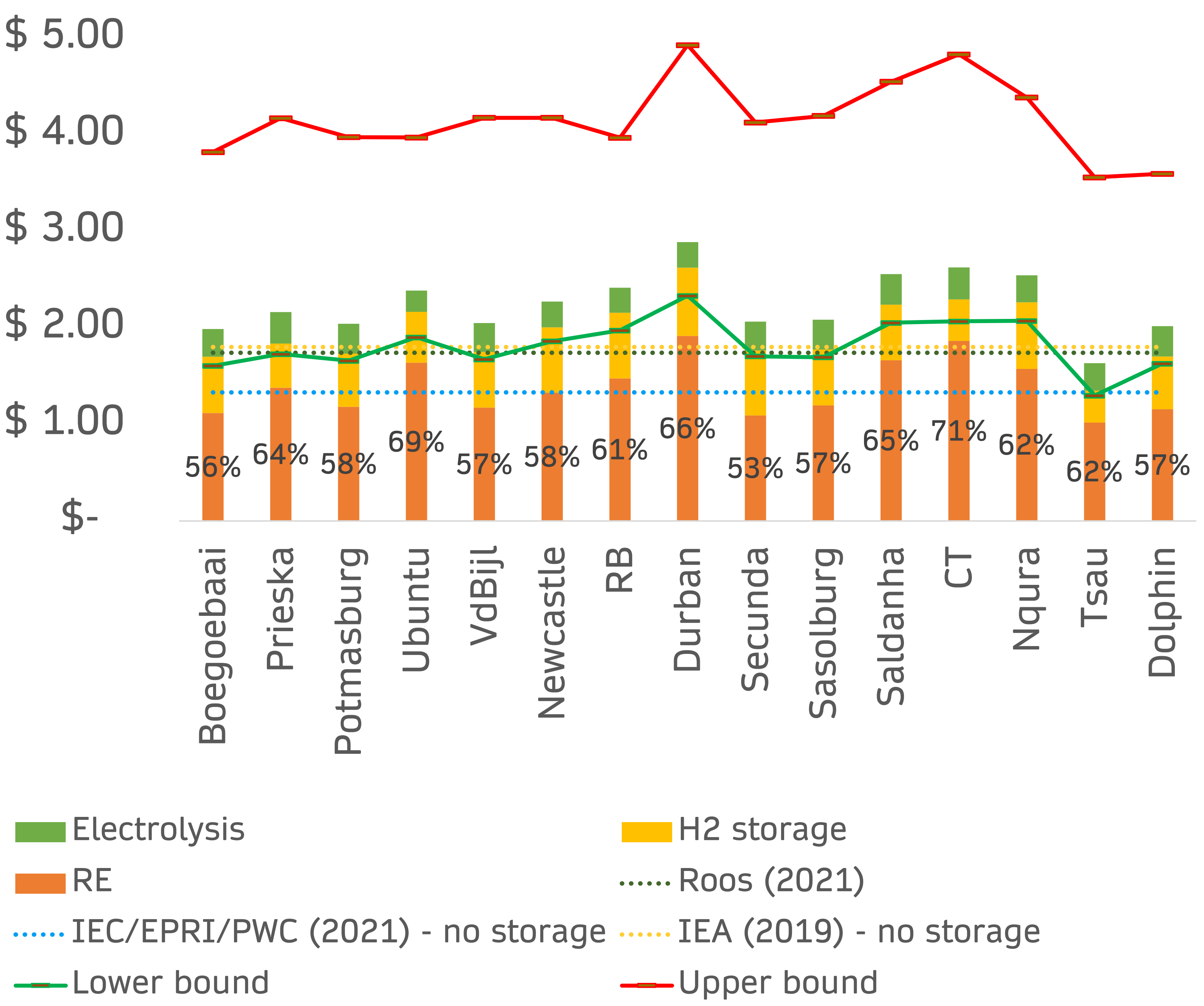
3. Results

Local steel: constant supply requirement makes storage a major cost component and increases cost variation between sites

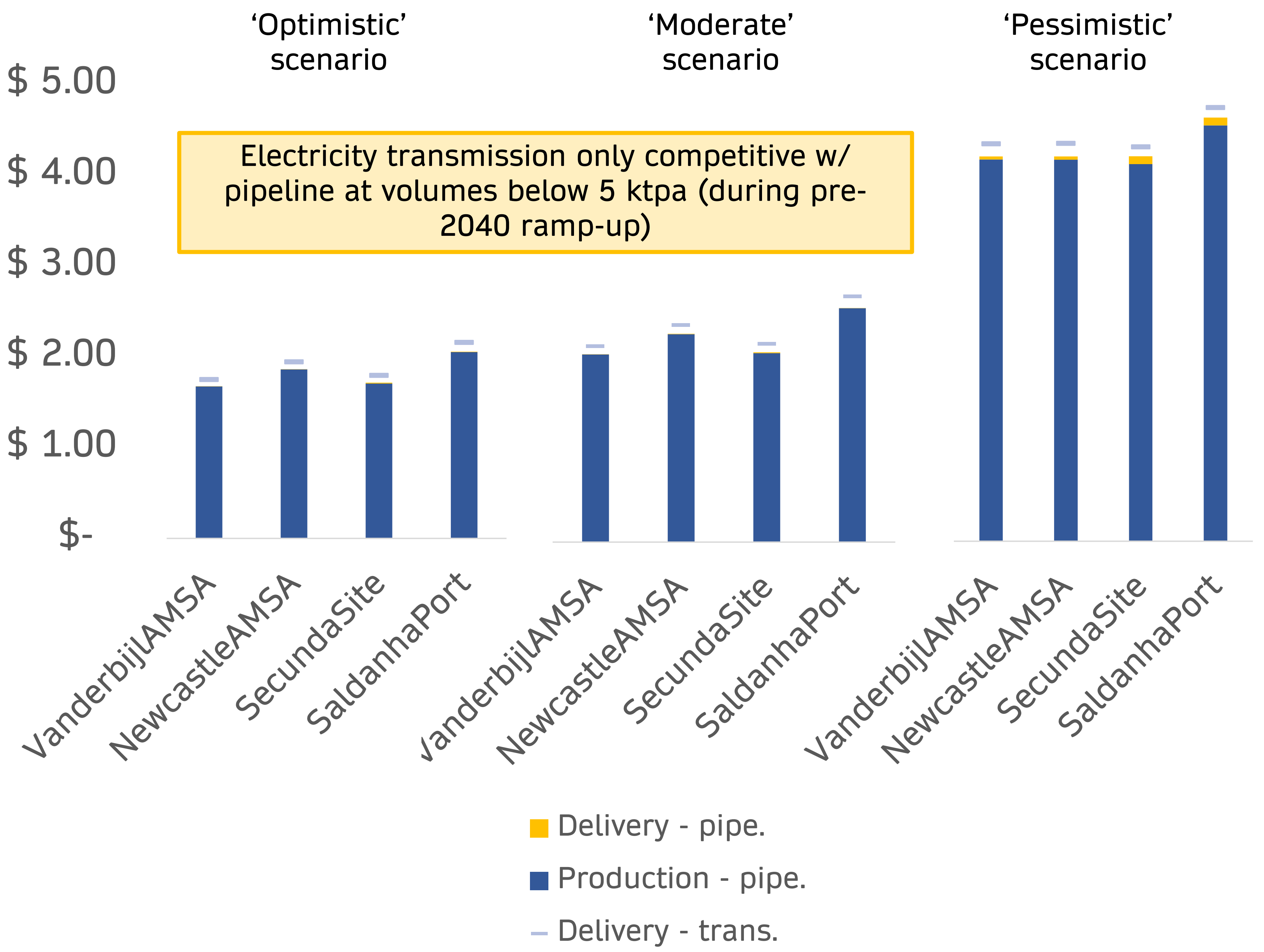
Constant supply requirement adds 20-25% to production cost in storage & high WACC scenarios can double LCOP/S

Pipeline delivery cheaper than electricity transmission for all demand nodes in 2050

LCOP/S by potential supply node (USD/kg H_2 – 2050)



Optimal DLCOH by demand node (USD/kg H_2 – 2050)



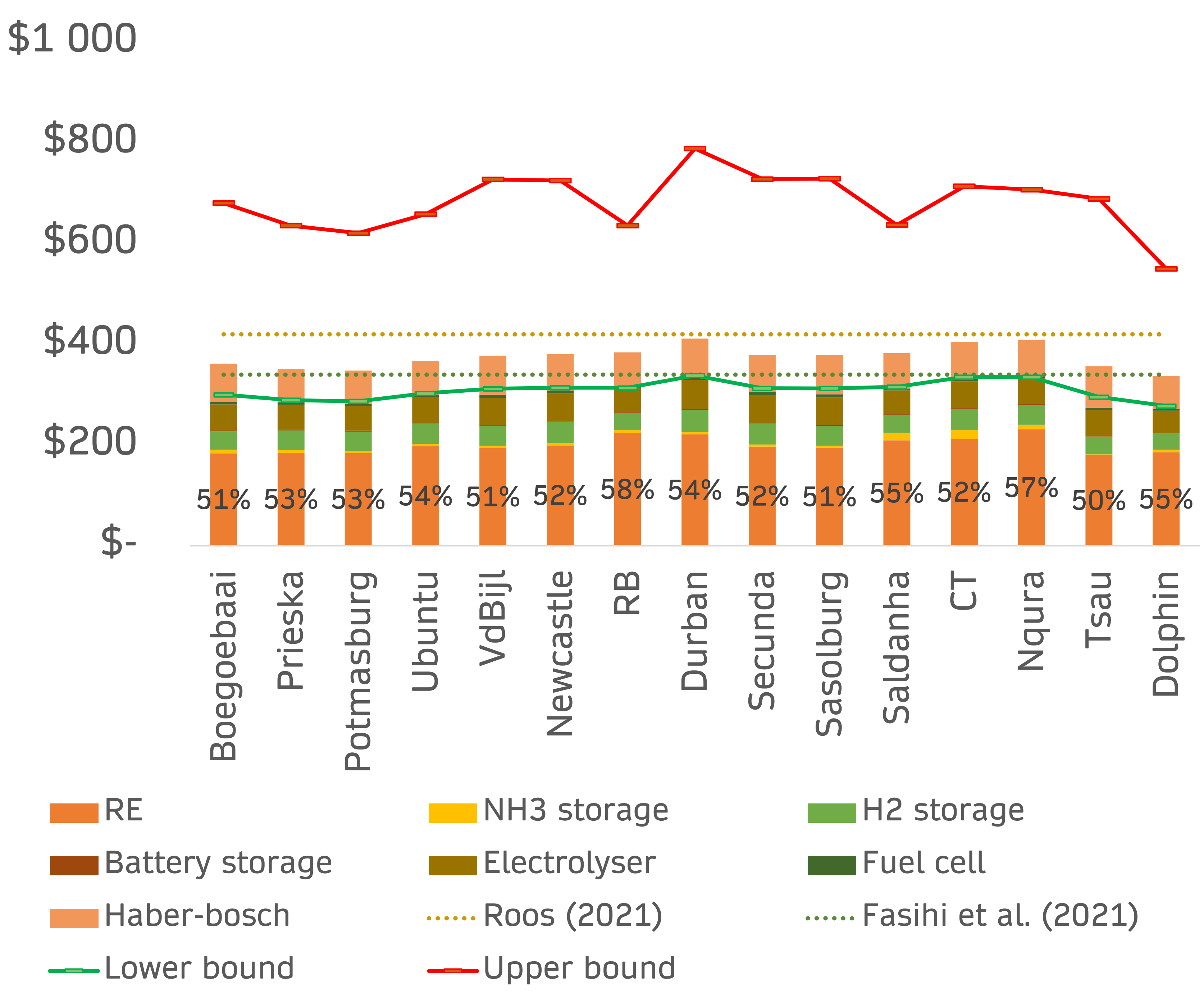
3. Results

Local fertiliser & marine fuel: no constant supply requirement means less cost variation between supply sites

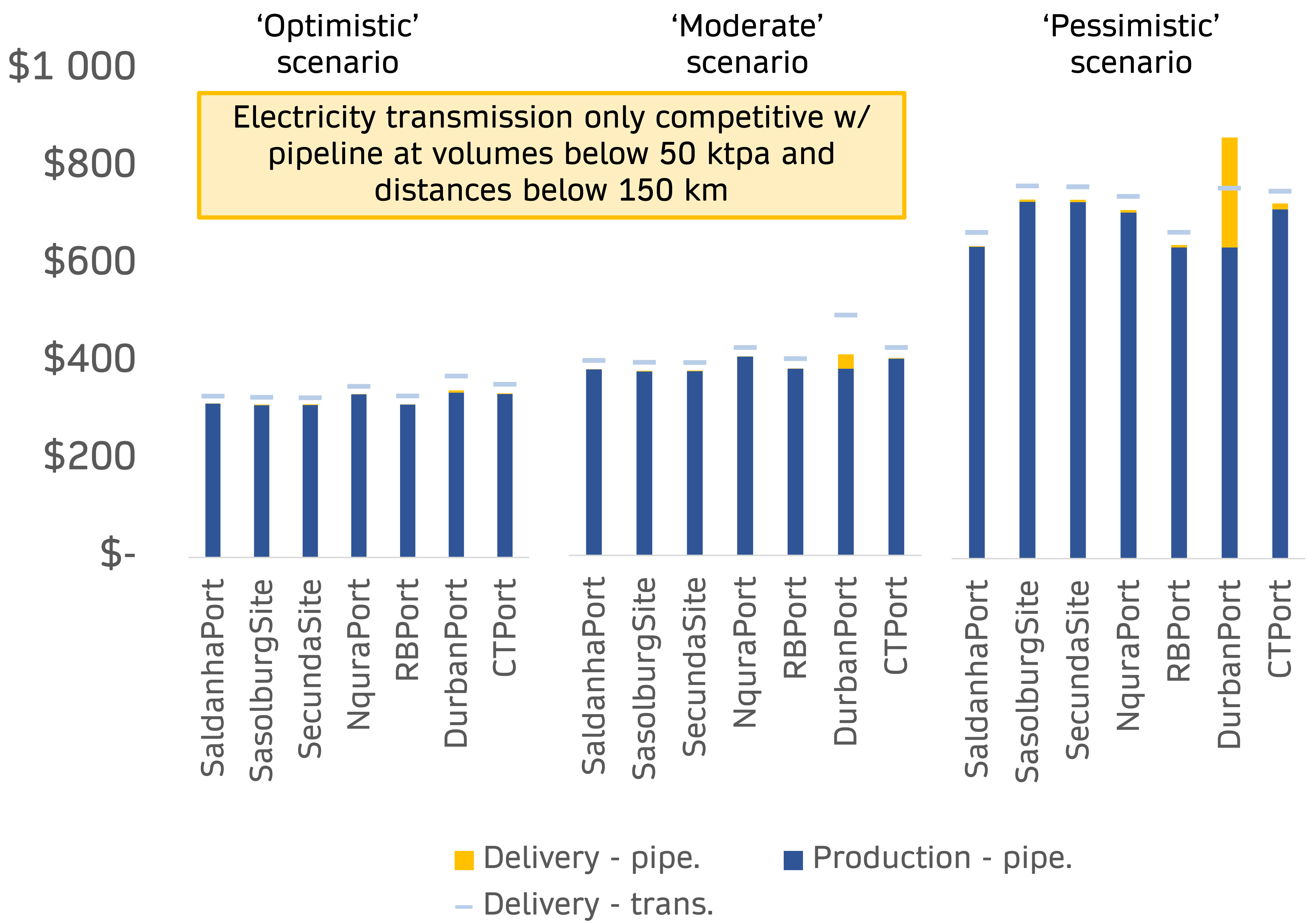
Lower variation in LCOP/S than steel use-case but production costs can double w/ poor WACC and technology cost conditions

Similarly, pipeline delivery cheaper than electricity transmission for nearly all demand nodes

LCOP/S by potential supply node (USD/tonne NH_3 – 2050)



Optimal DLCOA by demand node (USD/tonne NH_3 – 2050)



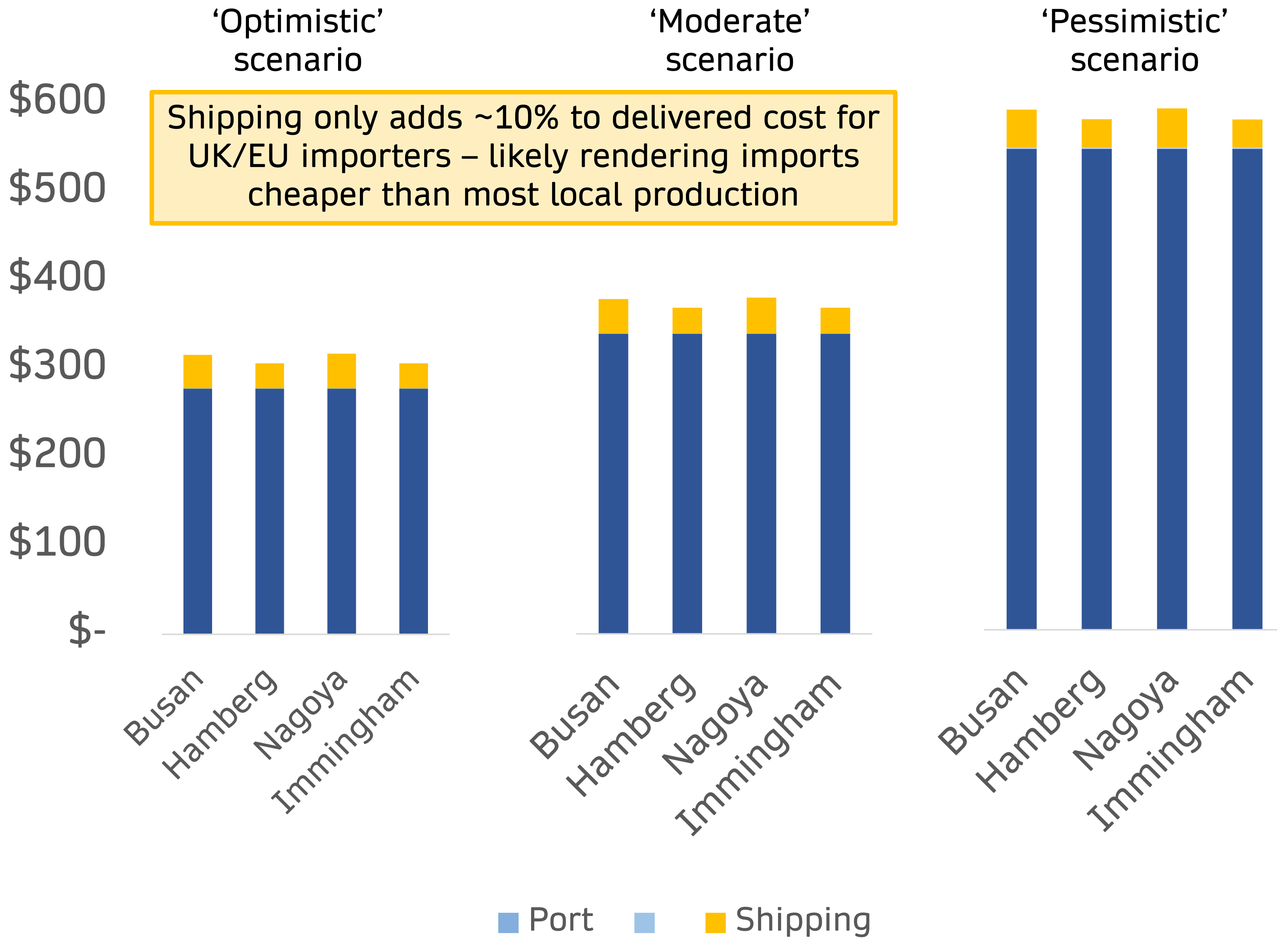
3. Results

Export GNH_3: Namibia could deliver exported GNH_3 for less than $550/tonne in 2030 and $300/tonne in 2050

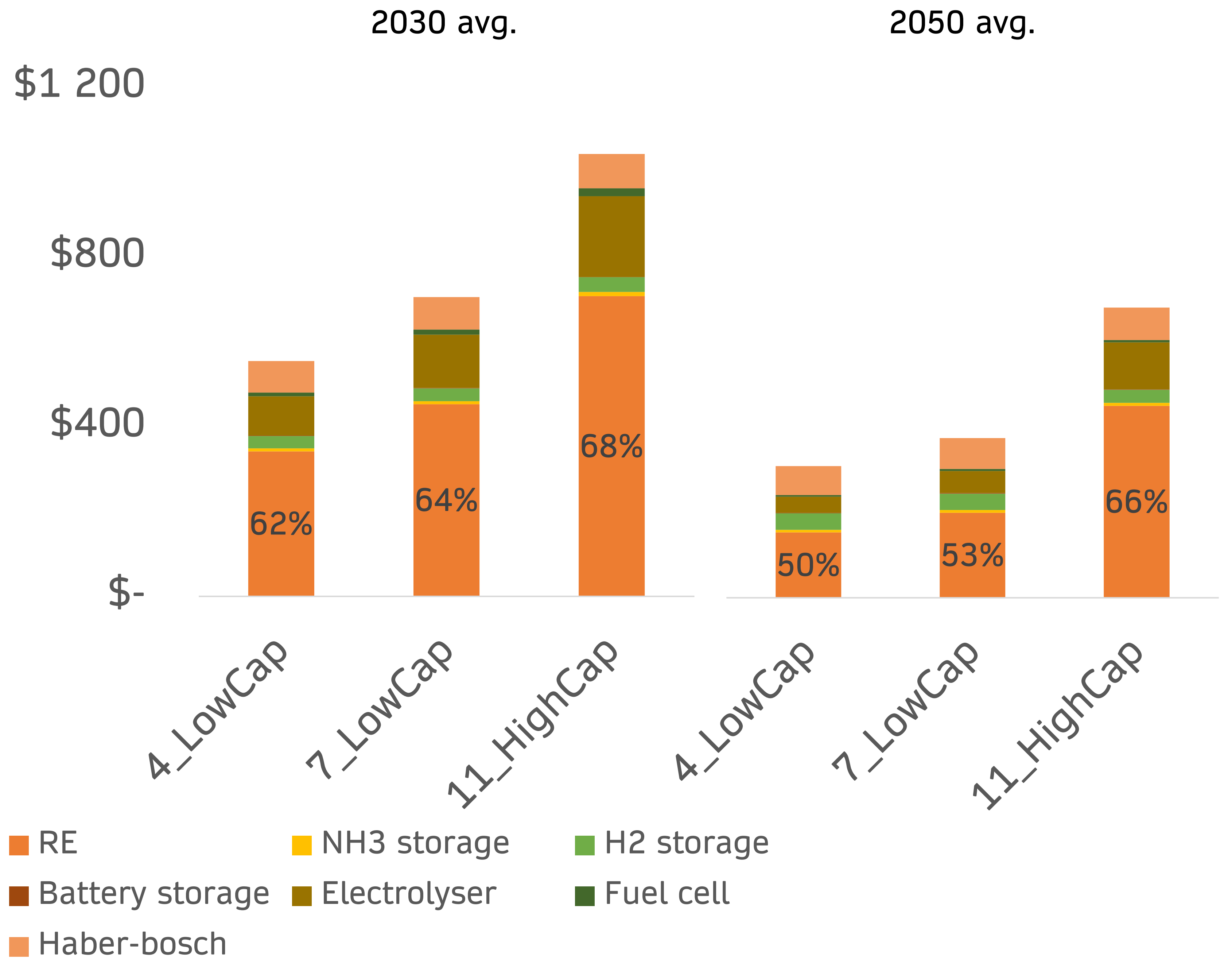
Namibian GNH_3 can be delivered to EU, UK and Asian markets at USD 300/tonne by 2050 with favorable WACC conditions

LCOA decreases 35-45% between 2030 and 2050, with RE cost playing gradually smaller role

Optimal DLCOH by demand node (USD/tonne NH_3 – 2050)

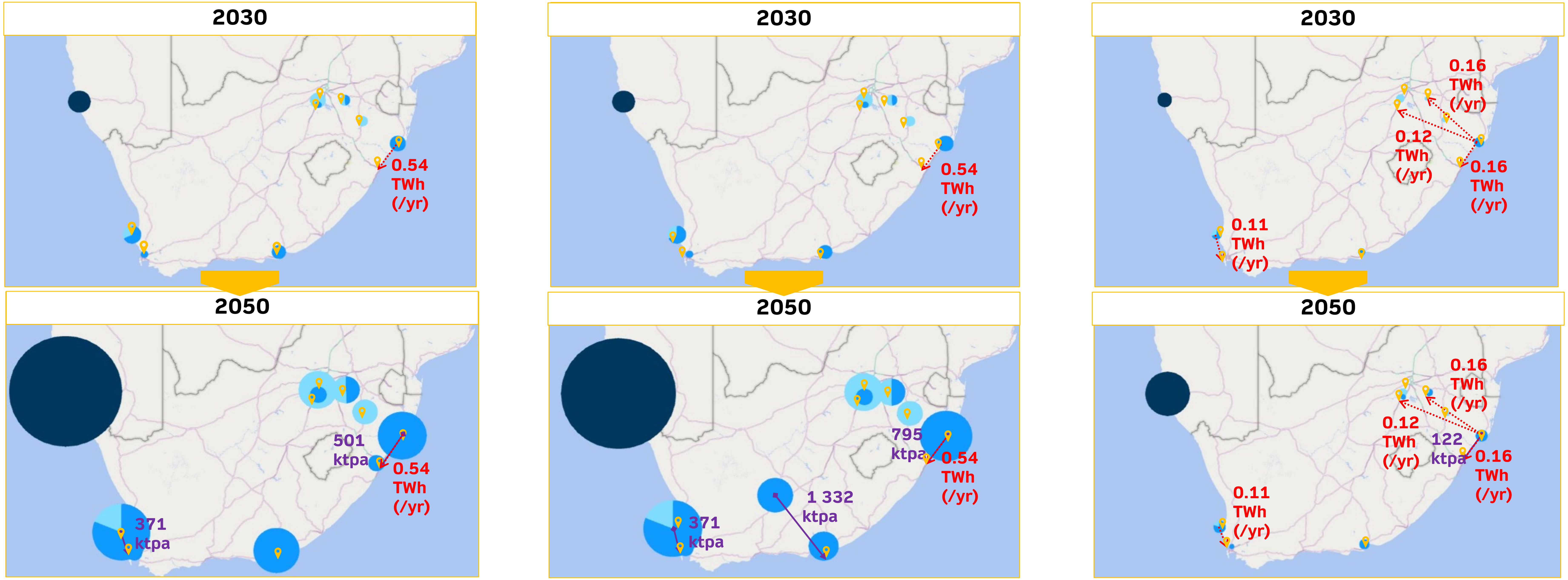


Average LCOA across supply nodes (USD/tonne NH_3 – 2030, 2050)



WACC, demand, and learning rate evolutions will have material impact on topography of least-cost infrastructure plan

4% WACC, High dem., High learning → 7% WACC, else same → 11% WACC, Low dem., Low learning



Key

- Local demand node
- H_2 prod. (local steel)
- NH_3 prod. (local fertiliser & marine fuel)
- NH_3 prod. (export)
- NH_3 pipeline
- H_2 pipeline
- Electricity transmission

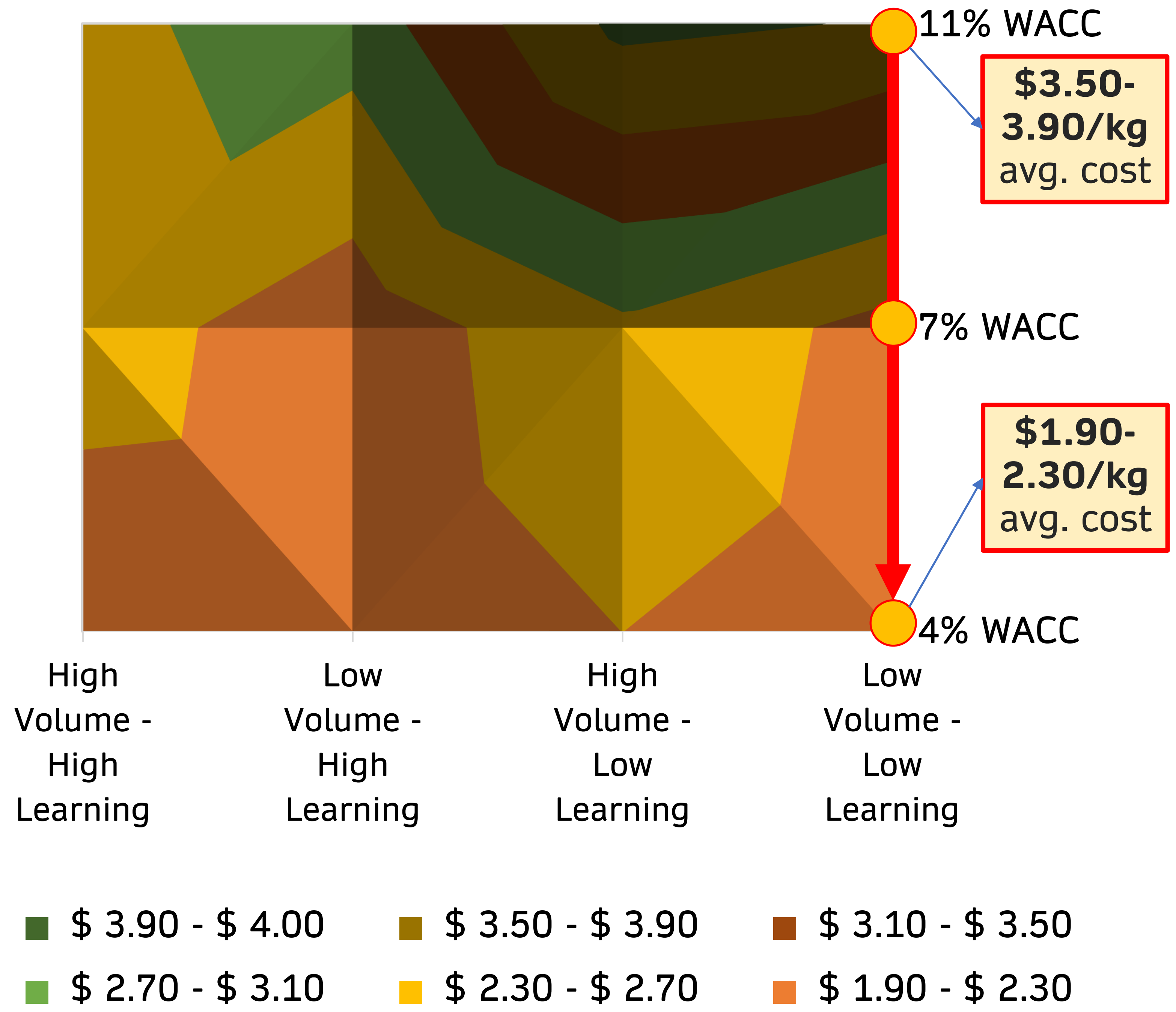
4. So what?

Bringing down RE project WACC is crucial to reduce least-cost planning sensitivity to learning rate uncertainties

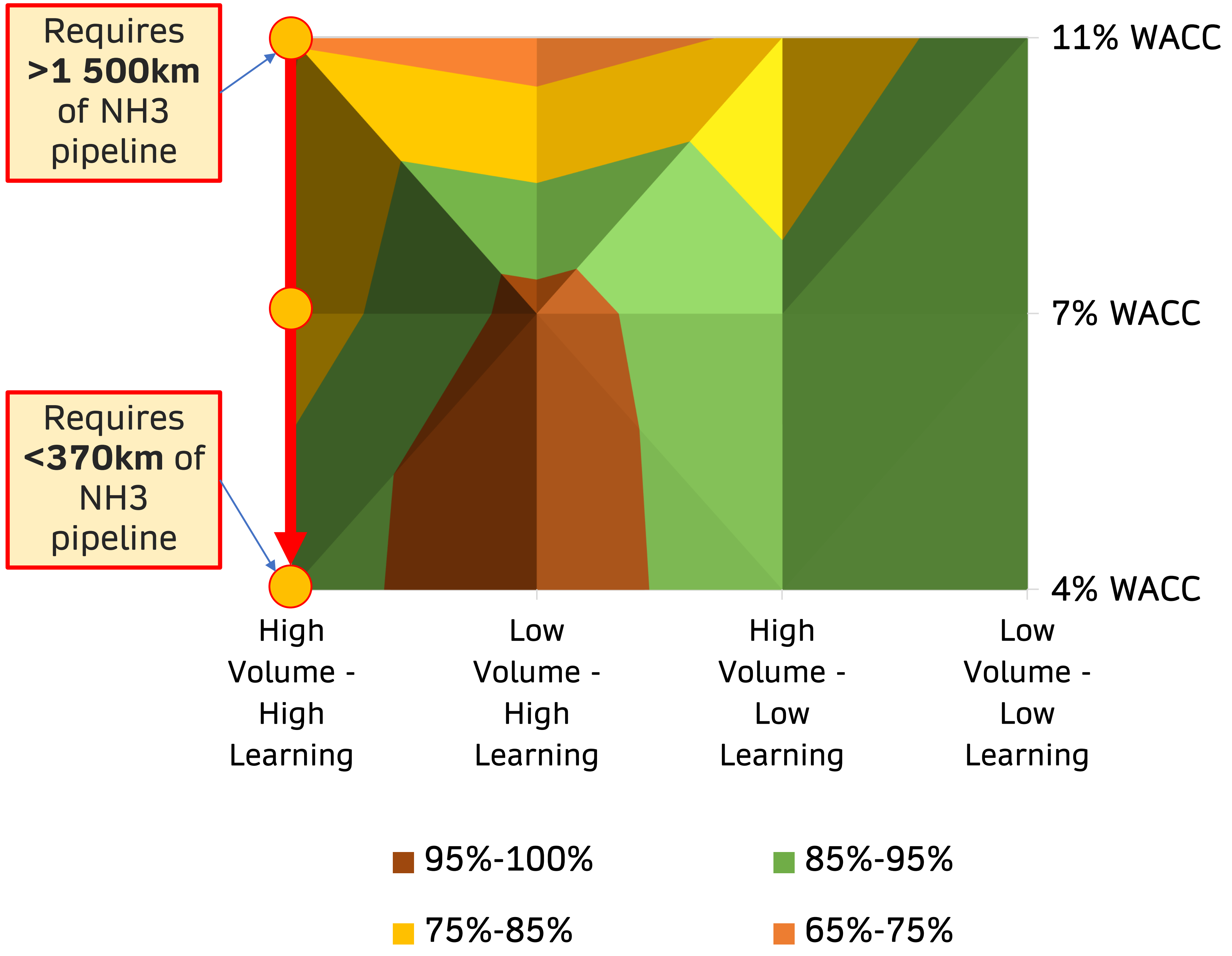
From a cost perspective, the avg. optimal DLCOH/DLCOA fluctuates from $1.50/kg-3.90/kg based on WACC alone

Topographically, optimal proportion of total supply from on-site production fluctuates from 65%-95% based on WACC alone

Avg. optimal DLCOH/DLCOA
(USD/kg H_2-equivalent - 2050)



Avg. % of local GH_2 and GNH_3 supply from co-located production
(% - 2050)

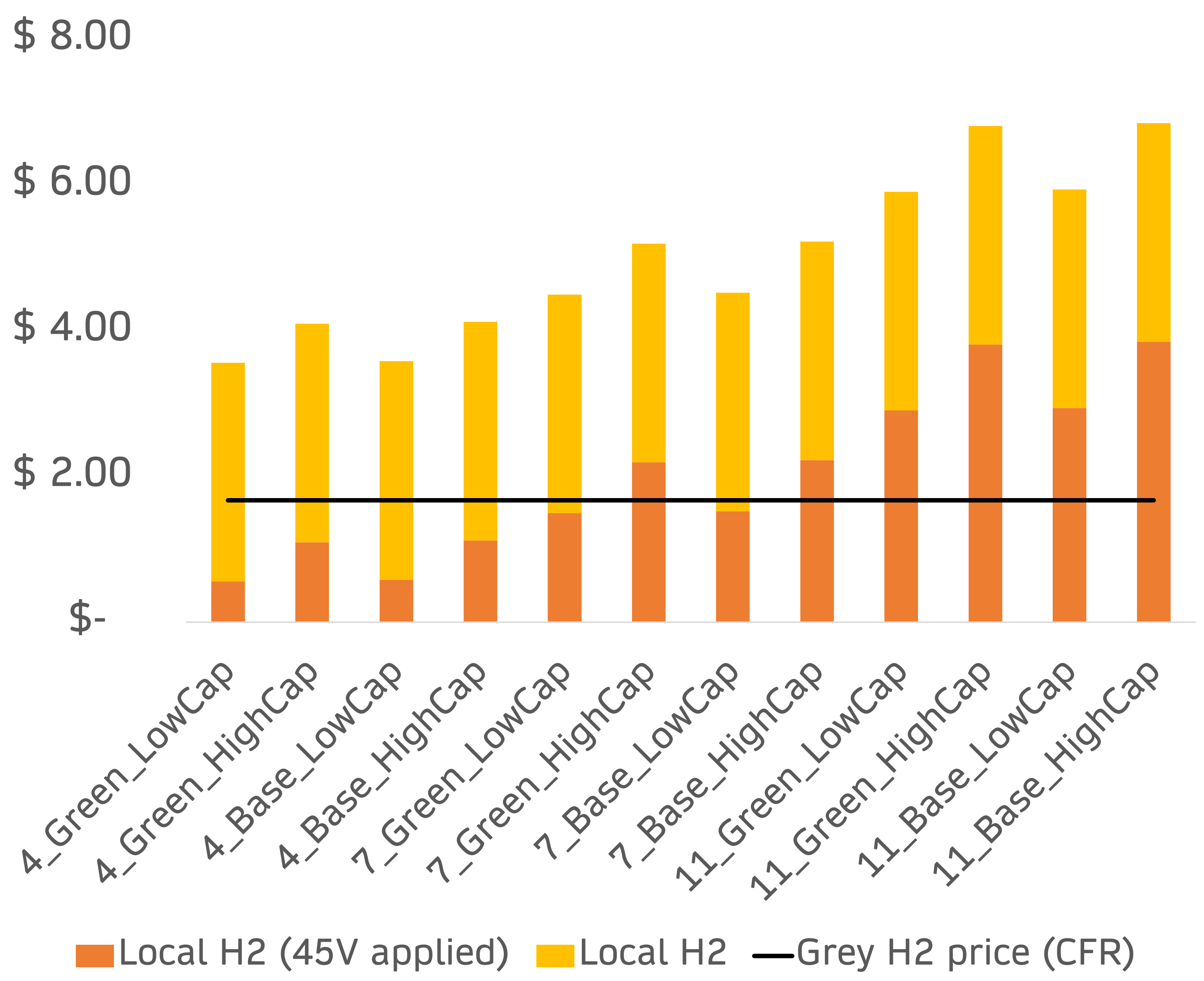


4. So what?

IRA-style production tax credit would bring GH_2 / NH_3 2030 delivered cost to grey-parity in most scenarios

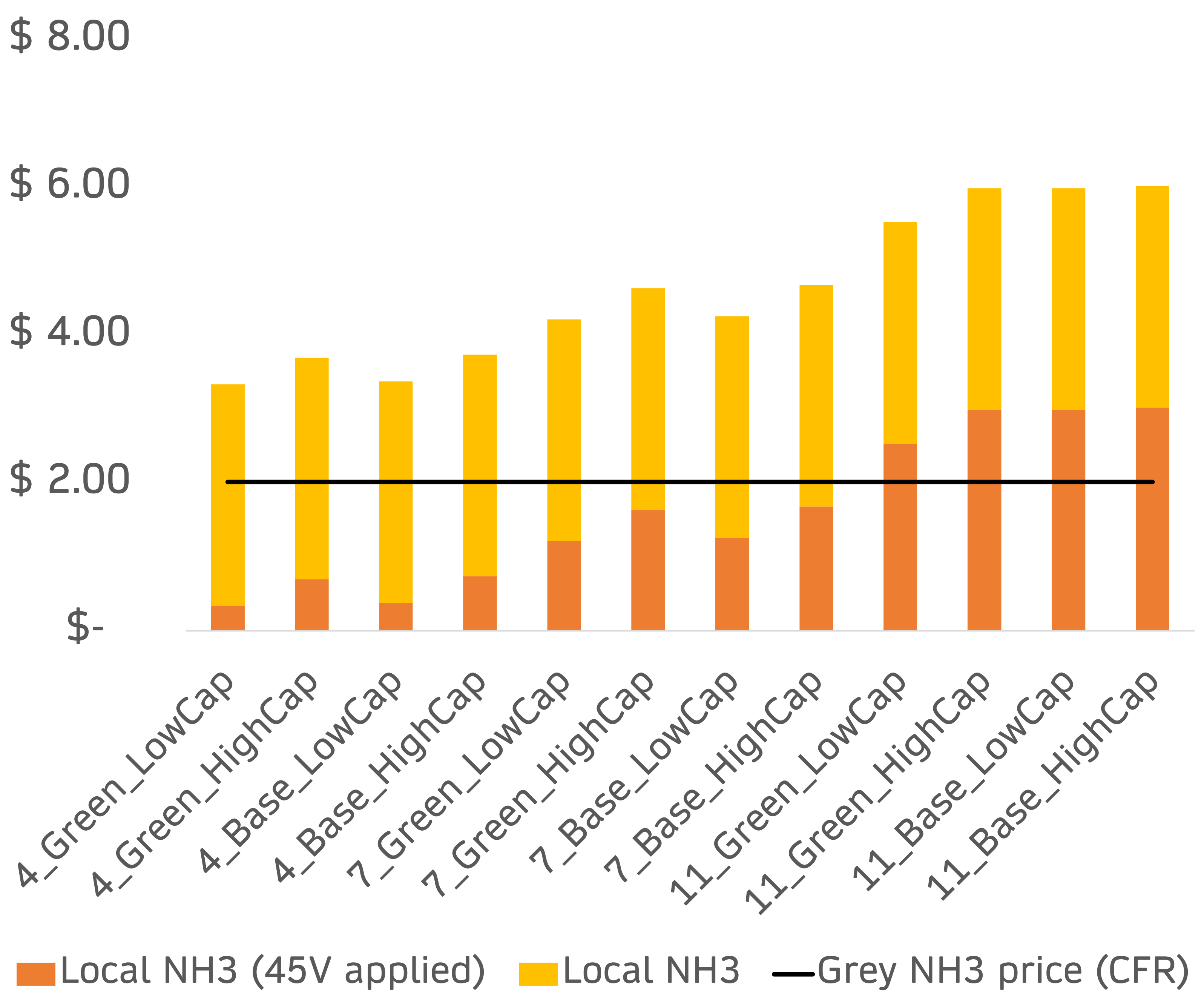
\$3/kg PTC enables local grey H_2 parity by 2030 in 50% of scenarios

Avg. optimal DLCOH by scenario and w/ PTC (USD/kg GH_2 – 2030)



\$3/kg PTC enables local grey NH_3 parity by 2030 in 66% of scenarios

Avg. optimal DLCOA by scenario and w/ PTC (USD/kg GNH_3 – 2030)



This MILP optimisation builds on the current National GH_2 Commercialisation Strategy in four ways

1
On-site production is king?

- Dearth of retrofittable gas pipeline networks means on-site GH_2 and GNH_3 production is the optimal supply solution for 87% of all GH_2 and GNH_3 for local consumption by 2050 (averaged across scenarios)
- Off-site supply only plays a significant role (~25% of all supply) under pessimistic 11% WACC scenarios and for GNH_3 supply between proximate nodes (<250 km apart) with at least 15-25% LCOA discrepancies

2
Pipelines beat electricity?

- When new-build off-site supply is used, pipelines are almost always more cost-effective than HVDC electricity transmission across optimised scenarios…
- …except when short transmission distances (<100 km) are combined with low volumes (<5 ktpa for H_2 and <50 ktpa for NH_3) as electricity losses are minimised with short-distance AC systems

3
IRA-style incentive impact

- USD 3/kg H_2-equivalent PTC in the region (comparable to the US 45V credit) enables green H_2 and green NH_3 cost parity with grey H_2/NH_3 by 2030 in 50% and 66% of optimised scenarios respectively
- Requires USD 74 – 224 Mn and USD 110 – 358 Mn of spending in 2030 respectively

4
Regional collaboration key

- Southern Namibian supply sites consistently the optimal supply to all export markets (achieving $290-350/tonne DLCOA in 2050), even when accounting for new-build single-mooring port construction cost
- GNH_3 export in Southern Africa may be $4.7 - 8.6 Bn/yr industry by 2050 (approx. same as production for local demand) and beneficiation opportunities between Namibia and South Africa should be explored

References (full study reference list included in report)

Argus Media, 2021. *ARGUS Green Ammonia Strategy Report,* s.l.: s.n.

Ayodele, T. & Munda, J., 2019. Potential and economic viability of green hydrogen production by water electrolysis using wind energy resources in South Africa. *International Journal of Hydrogen Energy,* Volume 44, pp. 17669-17687.

BCG, 2021. *Decarbonisation of South Africa's Petrochemicals and Chemicals Sector,* Johannesburg: National Business Initiative; Boston Consulting Group.

BCG, 2021. *Decarbonising South Africa's Heavy Manufacturing Sector,* Johannesburg: National Business Initiative (NBI); Boston Consulting Group.

Bofinger, S., Zimmermann, B., Gerlach, A. & Bischof-Niemz, T., 2016. *Wind and solar PV resource aggregation study for South Africa: Public presentation of results,* Johannesburg: CSIR, SANEDI, ESKOM, Fraunhofer IWES.

DEFF, 2021. *National Environmental Management Act, Gazette No. 44191,* Pretoria: DEFF.

DeSantis, D. et al., 2021. Cost of long-distance energy transmission by different carriers. *iScience,* 24(12).

DNV GL, 2020. *Maritime Forecast to 2050: Energy Transition Outlook 2020,* s.l.: s.n.

DSI, 2021. *Hydrogen Society Roadmap for South Africa 2021,* Pretoria: DSI.

DTIC, 2020. *The South African Steel and Metal Fabrication MasterPlan 1.0,* Pretoria: DTIC.

DTIC, 2022. *Green Hydrogen Commercialisation Strategy for South Africa,* s.l.: Department of Trade, Industry, and Competition.

Eskom, 2022. *The Eskom Transmission Development Plan (2023-2032),* Johannesburg: Eskom.

Government of South Africa, 2022. *Government Gazette: 47658,* Pretoria: Government Printing Works.

IEA, 2019. *The Future of Hydrogen: Seizing today's opportunities,* Paris: s.n

IEA, 2021. *Ammonia Technology Roadmap,* Paris: IEA.

IEC, EPRI, & PWC, 2021. *Hydrogen Demand and Cost Dynamics,* London: International Energy Council.

IHS Markit, 2021. *Super H2igh Road for South Africa,* Johannesburg: Agora Energiewende.

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References (full study reference list included in report)

Moritz, M., Schonfisch, M. & Schulte, S., 2023. Estimating global production and supply costs for green hydrogen and hydrogen-based green energy commodities. *International Journal of Hydrogen Energy,* Volume 48, pp. 9139-9154.

NREL, 2021. *Annual Technology Baseline,* s.l.: NREL.

NREL, 2021. *Annual Technology Baseline,* s.l.: NREL.

PyPSA, 2023. *PyPSA Introduction.* [Online]
Available at: https://pypsa.readthedocs.io/en/latest/introduction.html

Roos, T., 2021. The cost of production and storage of renewable hydrogen in South Africa and transport to Japan and EU up to 2050 in different scenarios. *International Journal of Hydrogen Energy,* Volume 46, pp. 35814 - 35830.

Roos, T. & Wright, J., 2021. *Powerfuels and Green Hydrogen (public version),* Brussels: European Union

Salmon, N., Nayak-Luke, R. & Banares-Alcantara, R., 2021. Optimization of green ammonia distribution systems for intercontinental energy transport. *iScience,* 24(8).

Trollip, H., Mccall, B. & Bataille, C., 2022. How green primary iron production in South Africa could help globaldecarbonization. *Climate Policy,* 22(2), pp. 236-247.

US Department of the Treasury, 2023. *U.S. Department of the Treasury, IRS Release Guidance on Provisions to Expand Reach of Clean Energy Tax Credits Through President Biden's Investing in America Agenda,* Washington D.C.: s.n.

Way, R., Ives, M., Mealy, P. & Farmer, J., 2022. Empirically grounded technology forecasts and the energy transition. *Joule,* Volume 6, pp. 1-26.

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