



Energy
Transitions
Commission

Power Systems Transformation workshop

Cross-border transmission: understanding potential

[09/12/2024]

This year, focus on two key challenges for power systems transformation

Building and optimising grids

Tx:
Grow the transmission network

Dx: Reinforcing existing & building new network infrastructure

Tx: Optimising use of existing assets via new technologies

Dx – Spreading peak load to increase grid utilisation & balance the system



Grids – e.g. interconnectors and long-distance transmission can – in part – help to solve balancing challenge

Storage and flexibility deployed to solve system balancing can – in part – reduce the grid build needed & help to optimise



Managing the system balancing challenge (in high variable renewable systems)

Ix / Tx – balancing the system via interconnection / long distance transmission

Balancing the system via storage, flexibility & generation technologies



Managing the system balancing challenge: what have we done so far and what is changing in our thinking?

Managing the system balancing challenge (in high variable renewable systems)

Revisit power system transformation trajectory

- Until ~50% penetration of wind and solar, balancing challenge can primarily be met by running existing fossil more flexibly

Revisit shape of the balancing challenge

- Understanding the mix of daily/weekly/seasonal balancing needed in different regions

Revisit role of different routes to meet balancing challenge

- For short-duration storage, renewed confidence in the role of lithium-ion batteries
- Increasing number of technology options for medium-duration storage, set of options to meet long duration storage is more limited
- High potential for demand-side flexibility
- Heat storage opportunities for industrial heat provision



Role of **cross border transmission** links

Upcoming focus

Focus today

Revisit power market design & key enablers for balancing needs

- Market design needs to evolve to provide revenue certainty for storage
- Role of locational pricing is critical



Workshops

Grid build challenge

Briefing note published in September 2024

March 26th

Key technologies to balance the system : *dispatchable generation, energy storage, heat storage*

June 18th

Key technologies to balance the system : *demand side flexibility*

Blog published in November 2024

Oct 9th

Sizing the system balancing challenge

Oct 24th

Potential of cross-border transmission

End 2024

Key enablers

Early 2025



Workshop agenda

- 1) **Context: why and how to build new transmission links across countries**
- 2) **Long distance HVDC transmission costs: how do they vary according to project specifics?**
- 3) **High variable renewable systems: how can cross-border links optimise generation and balancing?**
 - 3A) How can cables optimise **generation** needs?
 - 3B) How can cables optimise **balancing** needs?
- 4) **What are the top global potential cables for cross-border transmission?**
 - Modelling methodology
 - Top interconnectors ranked by key criteria
 - What does this mean for network megaprojects?
- 5) **Key blockers and enablers**



1) Context: why and how to build new transmission links across countries



Flow of electricity over longer distances can be within or across countries

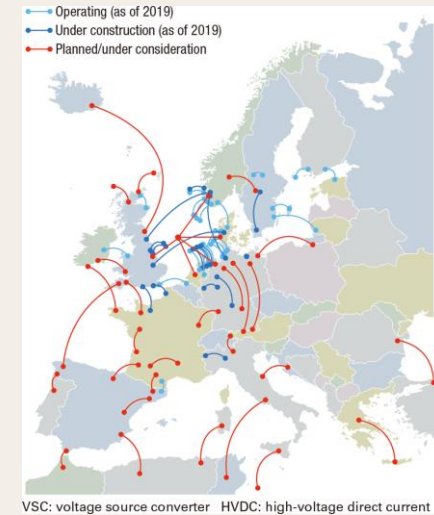
Within borders (national)



E.g. Xiangjiaba-Shanghai link in China, one of the world's longest at 2,000 km

Focus of this work

Cross-border (international)

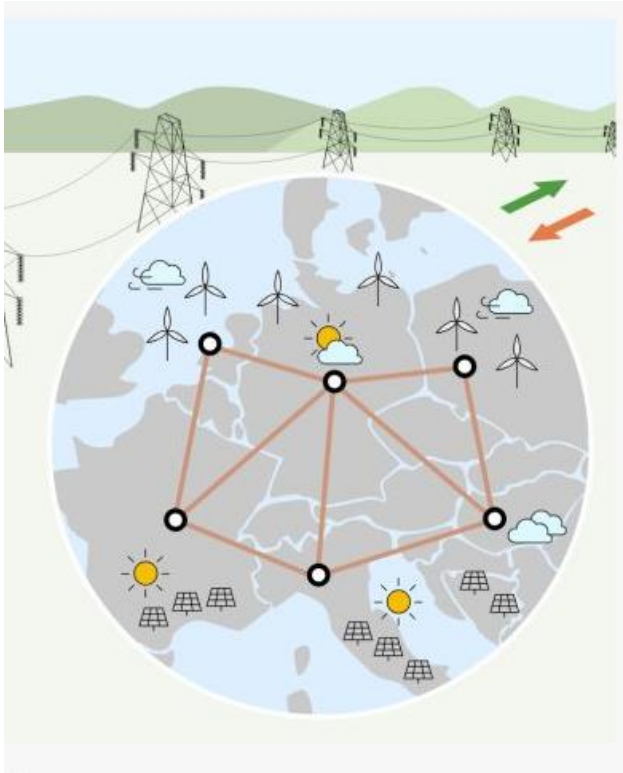


E.g. Interconnectors across Europe



Linking power grids across countries can be more cost effective than domestic generation

Europe's electricity system is world's largest interconnected grid



Grids and interconnectors carry electricity from areas with **excess electricity** **demand** to regions with higher demand.

When weather patterns turn, supplies may be **lower than demand**, relying on inflows of electricity from other countries.



- Europe is the world leader in having an interconnected grid network
- Significant benefits to interconnection; **average power prices across countries lower** than solely generating domestically

The system consists of over **400 interconnectors**, linking **39 national systems to connect over 600 million people**. In 2021 trade delivered benefits of **€34 billion** from lower price volatility.



Cross border transmission can be either (primarily) 2-way or 1-way

Primarily 2-way flow “Interconnection”

Short or Long

- Most existing links today are 2-way, short distance
- Not a continuous flow (can have lower utilization); flow of electricity driven by market signals
- Based on **arbitraging S/T price variations** across markets (e.g. UK<>Europe), can help with **balancing**.
- In some interconnectors, flow tends to be in one direction primarily (e.g. Norway <> UK is primarily from Norway, given the hydro resource)
- Can be built with high TSO involvement, or private

1 –way flow “transmission”

Long

Main focus of ETC work, exploring opportunities in a high variable renewable scenario

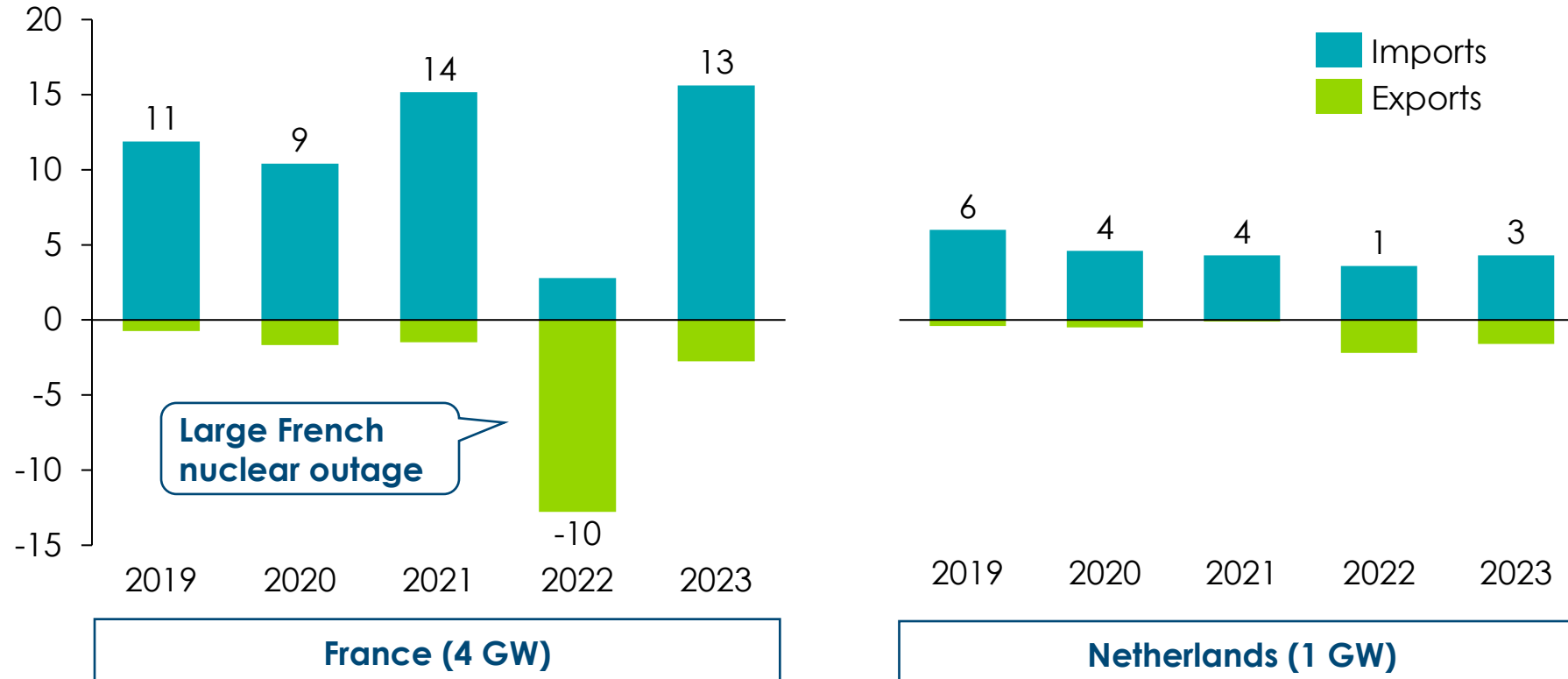
- Some existing or proposed links today (e.g. across China, Xlinks)
- Likely to be a continuous flow of electricity (high utilization rates), based on one-way cost arbitrage
- Based on **structural resource complementarity** across markets, e.g. lower costs/higher energy output (e.g. Western China has better wind and solar resources), can also help with **balancing**
- International links would typically be privately-owned



'2-way flow interconnection' short distance already widespread in Europe, including 9 links between GB and close neighbours

GB frequently trades power for short-term balancing

Annual TWh imported/exported



GB generally net importer via interconnection, purchasing power when it is cheaper than the GB wholesale price; **though wires are fully 2-way**



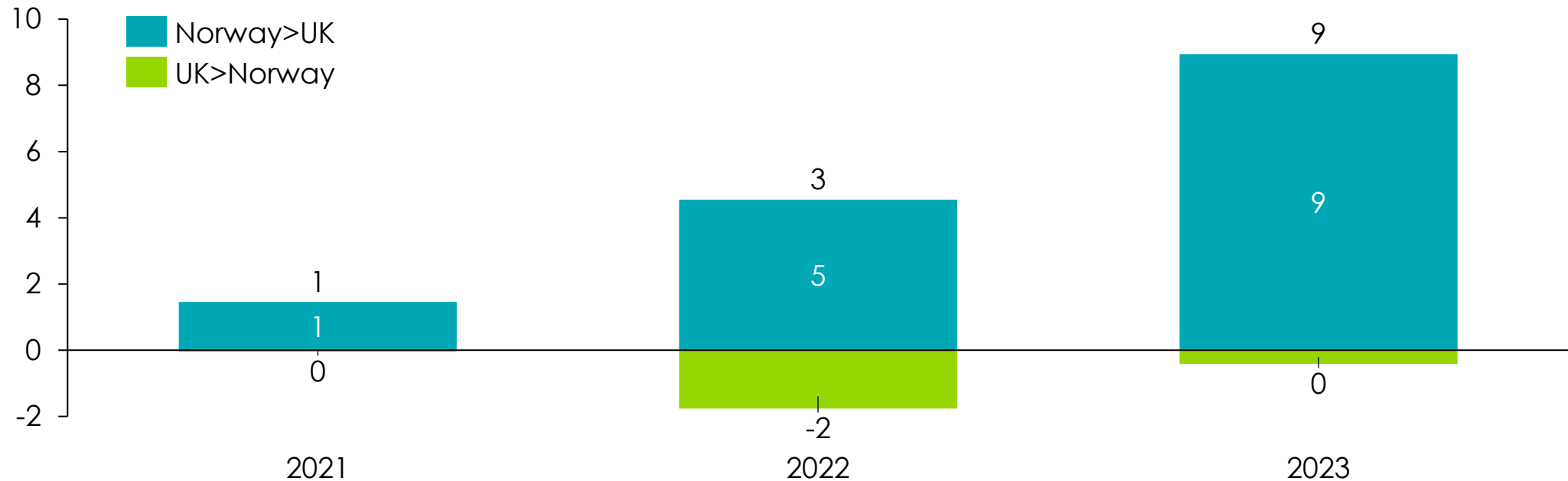
Source: Ember (2024) *Clean flexibility is the brain managing the clean power system*; DESNZ (2024) *DUKES table 5.13*.

'2-way flow interconnection' can primarily operate in one direction

The UK-Norway North Sea Link is **most often used for UK import of Norwegian hydro power**, however, when there is excess offshore wind power in the UK this can be sent to Norway, resulting in periods of Norway net imports, and dams staying closer to full capacity.

UK-Norway frequently trades power for short-term balancing

Annual GW imported/exported



Notes: Hydropower makes up ~90% of Norway's energy mix.
Source: DESNZ (2024) Dukes 5.13; Ember (2024) *Electricity data explorer*

1-way long-distance transmission links are less common today, but have high potential in high variable renewable systems

To provide importing country with

A



Generation

Based on allowing **countries with higher renewable potential, land availability and lower costs** to export to countries with less favourable conditions

B



Balancing

Based on either:

- Using **non-correlated weather and demand** patterns to provide electricity at grid optimal times
- **Using storage in addition to non-correlated weather and demand** patterns to provide electricity at grid optimal times



Long-distance links options vary between AC vs. DC and land vs. sea

HVAC



- ~7m kms installed globally today
- Losses ~7% per 1,000 km
- \$1m-2.5m/km

HVDC

Overground



- ~110,000 kms installed globally today
- Losses ~3% per 1,000 km
- \$0.5m-1.5m/km

Subsea

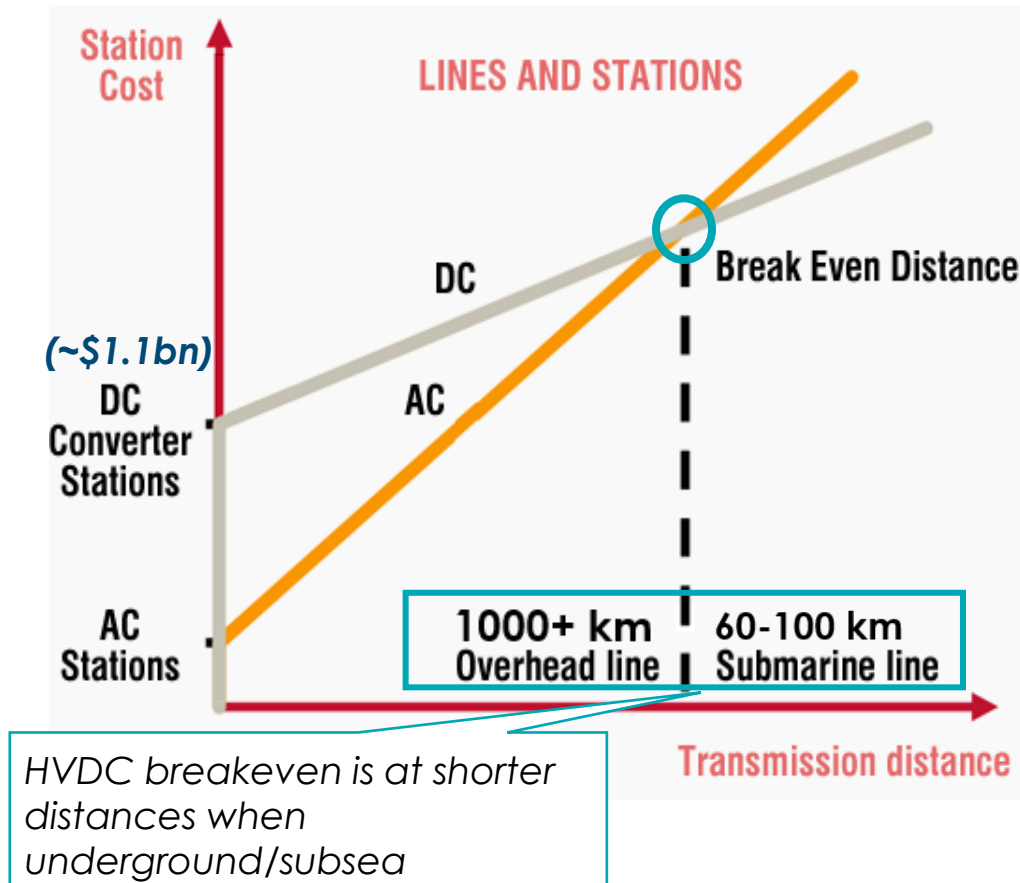


- ~20,000 kms installed globally today
- Losses ~3% per 1,000 km
- ~\$1m+/km



Over long distances, HVDC lines are more economical than HVAC

DC vs AC line economics



- Over long distances HVDC lines are advantaged by:
 - **Less power loss** – AC suffers from significant energy loss over transmission lines due to resistance and the “skin effect” causing excess energy to be lost as heat.
 - **Thinner cables** – are required for HVDC lines, which are cheaper per km than AC lines.
 - **Fewer pylons** – Less pylons are required in HVDC systems, as HVAC is limited to shorter power lines. HVAC towers also tend to be bulkier and more expensive to construct, to accommodate for the heavy mechanical load.
- However, **HVDC lines require expensive converter stations (~\$1.1bn for a pair)**, making HVAC lines more competitive for short distance

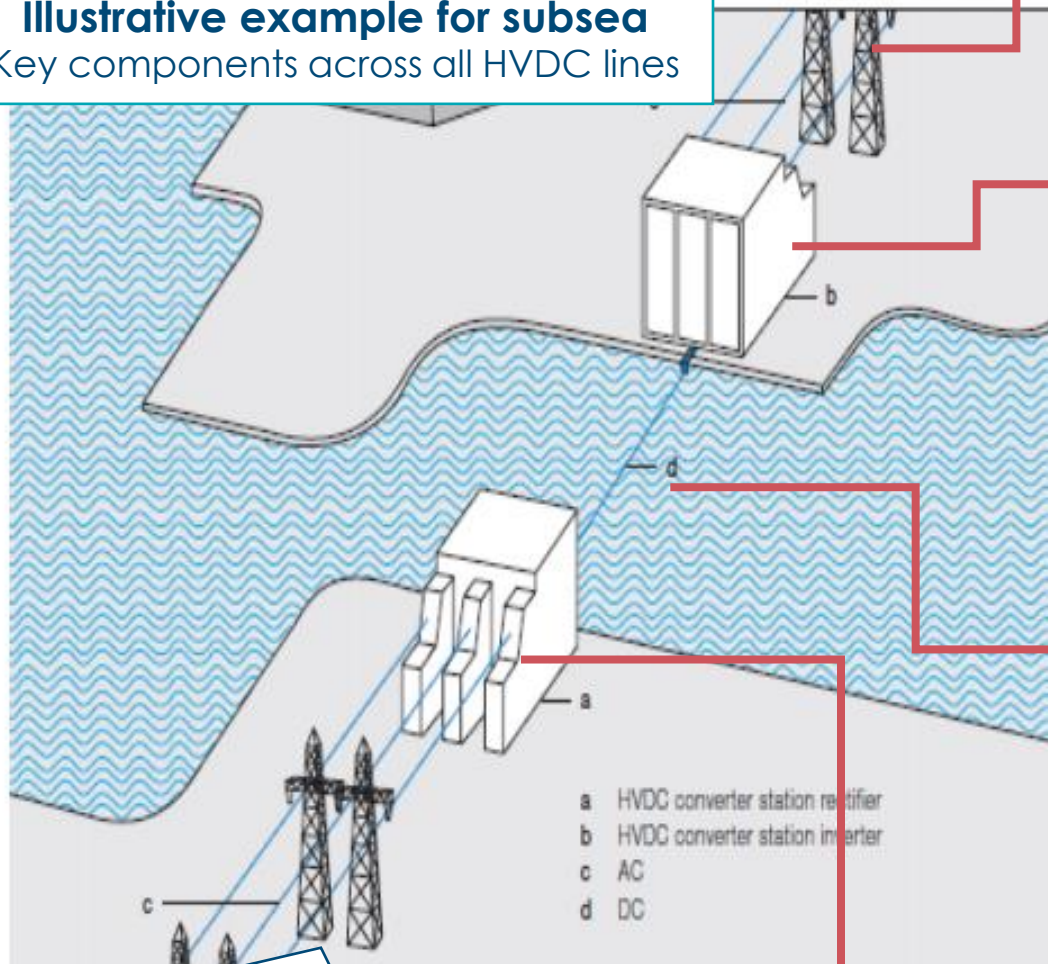
Costs/MWh/1000km for overhead lines, USA New England

	100 km	2000 km	4000km
HVAC (\$/MWh/1000km)	\$10.0	\$10.0	\$10.0
HVDC (\$/MWh/1000km)	\$46.1	\$9.9	\$6.8

Notes: US New England costs used; Project management, Terrain preparation, Acquisition and permitting, Line equipment, Other equipment, Structures come from BNEF GridVal model. HVDC converter stations assumed to cost \$1.1bn; Finance assumed to cost 5% per annum with 100% of project cost to be paid back over 10 years. Source: BNEF (2024) GridVal 1.0; ETC calculations based on stakeholder engagements.

Key elements of HVDC projects

Illustrative example for subsea
Key components across all HVDC lines



Transmission networks often must be reinforced to accommodate extra power

Transformer

- Step-down or step-up of voltage

Converter Station (Inverter, DC to AC)

- Power electronic valves to control power flow, (e.g. thyristor valves - solid-state semiconductor devices)
- AC filters and capacitor banks to limit amount of harmonics to the level required by network

Transmission lines

- Cables
 - Copper or aluminium conductor
 - Insulation (thickness of insulation depends on operational voltage), XLPE/MI
 - Metallic sheath to protect cable
 - Outer plastic coating
 - If subsea, additional steel armoring
- Overground, underground or subsea
- Monopole or bi-pole (bi-pole most common for underground or subsea)

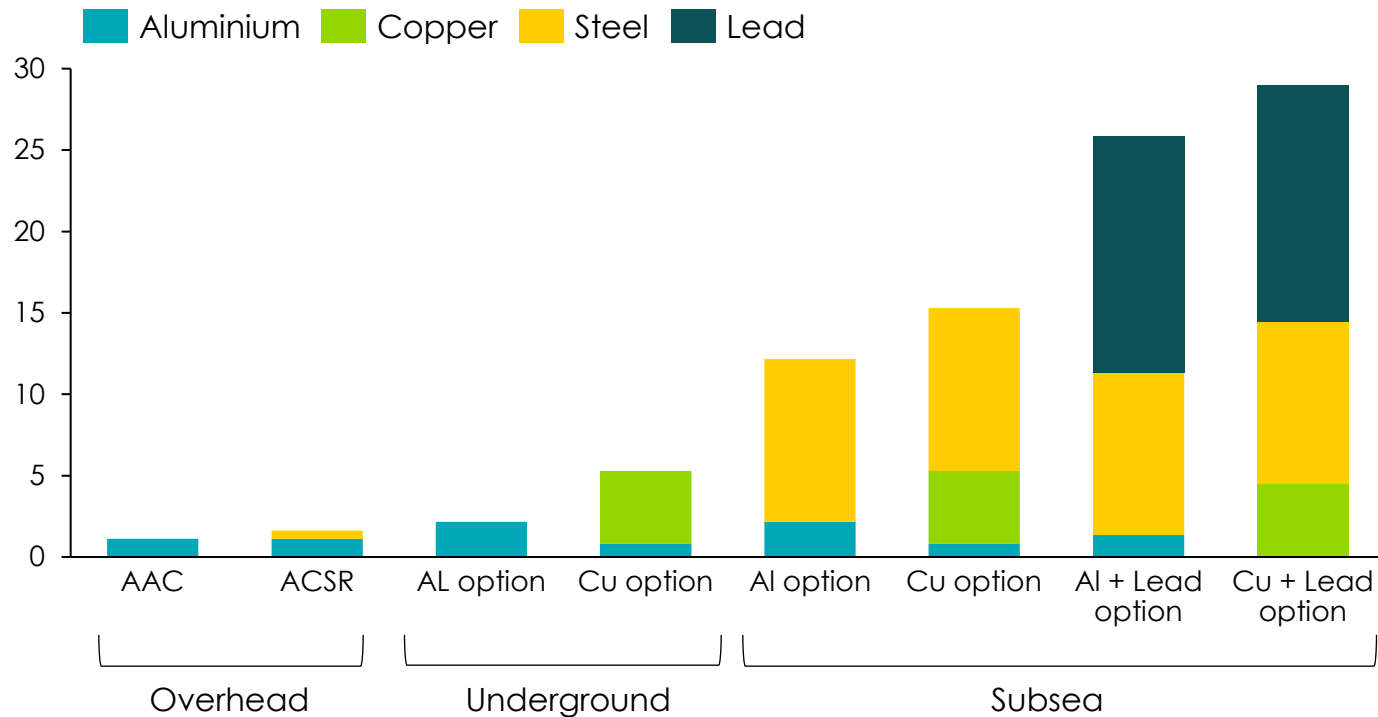
Converter Station (Rectifier, AC to DC)

- See above

Material requirements vary by type of cable, with underground and subsea much more metal intensive

Material requirements by power line type

Tonnes per km



- In developed grids, **new aboveground wires are aluminium-based**, due to cost and weight advantages over copper
- **Copper still favoured over aluminium in some use cases below ground and sea** where weight requirements not an issue
- **HVDC lines use half the metal requirements HVAC lines**, making them less sensitive raw material cost shifts (although limited number of suppliers is keeping costs high)

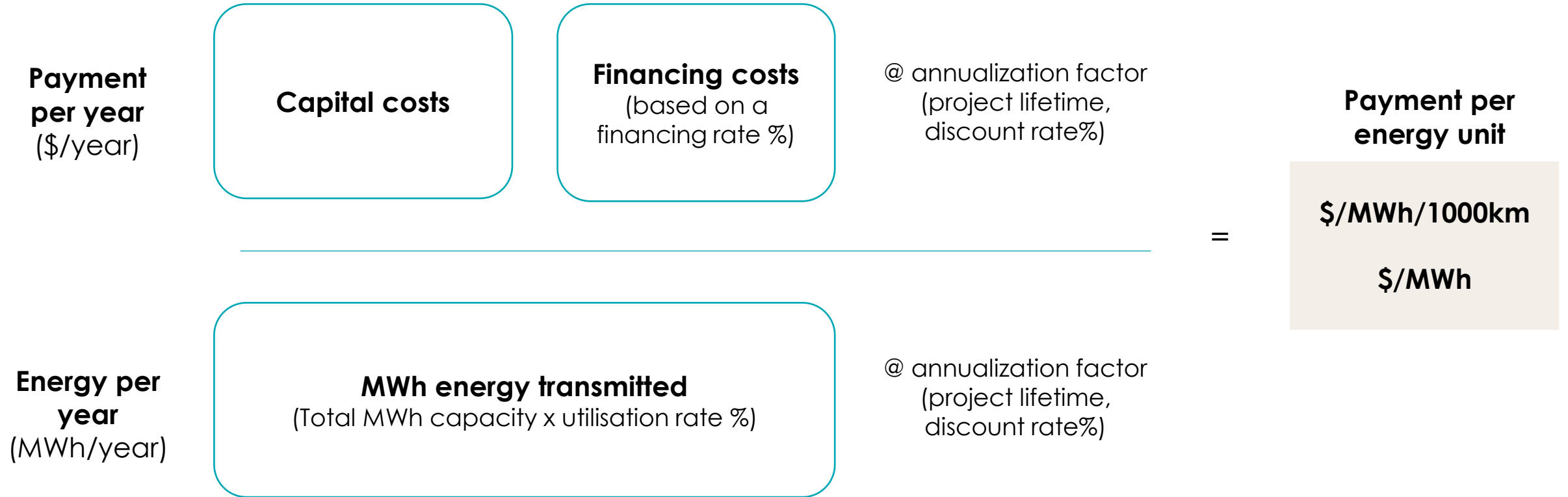


2) Long distance HVDC transmission costs: how do they vary according to project specifics?



There are several elements involved to understand the costs of HVDC

For a given project (e.g. distance, capacity, voltage, overground or subsea) ...



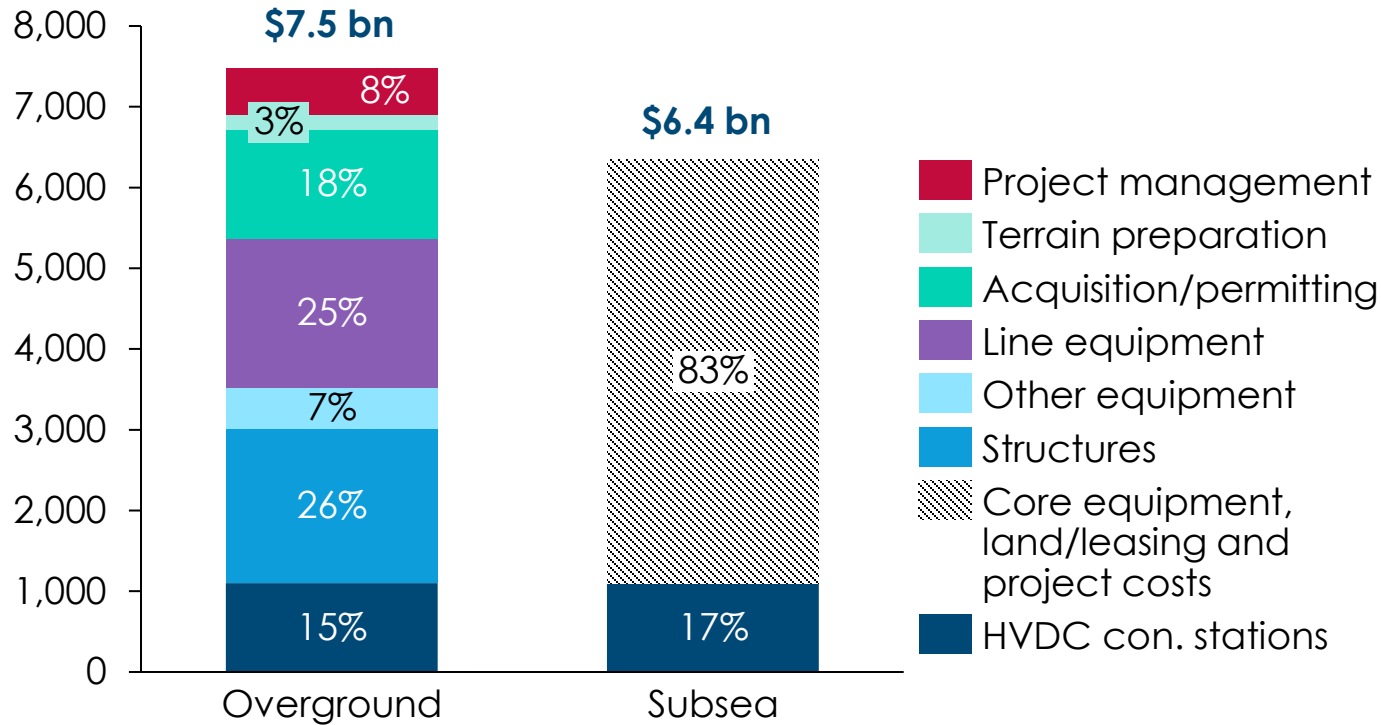
Capital costs: HVDC projects include significant land and equipment costs

Cost breakdown of a HVDC power line

Illustrative project: North America overhead, 2024, 2 GW, 400/525kV, USD



Capital costs



4,000 km

	Overground	Subsea
Cost per km	\$1.9m	\$1.6m

Overground lines come with **permitting challenges, experience frequent delays**, and often must have portions **buried at 7* the cost**, meaning subsea often ends up much cheaper over long distances

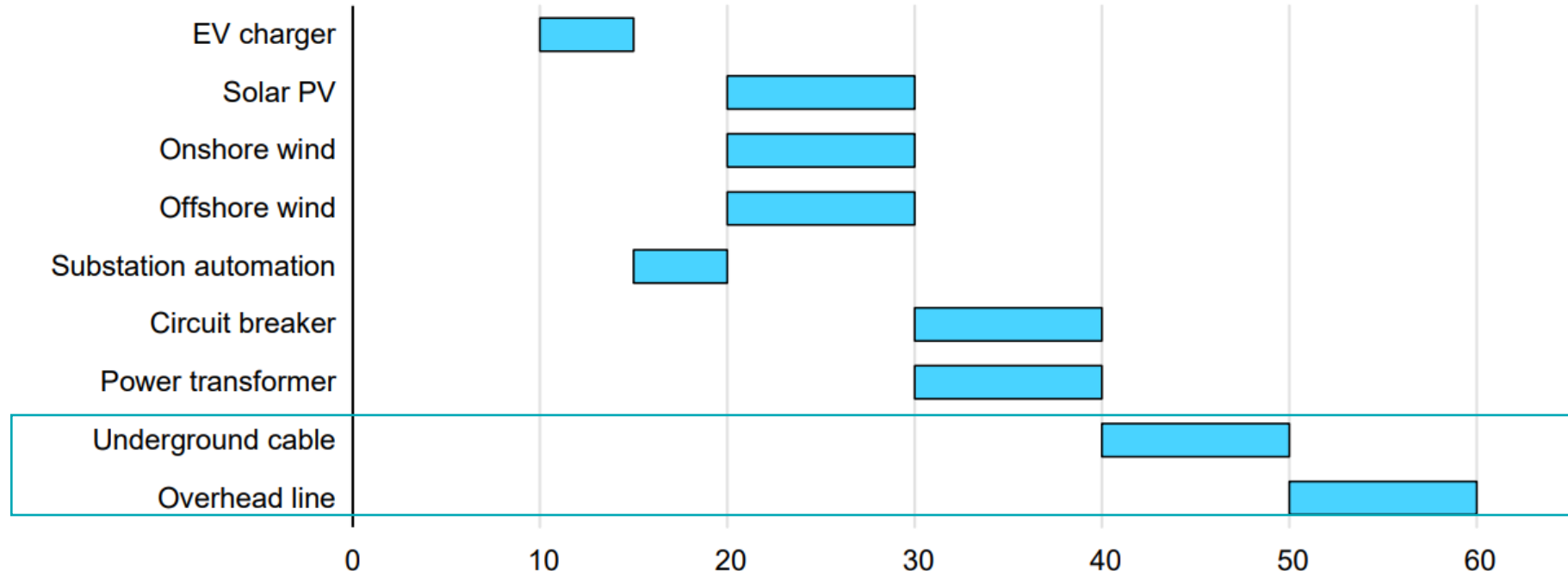
Notes: Project management, Terrain preparation, Acquisition and permitting, Line equipment, Other equipment, Structures come from BNEF GridVal model. HVDC converter stations assumed to cost \$1.1bn. Overhead lines at 400kV, subsea at 525kV. Source: BNEF (2024) GridVal 1.0; ETC calculations based on stakeholder engagements.

Power cables have lifetimes of 40 years or greater, so benefits must be considered over the long-term

Project lifetime

Power cables have longer lifetimes than most other energy products

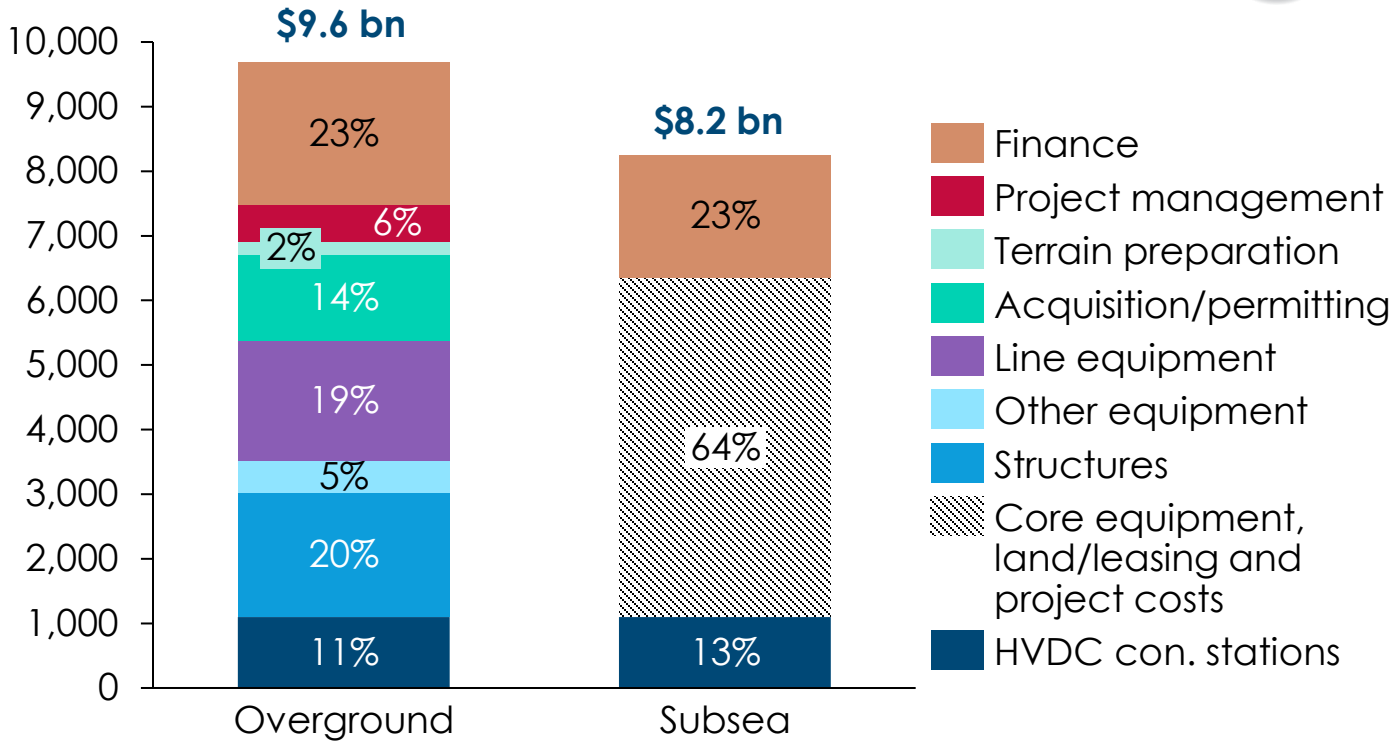
Typical design lifetime in years



Capital costs and financing costs: financing costs an important share

Cost breakdown of a HVDC power line

Illustrative project: North America overhead, 2024, 2 GW, 400/525kV, USD



4,000 km

Capital costs

Financing costs

- Key assumptions for Finance cost
- Assumes a 'project finance' model
 - Project financed over a 10-year period
 - Borrowing costs at 5%

	Overground	Subsea
Cost per km	\$2.4m	\$2.1m

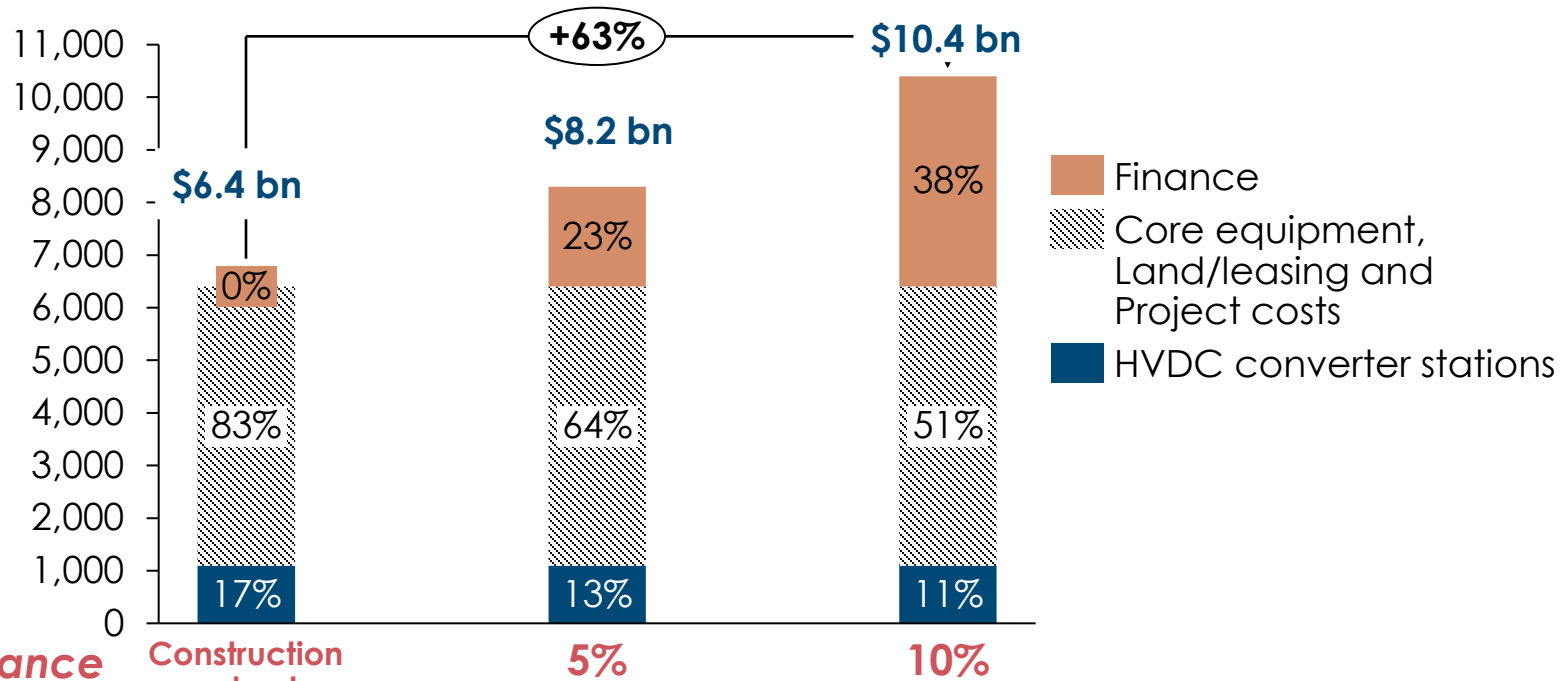


Notes: Project management, Terrain preparation, Acquisition and permitting, Line equipment, Other equipment, Structures come from BNEF GridVal model. HVDC converter stations assumed to cost \$1.1bn. Overhead lines at 400kV, subsea at 525kV. Finance assumed to cost 5% per annum with 100% of project cost to be paid back over 10 years. Source: BNEF (2024) GridVal 1.0; ETC calculations based on stakeholder engagements.

Subsea example: financing rates crucial to overall project economics, borrowing at 10% would add over 60% to cost per km

Cost breakdown of a subsea HVDC power line

Illustrative project: Subsea, 2024, 2 GW, 525kV, Subsea line, 4000km, USD



Financing costs

- Key assumptions for Finance cost
- Assumes a 'project finance' model
 - Project financed over a 10-year period
 - Borrowing costs at 5%

Finance

Cost per km



4,000 km

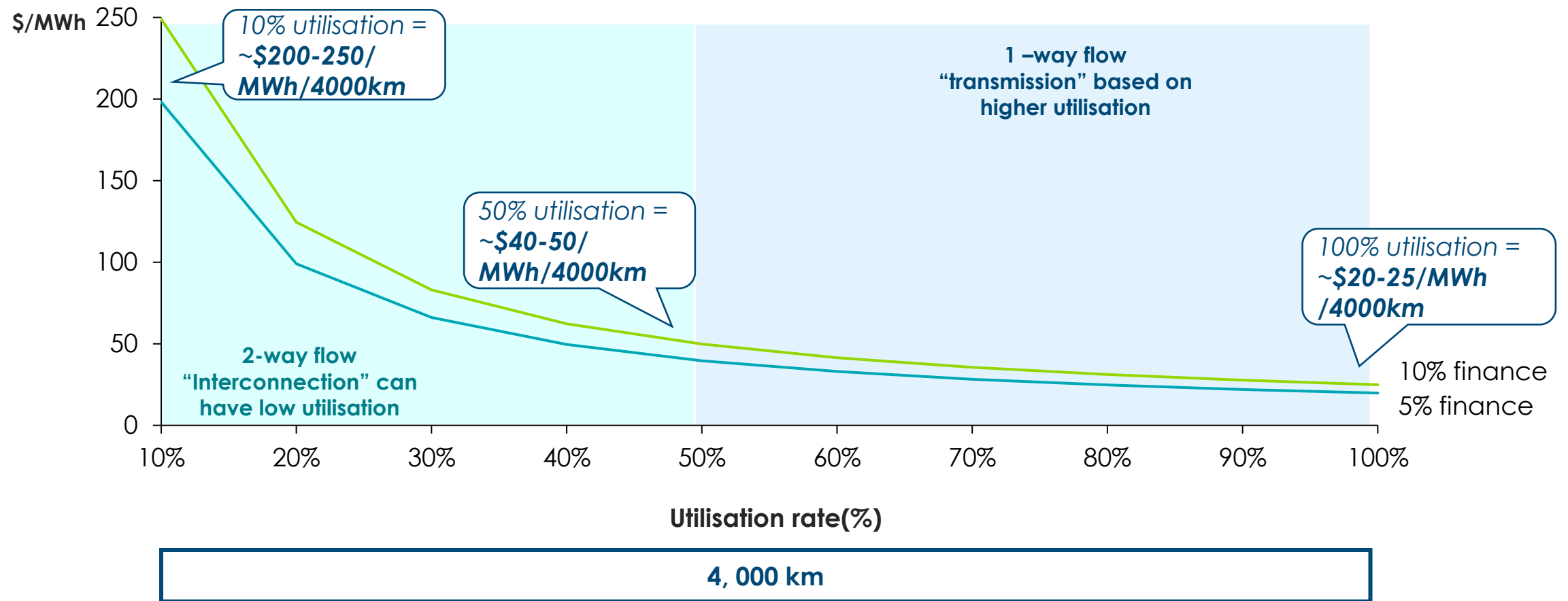
Notes: HVDC converter stations assumed to cost \$1.1bn; Finance assumed to cost X% per annum with 100% of project cost to be paid back over 10 years. Source: BNEF (2024) GridVal 1.0; ETC calculations based on stakeholder engagements.

Subsea example: utilisation rates have significant impacts on project economics

Costs per MWh per 4000km of subsea lines

Illustrative projects: 2024, 2 GW, 525kV, \$/MWh/4000km

Utilisation rate

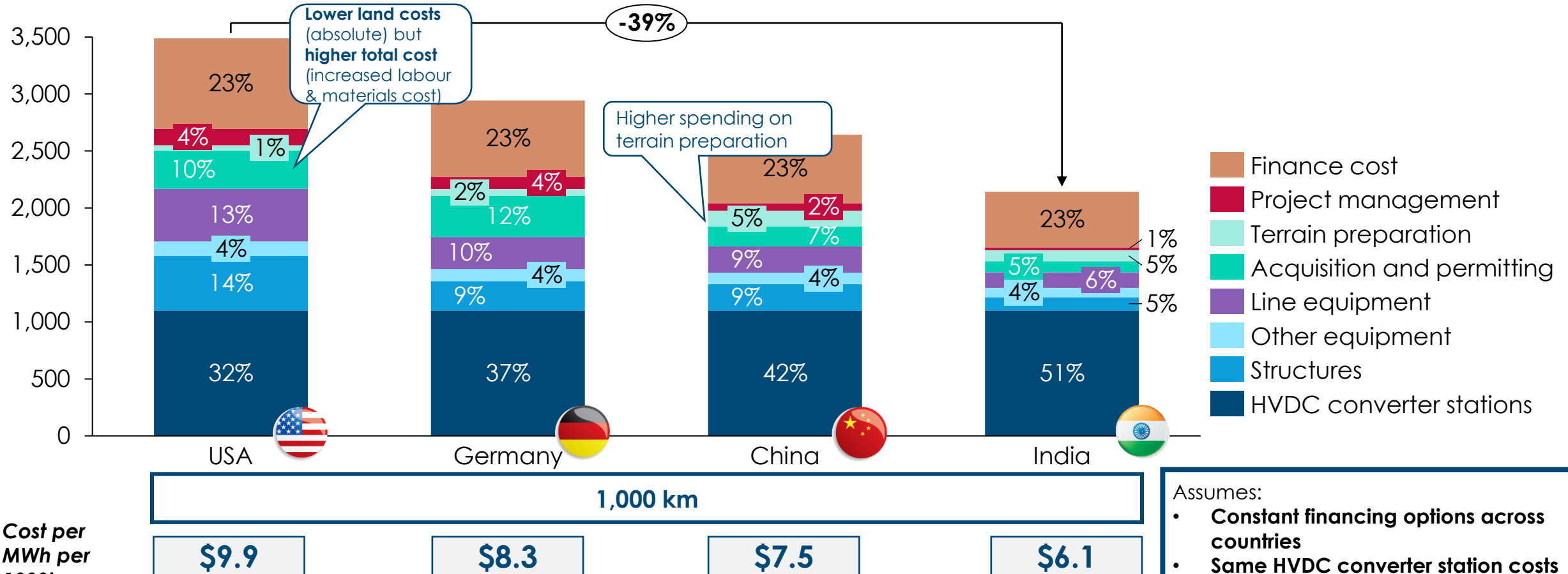


Notes: HVDC converter stations assumed to cost \$1.1bn; Finance assumed to cost 5/10% per annum with 100% of project cost to be paid back over 10 years; lifetime of cable assumed to be 50 years, with MWhs discounted at a rate of 3.5% per annum starting from the first year of generation. Source: BNEF (2024) GridVal 1.0; ETC calculations based on stakeholder engagements.

Regional variation: costs vary substantially across countries; 1,000 km lines 40% cheaper in India vs USA

Cost breakdown of a HVDC power line

Illustrative project: 1000km, 2024, 2 GW, 400kV, 85% utilisation rate, Aerial line, USD



Assumes:

- Constant financing options across countries
- Same HVDC converter station costs

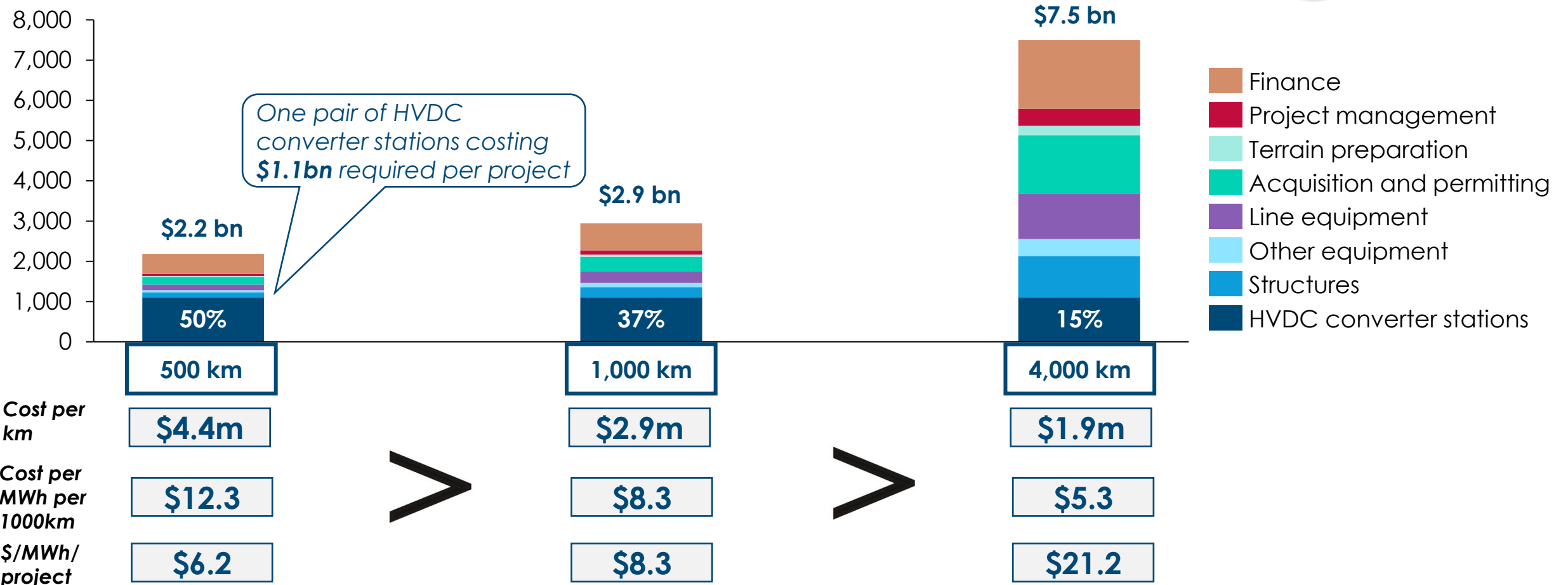
Cost per MWh per 1000km

Notes: Project management, Terrain preparation, Acquisition and permitting, Line equipment, Other equipment, Structures come from BNEF GridVal model. HVDC converter stations assumed to cost \$1.1bn; Finance assumed to cost 5% per annum with 100% of project cost to be paid back over 10 years. New England values used for USA; lifetime of cable assumed to be 50 years, with MWhs discounted at a rate of 3.5% per annum starting from the first year of generation; 85% utilisation rate equivalent to 2GW power being sent 7450 hours of the year. Source: BNEF (2024) GridVal 1.0; ETC calculations based on stakeholder engagements.

Costs vary by distance: cost per km cheaper over longer distances due to fixed costs for converter stations

Cost breakdown of a HVDC power line

Illustrative project: Germany, 2024, 2 GW, 400kV, 85% utilisation rate Aerial line, USD



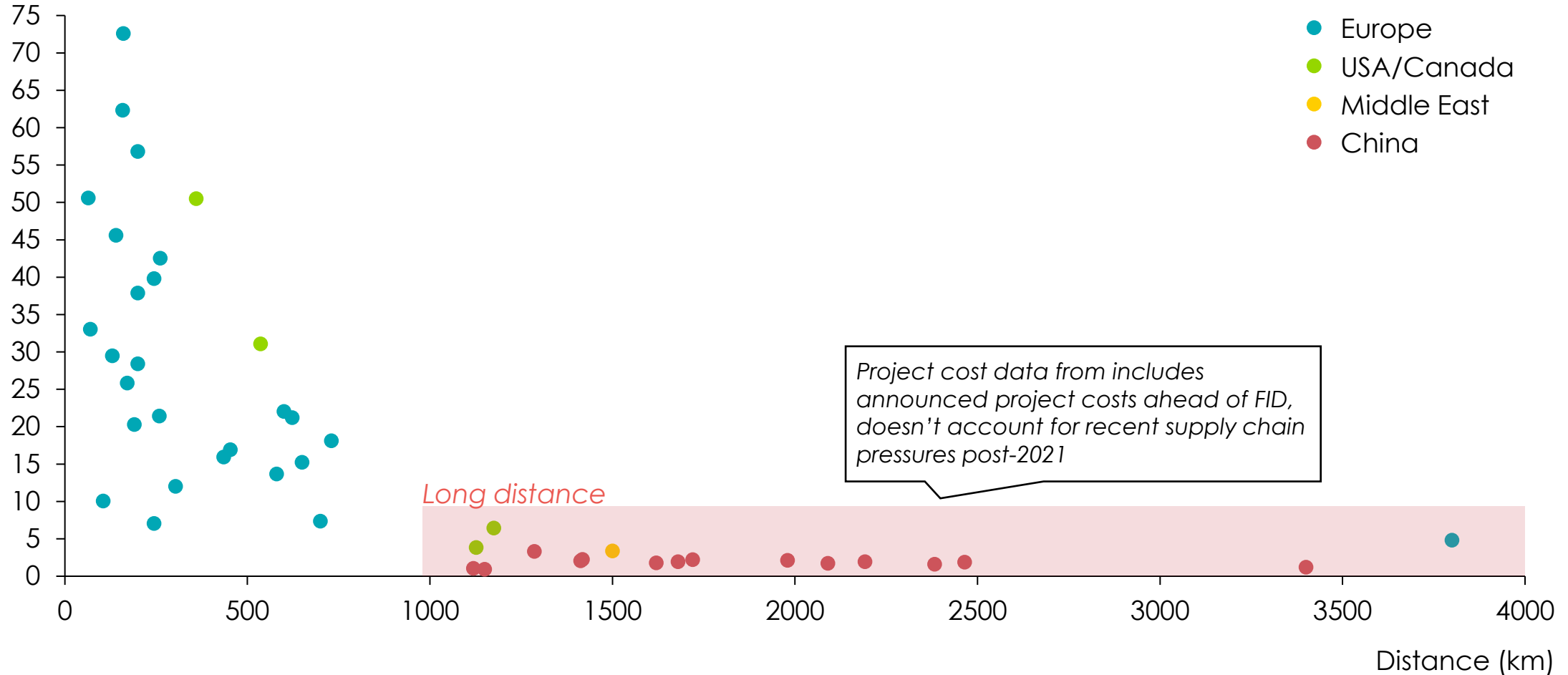
Notes: Project management, Terrain preparation, Acquisition and permitting, Line equipment, Other equipment, Structures come from BNEF GridVal model. HVDC converter stations assumed to cost \$1.1bn; Finance assumed to cost 5% per annum with 100% of project cost to be paid back over 10 years. Lifetime of cable assumed to be 50 years, with MWhs discounted at a rate of 3.5% per annum starting from the first year of generation; 85% utilisation rate equivalent to 2GW power being sent 7450 hours of the year. Source: BNEF (2024) GridVal 1.0; ETC calculations based on stakeholder engagements.



Project data from 2005-2016 shows correlation between longer distance and lower HVDC cost

HVDC Capex cost of electricity transport (projects from 2005-2016)

\$/ (MWh*1000 km), excludes finance costs

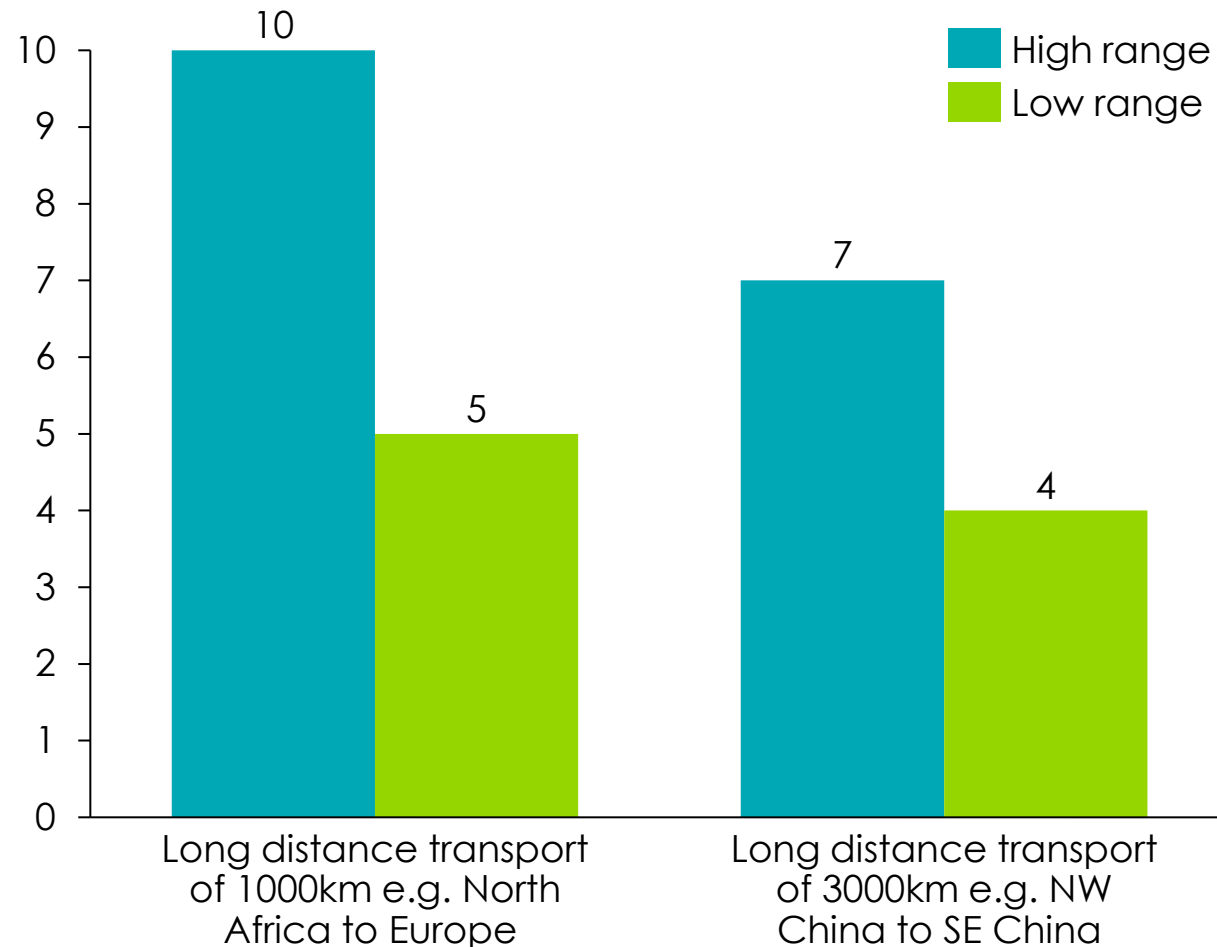


Notes: Excludes financing costs. Converter station costs included. Data is primarily from BNEF project database from 2016; represents data from all HVDC and UHVDC projects since 2005 (across all project stages, e.g. announced, commissioned, and permitted) evaluated with known project cost and length, assuming 50% utilisation, and project lifetime of 30 years. Source: Industry interviews, BloombergNEF (2016), Global HVDC and interconnector database and overview

Project costs are within the range previously highlighted in ETC's 2021 report

All-in-indicative cost of HVDC electricity transmission across distances

\$/ (MWh*1000km)



Lower cost range:

Indicative costs for China, where multiple long distance and very high capacity (8GW) lines are being installed, with economies of scale from transmission line build out, as well as faster permitting processes, and lower land acquisition and installation costs

Higher cost range:

Indicative costs for Europe, where both distance and capacities tend to be lower (6GW) and where fewer long distance HVDC lines are being installed. Therefore, economies of scale typically lower, in addition to lengthier permitting processes, higher land acquisition and installation costs

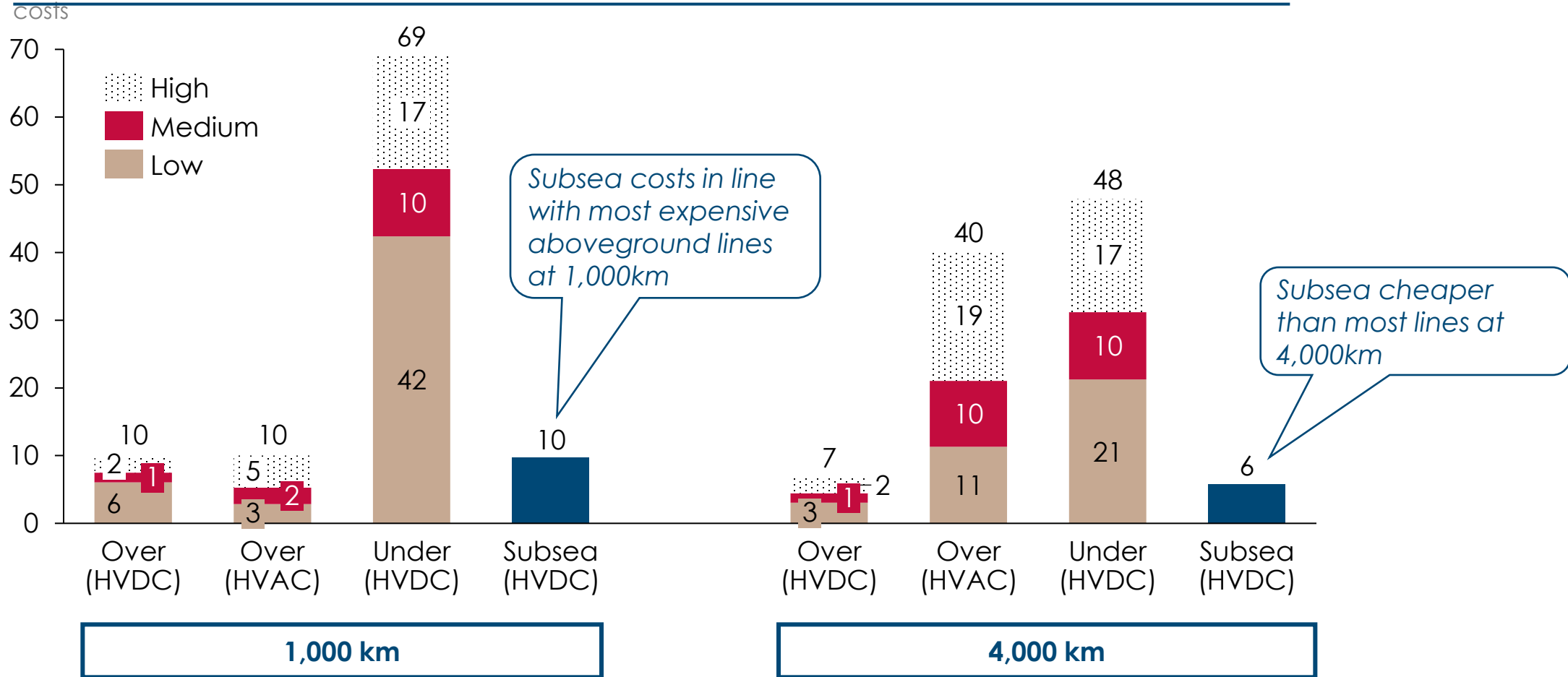
Source: Industry interviews, BNEF (2016), Global HVDC and Interconnector database and overview

Note: Excludes financing costs. Data is primarily from BNEF project database from 2016; represents data from all HVDC and UHVDC projects since 2005. Financing costs assumed to be approximately 100% of Capex. For China, assumed c. 8GW capacity, for Europe/US x. 6GW capacity.

Summary view: over long distances, subsea cables competitive vs other options

Costs per MWh per 1000km of various types of line

Illustrative projects: India, China, US, 2024, 2 GW, 400/525kV, 85% utilisation rate, \$/MWh/1000km, including finance



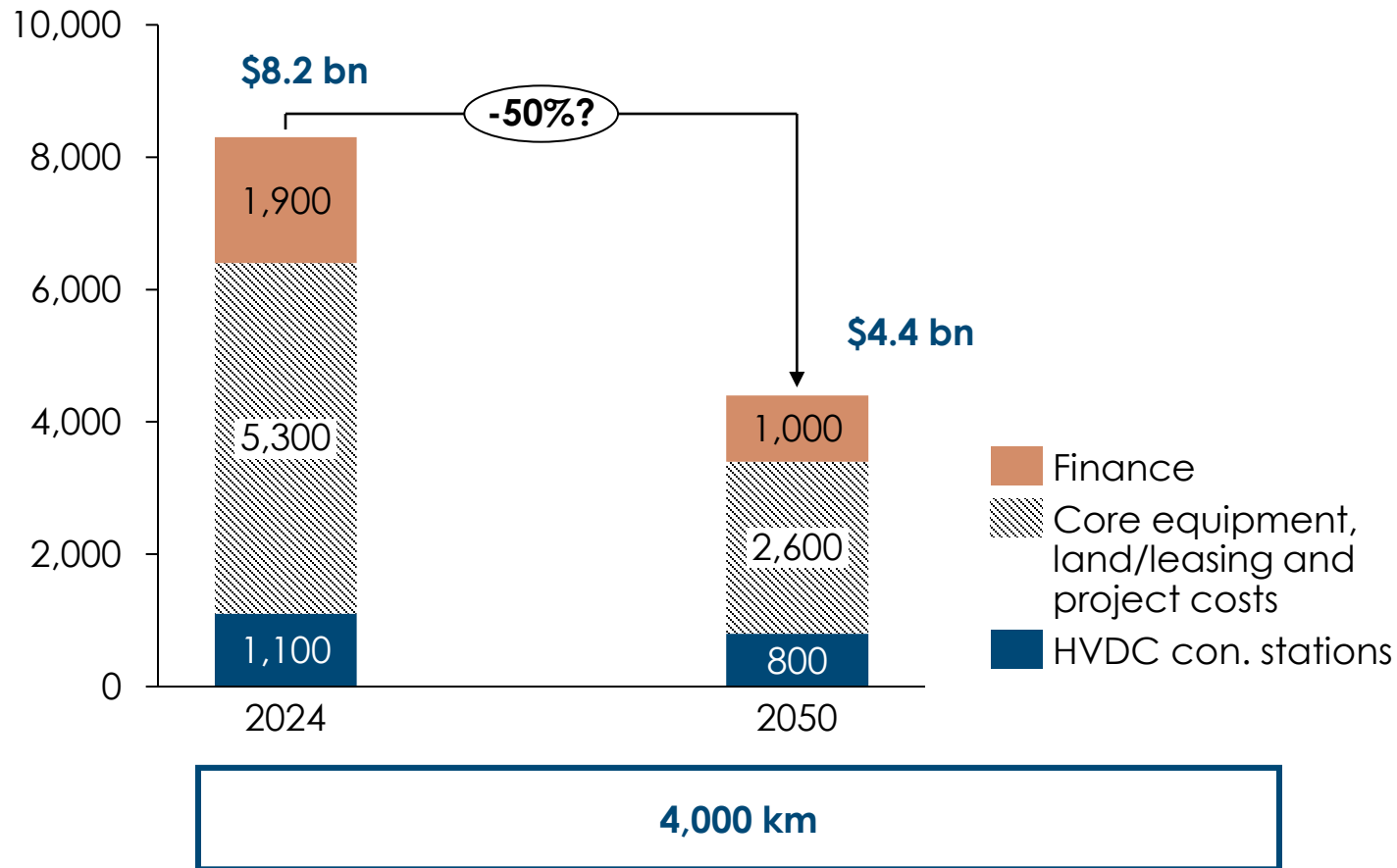
Notes: Low/Medium/High examples taken from India/China/US New England. Underground costs = aboveground costs multiplied by 7. Subsea costs estimated. Project management, Terrain preparation, Acquisition and permitting, Line equipment, Other equipment, Structures come from BNEF GridVal model. HVDC converter stations assumed to cost \$1.1bn; Finance assumed to cost 5% per annum with 100% of project cost to be paid back over 10 years. Lifetime of cable assumed to be 50 years, with MWhs discounted at a rate of 3.5% per annum starting from the first year of generation; 85% utilisation rate equivalent to 2GW power being sent 7450 hours of the year. Source: BNEF (2024) GridVal 1.0; ETC calculations based on stakeholder engagements.



There may be potential for HVDC costs to decline in price on route to 2050 however competing forces could drive prices up or down

Cost breakdown of a subsea HVDC power line

Illustrative project: 2024, 2 GW, 525 to 640kV, 85% utilisation rate subsea line, USD



Prices could come down...

As supply expands, and cables increase in voltage, room for costs to decline in the long-term (i.e. if market tightness relents post ~2035):

- **Converter stations – 20-30%** – costs for components much lower than current costs due to current high demand & low supply
- **Cables – 50/60%** – high demand and raw material costs cause price pressure, however global capacity being expanded & higher voltage cables (640 kV+) will send more power for a modest cost increase

Prices could rise...

Alternatively, if new entrants are unable to enter the market, and incumbents are unwilling or unable to expand supply, sustained high demand could lead to higher prices.

Notes: HVDC converter stations initially assumed to cost \$1.1bn; Finance assumed to cost 5% per annum with 100% of project cost to be paid back over 10 years. Assumed decline of 30% in converter stations and 50% in core equipment, land/leasing and project costs. Replacing lead sheath with aluminium and increasing voltage from 525kV to at least 640kV should mean a ~22% increase in power with only a modest change to insulation and outer layers; 85% utilisation rate equivalent to 2GW power being sent 7450 hours of the year. Source: BNEF (2024) GridVal 1.0; ETC calculations based on stakeholder engagements.

**3) High variable
renewable systems: how
can cross border links
optimise generation and
balancing?**



ETC analysis will focus on several key questions



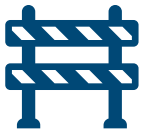
What drives the case for 1-way long distance transmission links in high variable renewable systems?

- Generation
- Balancing



What are the global top cable opportunities in high variable renewable systems?

- Modelling matching demand & supply profiles for each country to outline the locations of top new cables
- Results will demonstrate the most impactful new cables against a range of key criteria (e.g. highest volume, highest cost savings, emissions mitigated, land constraints overcome)
- Final view of the most impactful transmission 'megaprojects'



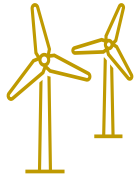
What are some of the key barriers and enablers to cross border links?



Key question: what drives the case for 1-way long distance transmission links in high variable renewable systems?

Primarily for

A



Generation

Can also provide some balancing if generation of country A is significantly uncorrelated to country B

Country A (Export)

Country B (Import)

What determines whether long distance transmission is competitive for generation vs other routes?

Generation (LCOE) + transmission < Generation (LCOE)

Focus of ETC in-depth modelling

B



Balancing

For some balancing needs (e.g. short)

Fully firm (meeting all balancing needs)

1

Generation (LCOE) + transmission

<

Generation (LCOE) + batteries

2

Generation + batteries + transmission

<

Generation + all short/medium/long-duration storage



3A) Generation



Generation: economics depend on difference between LCOEs + transmission

Primarily for

A



Generation

Can also provide some balancing if generation of country A is significantly uncorrelated to country B

Country A (Export)

Country B (Import)

What determines whether long distance transmission is competitive for generation vs other routes?

Generation (LCOE) + transmission < Generation (LCOE)

What determines whether long distance transmission will also be competitive to meet balancing needs vs other balancing routes?

B



Balancing

For some balancing needs (e.g. short)

1

Generation (LCOE) + transmission < Generation (LCOE) + batteries

Fully firm (meeting all balancing needs)

2

Generation + batteries + transmission < Generation + all short/medium/long-duration storage



Context: Globally, easily sufficient wind and solar resources to meet total power generation needs

Over 80,000 TWh of clean power will be needed in 2050.

This could be generated multiple times over with land that is available for solar, onshore and offshore wind.

Solar

13m sq. km of land are suitable for solar, **9%** of the Earth's land area

This is enough to install **900 TW** of solar panels

A 15% efficiency rate this could generate **1,200,000 TWh** per annum

0.5% Earth's total land area for solar could provide 60,000 TWh

Onshore wind

17m sq. km of land are suitable for solar, **11%** of the Earth's land area

This is enough to install **86 TW** of wind turbines

A 40% efficiency rate this could generate **300,000 TWh** per annum

2.2% Earth's total land area for solar could provide 60,000 TWh

Offshore wind

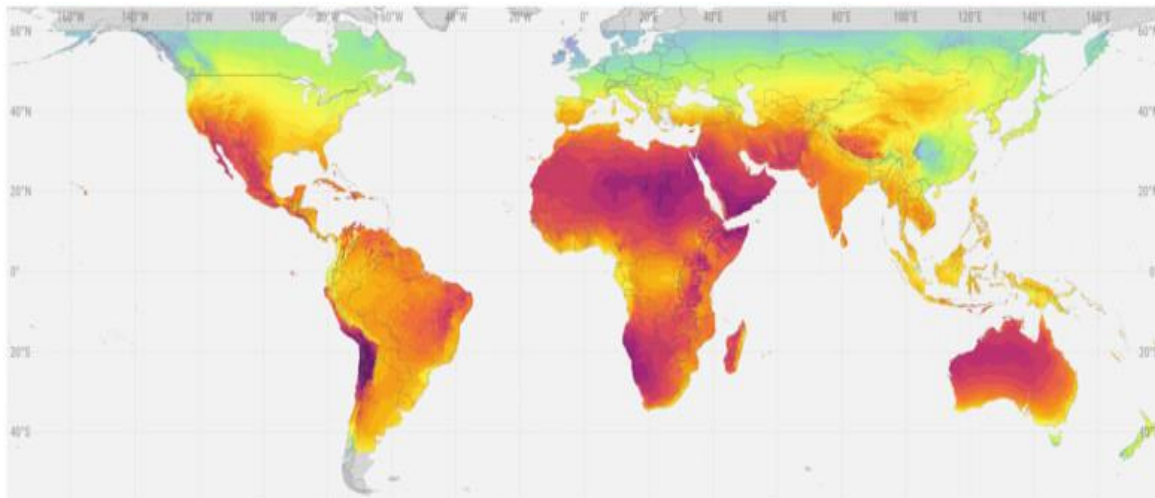
IEA estimates suggest offshore wind resource could generate more than **420,000 TWh** per year.



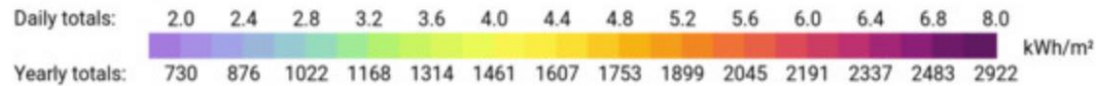
Wind and solar potential varies greatly with high latitude countries reliant on wind, whilst mid latitude countries have vast solar potential

Irradiation varies across the globe

Long-term yearly average of daily and yearly GHI totals

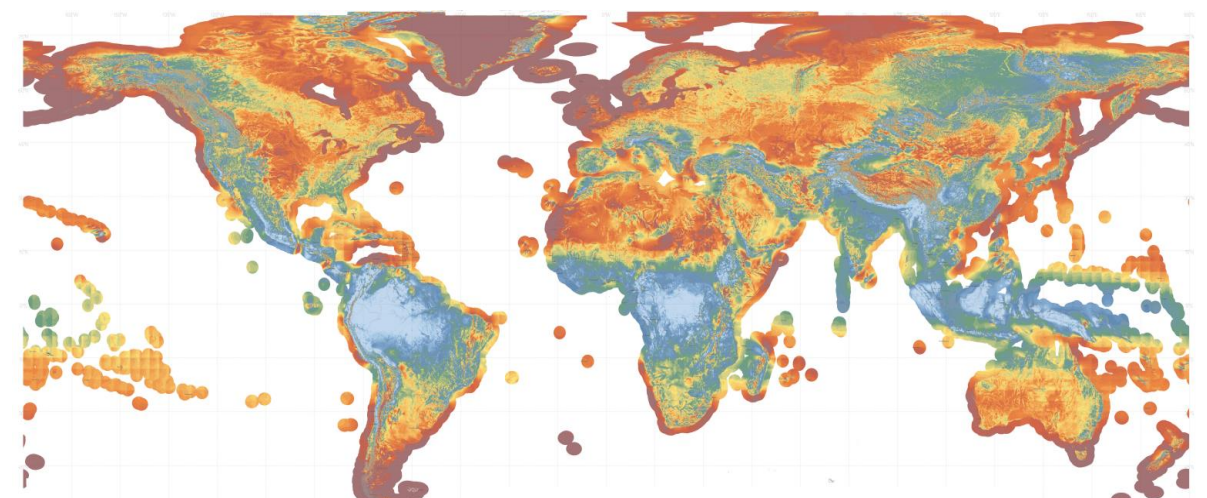


Long-term average of GHI

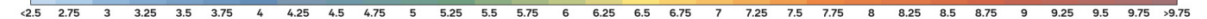


Wind power density also varies substantially

Mean wind power density at 100 m above surface level



Mean Wind Speed @ 100m - [m/s]



Note: GHI = Global Horizontal Irradiation
Source: Global Solar Atlas (2024) *Global Photovoltaic Power Potential by Country*; Global Wind Atlas (2024) *Wind Resource Map*

High population density countries may face local constraints land resources relative to national demand

Singapore



Population density

8,300

people per sq km

Land available

~100 sq km (limited potential for rooftop solar)

Supply and demand

Rooftop solar alone will not come close to meeting demands of entire population of 6 million people's demand of **128 TWh** by 2050

China



150

people per sq km

860,000 sq km and **1,100,000 sq km** available for wind and solar respectively

Wind and solar could generate **100,000 TWh per year**, far surpassing the needs of the 1.4 billion population's demand of **14,000 TWh** by 2050, and leaving plenty of surplus which could be exported

Clearly given these discrepancies interconnection can play a key role in transporting power from countries with surplus clean power to those with deficit

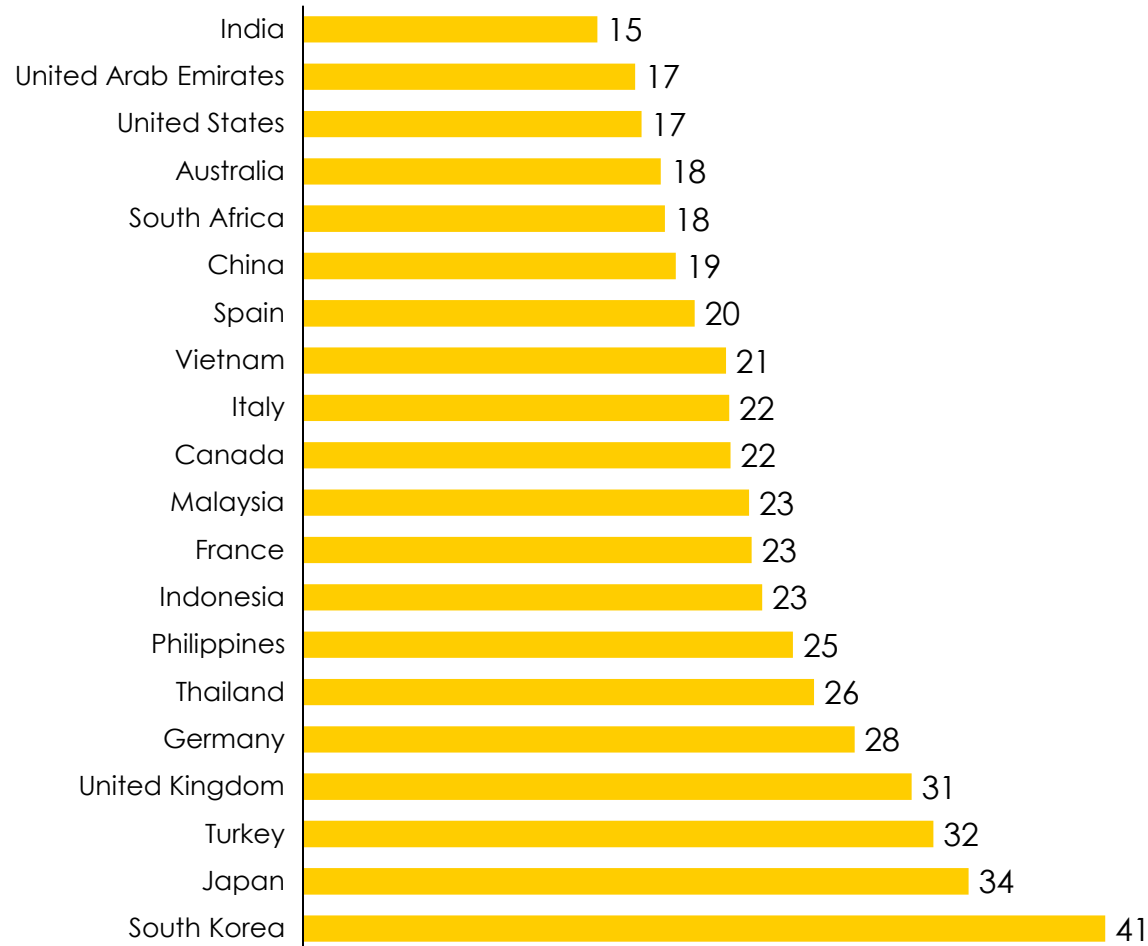


Notes: Assuming 71 MW/sq km for solar, 5 MW/sq km for wind. Assuming capacity factors of 40% for wind and 15% for solar. Source: Systemiq analysis for the ETC; Ember (2024), *Regional grids key to Singapore's energy future*; BENF (2024), *NEO 2024*

There is significant variation in the cost of solar and wind around the world

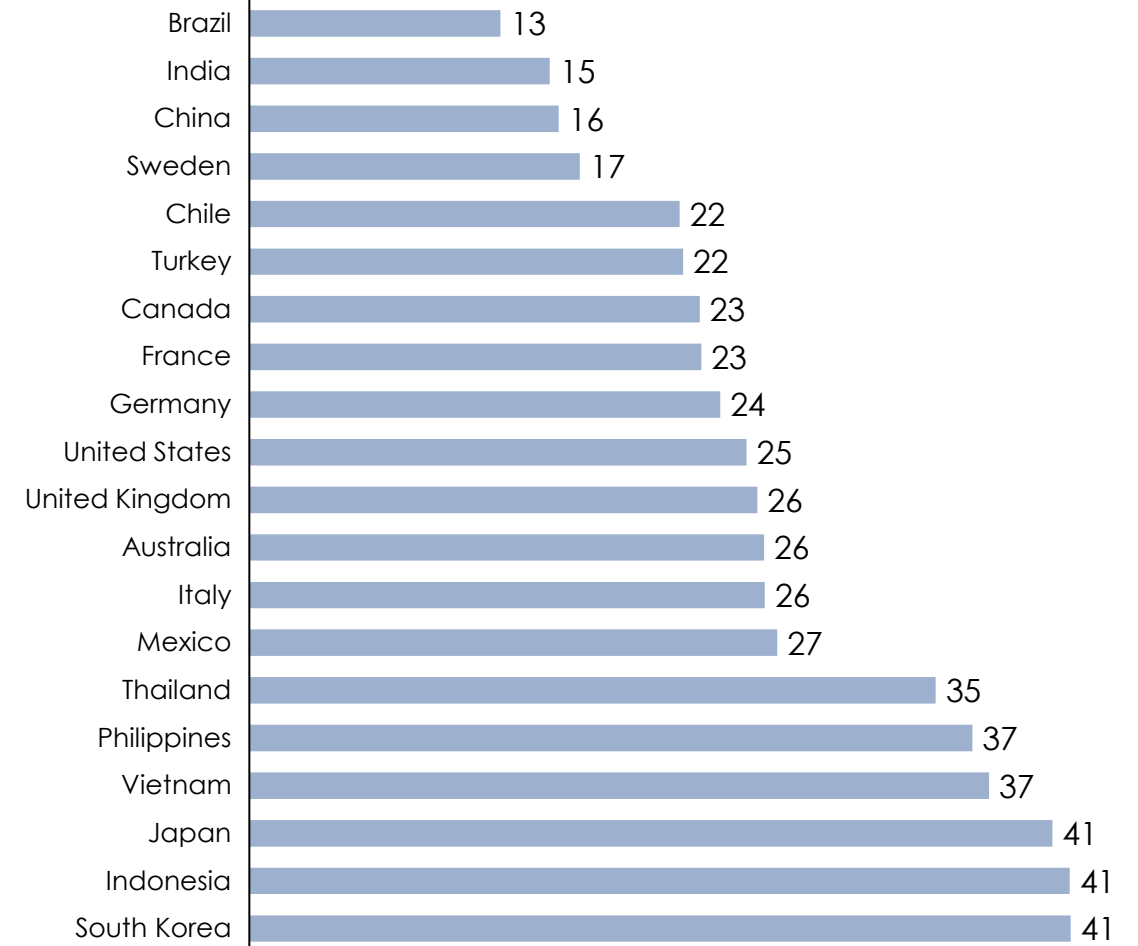
Estimated solar PV LCOE, 2050

\$/MWh



Estimated onshore wind LCOE, 2050

\$/MWh

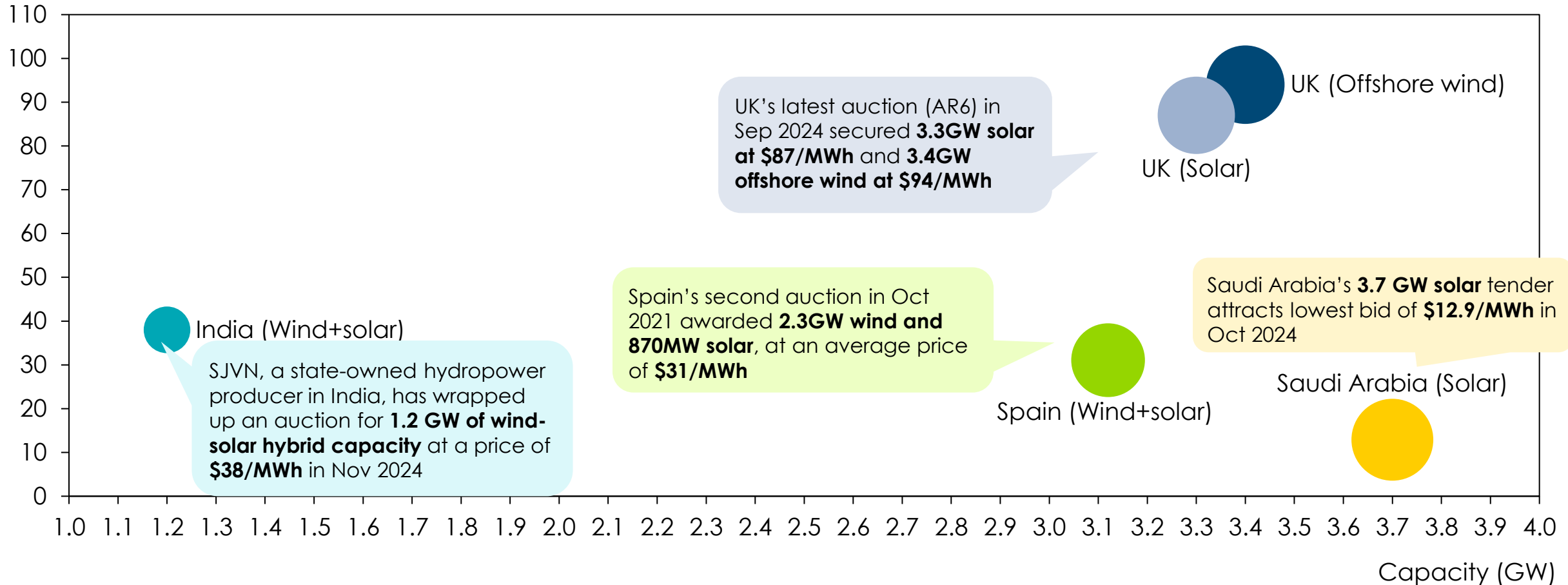


Note: Solar LCOE based on solar PV photovoltaic plants without trackers; both from BNEF mid scenario
Source: BNEF (2023), 1H 2023 LCOE: Data Viewer

Recent auctions show solar price has reached as low as \$12.9/MWh

Realised examples of recent auctions

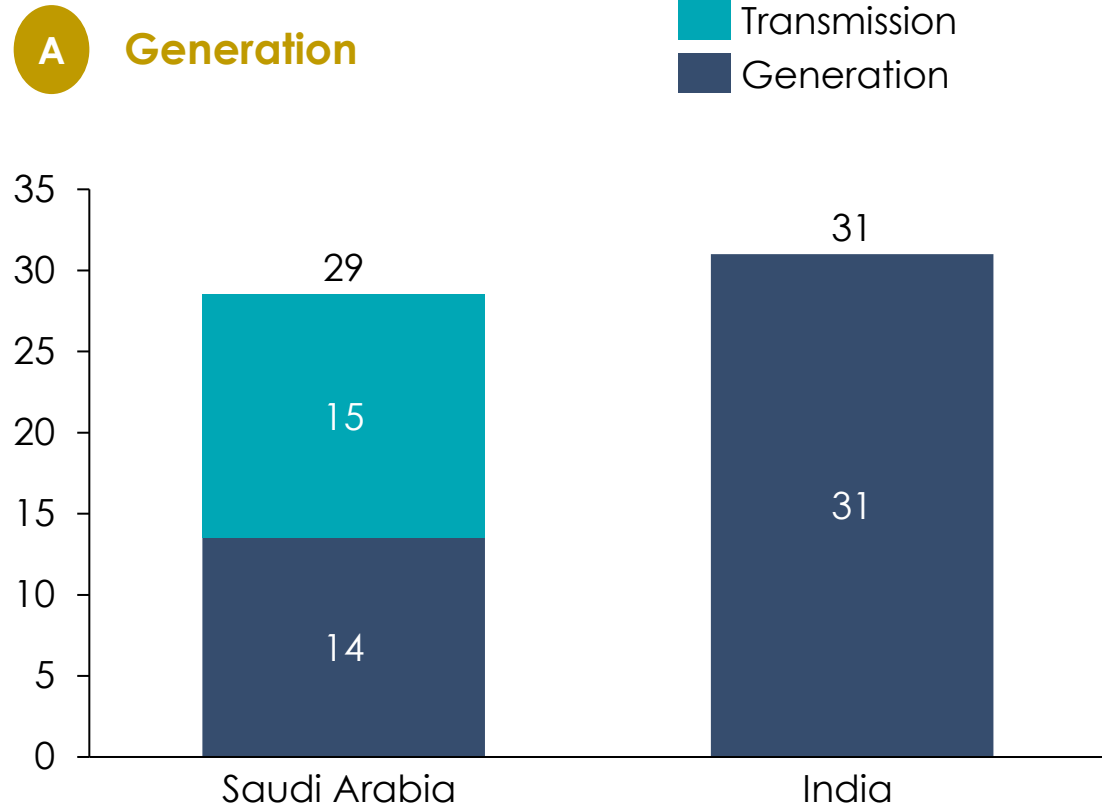
\$/MWh, 2024 nominal prices



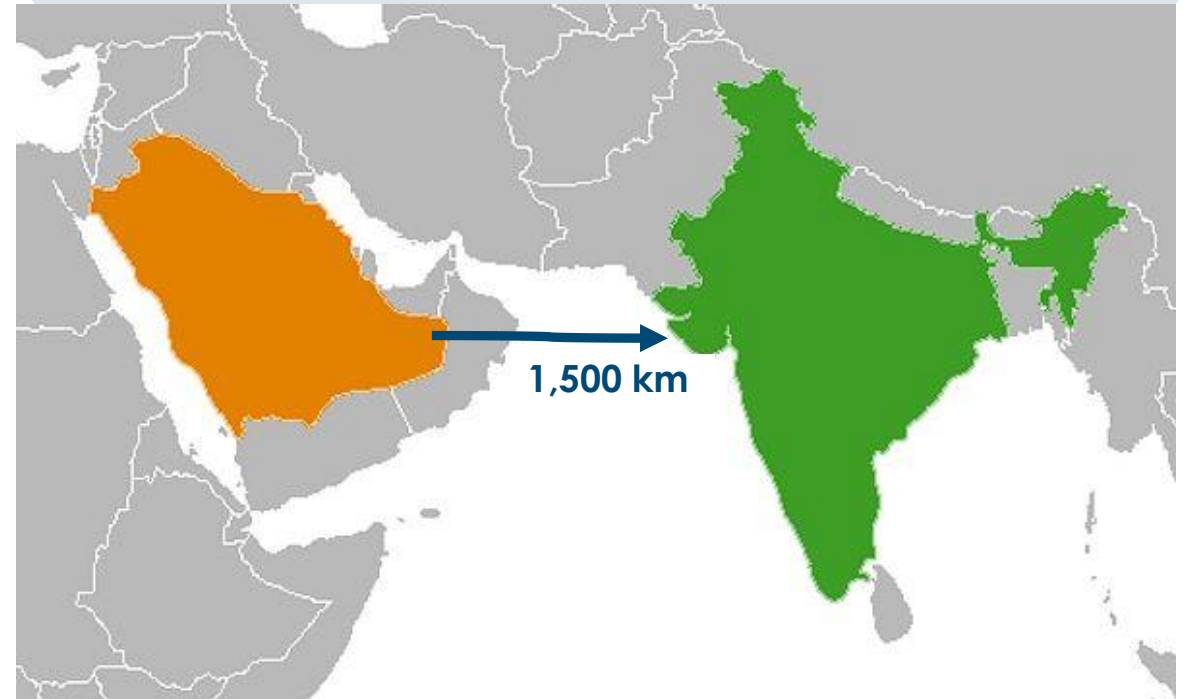
Case study: Saudi Arabia-India link could be competitive with today's generation and transmission prices

Cost of power generation and cross-border transmission, for Saudi Arabia and India

\$/MWh, real 2024 prices, 2024 costs of generation



Key takeaway; Generation + transmission from Saudi Arabia to India could be cost competitive given ultra-low solar prices in Saudi Arabia



Notes: Calculations assume a subsea cable cost of \$9.9/(MWh * 1000km); Saudi Arabia recent solar auction results of \$12.9/MWh amended for 3% losses per 1,000 km over a **1,500 km** stretch to provide generation costs of \$13.5/MWh; Indian 2024 LCOEs of \$31/MWh for solar used for generation. A preliminary study has envisaged a 1,000 km high voltage direct current (HVDC) undersea cable connecting Gujarat in India's West Coast to Oman, which would connect through to Saudi Arabia. Source: Systemiq analysis for ETC; BNEF (2023) 2H 2023 LCOE: Data Viewer Tool.



Case study: Australia-Singapore could be competitive

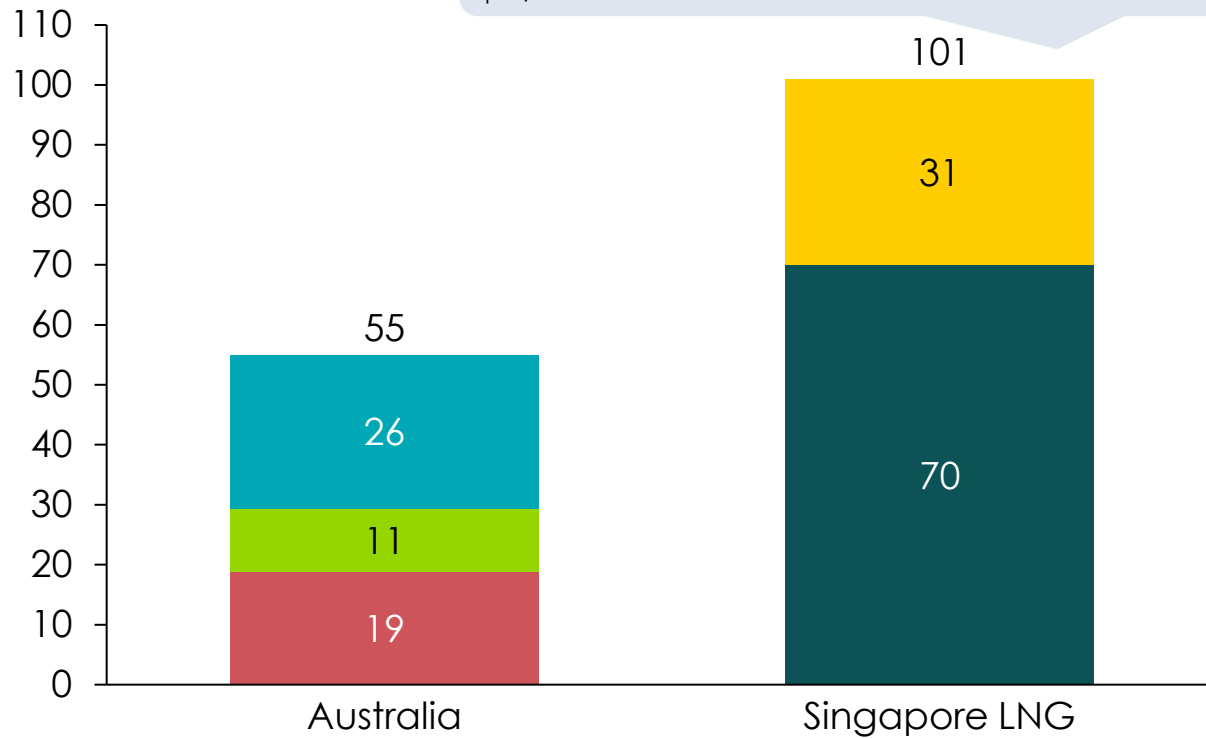
Cost of power generation, cross-border transmission, battery storage and LNG for Australia and Singapore

\$/MWh, real 2022 prices, 2050 LCOEs

- Transmission
- LNG
- Batteries
- Clean Generation
- Carbon Price

A Generation

Equivalent to \$14.4/MMBtu. Includes a carbon cost of \$30.8/MWh due to Singaporean carbon price of \$80/tCO₂e from 2030 onwards



Key takeaway; transmission to Singapore from Australia is \$46/MWh more cost competitive than LNG generation in Singapore in 2050



Source: Systemiq analysis for ETC; BNEF (2023) 2H 2023 LCOE: Data Viewer Tool. Note: Transmission calculations vary based on an assumed utilization rate of 1) 50% for lines without batteries and 2) 85% for lines featuring batteries. As a result, the former is more costly at \$9.9/(MWh * 1000km) and the latter less at \$5.83/(MWh * 1000km). LCOE calculations assume an 100% PV outlook for power generation in Australia in 2050, compared with an LNG price in Singapore that includes a carbon price of \$80/tCO₂e that will be implemented by government from 2030 onwards



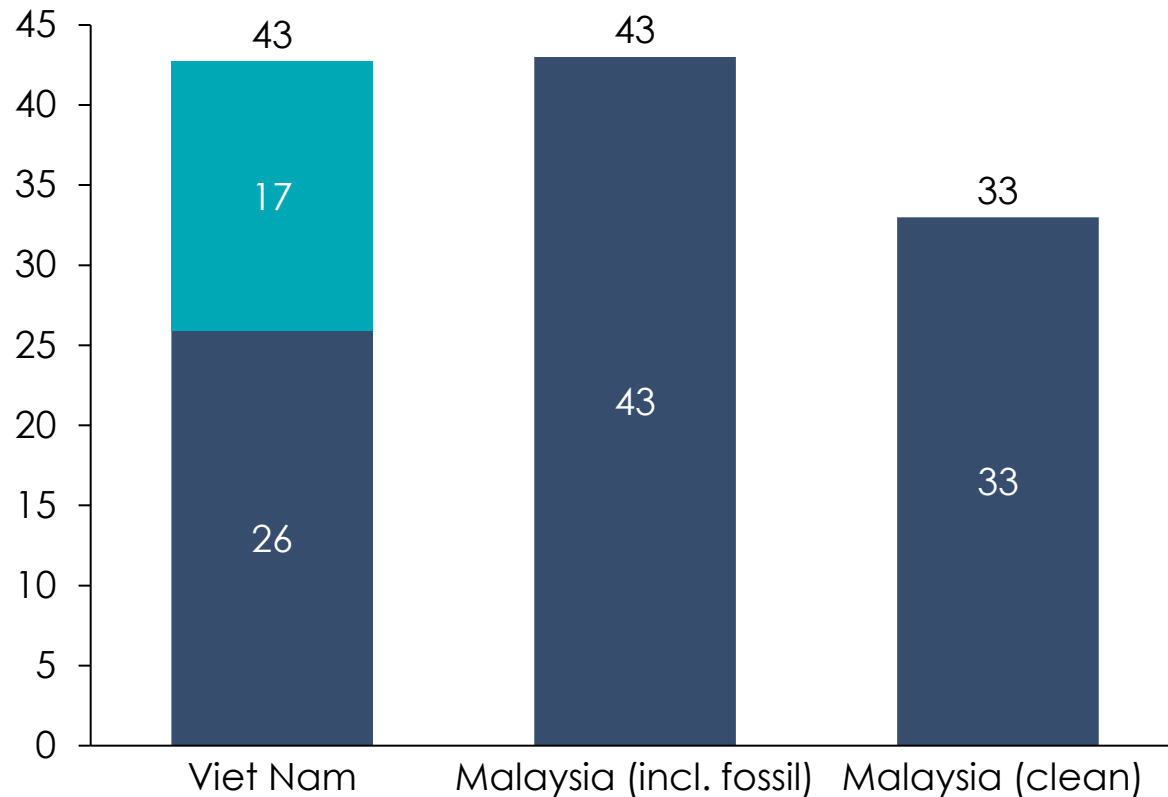
Case study: Vietnam-Malaysia link not competitive

Cost of power generation, cross-border transmission and battery storage for Viet Nam and Malaysia

\$/MWh, real 2022 prices, 2050 LCOEs

Transmission Generation

A Generation



Key takeaway: cost-competitiveness of the project limited by high transmission costs, particularly if Malaysia achieves a clean energy system by 2050



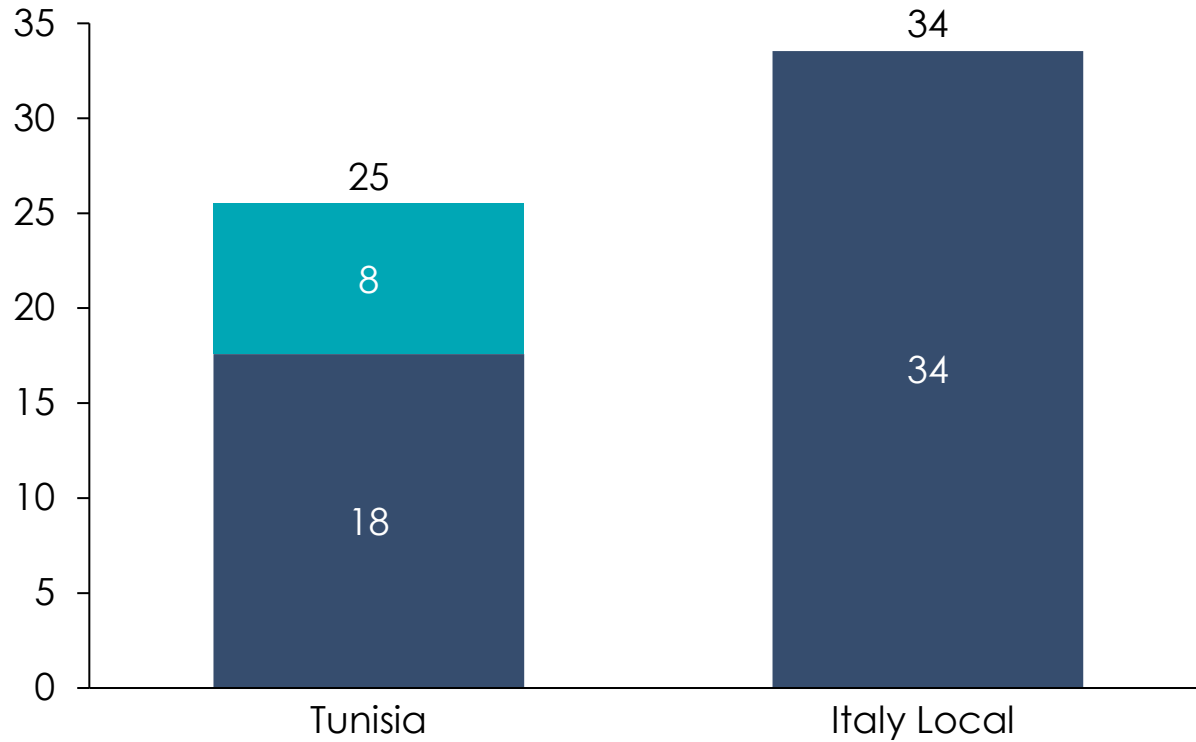
Source: Systemiq analysis for ETC; BNEF (2023) 2H 2023 LCOE: Data Viewer Tool. Note: Transmission calculations vary based on an assumed utilization rate of 1) 50% for lines without batteries and 2) 85% for lines featuring batteries. As a result, the former is more costly at \$9.9/(MWh * 1000km) and the latter less at \$5.83/(MWh * 1000km). LCOE calculations assume 1) 50% solar PV and 35% onshore wind mix in Vietnam in 2050 2) 60% solar PV, 10% Hydropower and 30% fossil fuel outlook for Malaysia in 2050.

Case study: Tunisia-Italy link could be competitive

Cost of power generation, cross-border transmission and battery storage for Tunisia and Italy

\$/MWh, real 2022 prices, 2050 LCOEs

A Generation



Key takeaway; due to Tunisia's excess solar power, and the short transmission distance, this case study shows a cost-effective link

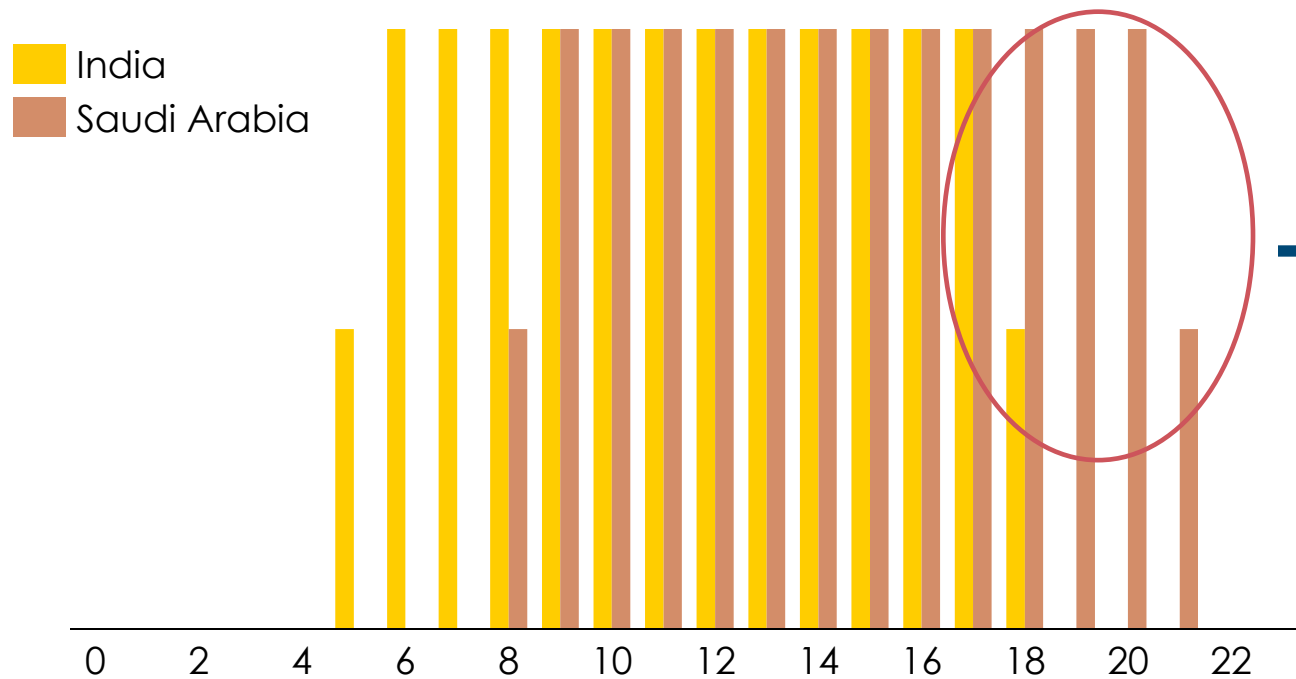


Source: Systemiq analysis for ETC; BNEF (2023) 2H 2023 LCOE: Data Viewer Tool. Note: Transmission calculations vary based on an assumed utilization rate of 1) 50% for lines without batteries and 2) 85% for lines featuring batteries. As a result, the former is more costly at \$9.9/(MWh * 1000km) and the latter less at \$5.83/(MWh * 1000km). LCOE calculations assume 1) 35% onshore wind and 65% PV outlook for Tunisia and 2) 15% offshore wind, 30% onshore wind and 55% PV for Italy.

Some 1-way long-distance transmission links will be able to meet specific demand needs of “import” countries

Hours of sunlight complementarity between India and Saudi Arabia

Sunrise and sunset for month of May (Indian Standard Time)



Saudi solar can help to provide cheap clean power when the sun has already set in India




- **The sun rises over India 2.5 hours before it does in Saudi Arabia**, when solar panels can start to generate.
- Whilst there is not much demand for power in Saudi at this time (as most citizens are asleep), when the sun sets in India there is still solar power available in Saudi for another 2.5 hours.



3B) Balancing



Reminder: there are a set of balancing options across durations

			System operation	Short duration	Medium duration	Long duration
Dispatchable generation 	Other zero carbon	Hydro, nuclear ¹	✓	✓	✓	✓
	Fossil	Fossil (or bioenergy) + CCS	✓	✓	✓	✓
		Fossil – low/very low utilisation	✓	✓	✓	✓
Cross border transmission 		Accessing complementary weather patterns and time shifting generation	✓	✓	✓	✓
Energy storage 		Pumped hydro	✓	✓	✓	✓
		Lithium ion battery ²	✓	✓	✓	✓
		Other technology (i.e. CAES, liquid air, etc.) ³	✓	✓	✓	✓
		Power-to-X (i.e. H ₂) ⁴	✓	✓	✓	✓
Heat storage		Heat battery		✓		
Demand side flexibility 		EV (smart charging, V2G)		✓		
		Heating load ⁵		✓		
		Industrial load ⁶		✓	✓	

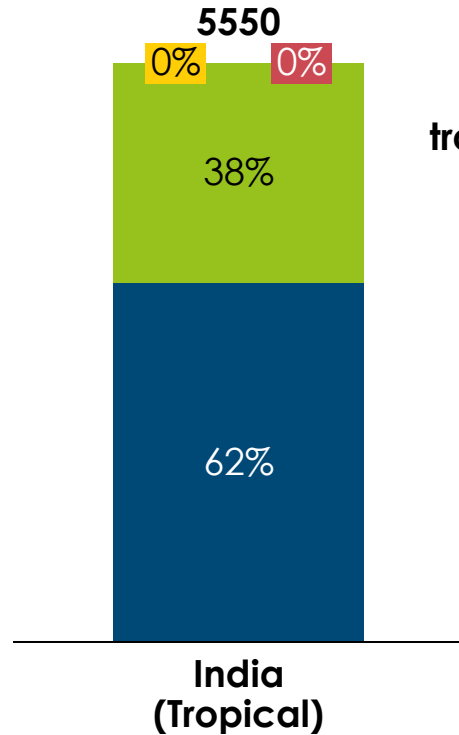
Notes: 1. Limited nuclear capacity for flexible ramping. 2. Li-ion storage is utility-scale and behind-the-meter. 3. Emerging tech might include gravitational storage and molten sands storage. 4. Examples of Power-to-X include the production of H₂ from electrolysis and re-conversion of hydrogen in power via gas turbines or fuel cells. 5. Residential and commercial standard heating needs. 6. Including hydrogen electrolysis, where production can be shifted to optimal times. Source: Adapted from Climate policy Initiative for the Energy Transitions Commission (2017), *Low-cost, low-carbon power systems*

Reminder: balancing needs vary for Tropical & Northern Latitude archetypes

Balancing variability for India and UK in a 100% wind and solar system

% of TWh of annual demand provided by specified generation/storage

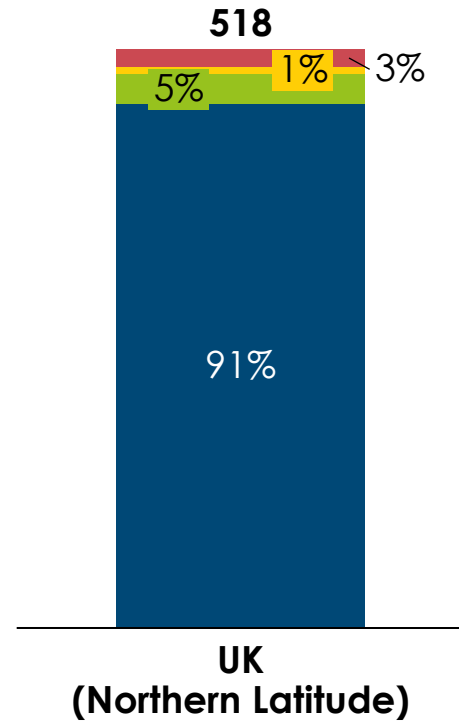
- Long storage
- Medium storage
- Short storage
- Wind and solar



Cross border transmission could meet some short storage needs

Primarily a diurnal challenge

1560



Cross border transmission could meet multiple different storage needs

Balancing required across short, medium and long durations

229

TWh surplus (minimum weather year)




Source: Systemiq analysis for the ETC (2024)

Cross border transmission could potentially contribute to all balancing needs

System operation	Short duration	Medium duration	Long duration
✓	✓	✓	✓
<ul style="list-style-type: none"> • Cross border power line itself doesn't have any drawbacks; could ramp very fast to adjust for immediate demand/supply needs i.e. over 100 MW/min (in line with gas peaker plants) • Key issue is availability of the generation from exporting country, as well as system operators permitting high ramp rates (i.e. 100MW/min allowed in UK, and only 30MW/min allowed in Nordics) 	<ul style="list-style-type: none"> • Could provide balancing need if: <ul style="list-style-type: none"> • Using non-correlated weather and demand patterns to provide electricity at grid optimal times • Using storage in addition to non-correlated weather and demand patterns to provide electricity at grid optimal times 	<ul style="list-style-type: none"> • Could provide balancing need if: <ul style="list-style-type: none"> • Using storage in addition to non-correlated weather and demand patterns to provide electricity at grid optimal times 	

Cross border transmission



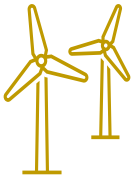
Notes: A dedicated 'islanded' connection provides substantial system operation benefits, as it provides power only to the host grid; the Xlinks project is expected to provide 80% of nameplate capacity, enabling cost effective ramping up and down to help with ancillary services of voltage support, frequency regulation and black start assistance as needed; especially true of newer Voltage Source Converter lines. Source: Systemiq analysis for the ETC (2024); conversations with National Grid and Xlinks experts.



Balancing: economics depends on import option stacking up vs local balancing options

Primarily for

A



Generation

Can also provide some balancing if generation of country A is significantly uncorrelated to country B

Country A (Export)

Country B (Import)

What determines whether long distance transmission is competitive for generation vs other routes?

Generation (LCOE) + transmission < Generation (LCOE)

What determines whether long distance transmission will also be competitive to meet balancing needs vs other balancing routes?

B



Balancing

For **some balancing needs** (e.g. short)

1

Generation (LCOE) + transmission < Generation (LCOE) + batteries

Fully firm (meeting all balancing needs)

2

Generation + batteries + transmission < Generation + all short/medium/long-duration storage



Case study: Morocco-UK

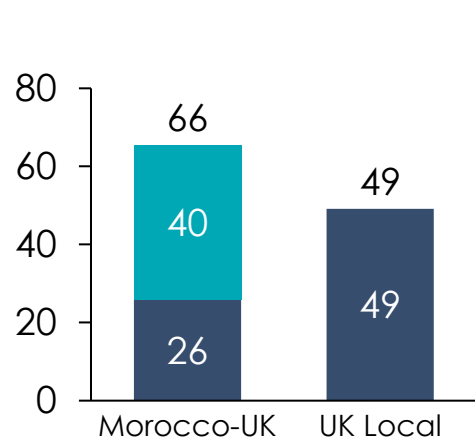
Cost of power generation, cross-border transmission, battery storage and all duration storage for Morocco and UK

\$/MWh, real 2022 prices, 2050 LCOEs

■ Transmission ■ All Storage
■ Batteries ■ Generation

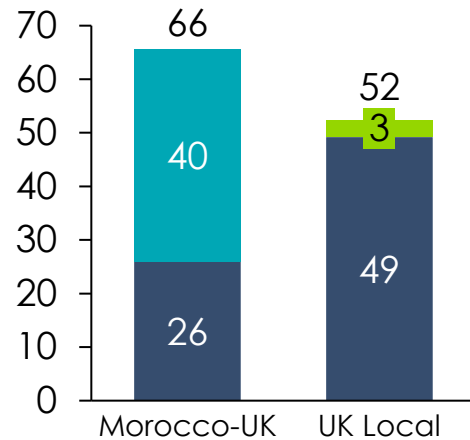
Key takeaway; the cost-competitiveness makes cross-border transmission attractive when including batteries, could be **one** of **multiple** strategies employed in the UK's balancing agenda

A Generation



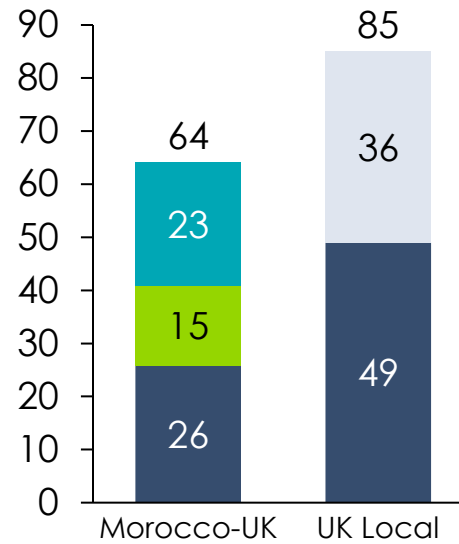
Case A is uncompetitive due to relatively high transmission costs, assuming a 50% utilisation rate

B 1 Balancing

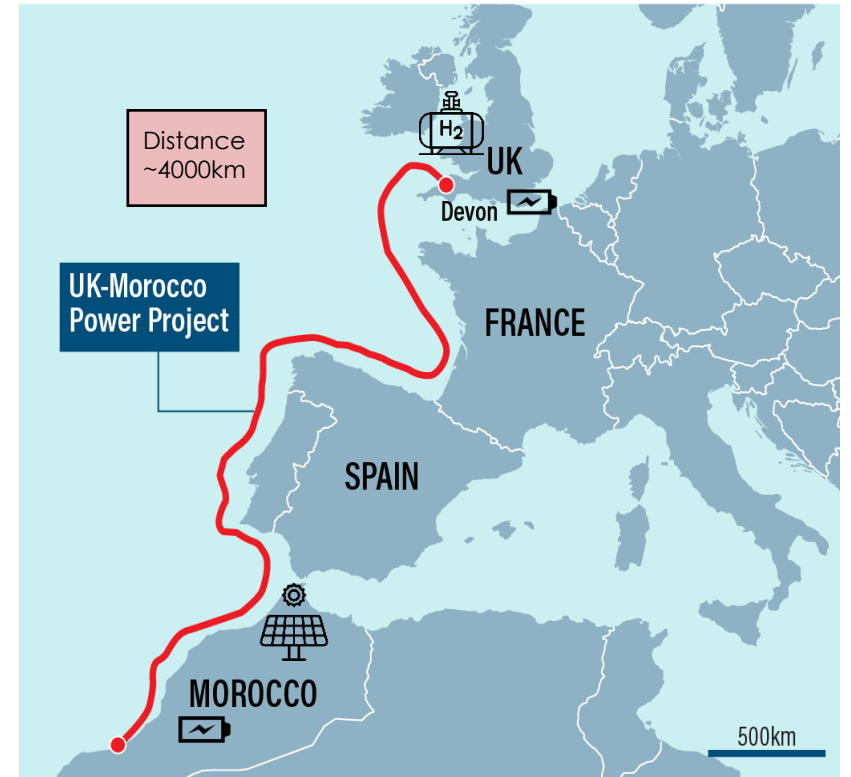


Case B1 is uncompetitive vs local UK short duration balancing

B 2 Balancing



Case B2 shows that the cross-border link is close to competitive to provide longer duration balancing



Source: Systemiq analysis for ETC; BNEF (2023) 2H 2023 LCOE: Data Viewer Tool. Note: Transmission calculations vary based on an assumed utilization rate of 1) 50% for lines without batteries and 2) 85% for lines featuring batteries. As a result, the former is more costly at \$9.9/(MWh * 1000km) and the latter less at \$5.83/(MWh * 1000km). For LCOEs, we assume 100% clean generation, with an energy mix of 5% offshore wind, 30% onshore wind and 65% solar PV for Morocco in 2050, and 100% offshore wind for the UK. In our LCOS calculation for all storage, we assume long duration storage (LDES) forecasts for the UK include a 2050 split between LDES technologies including lithium-ion batteries, flow batteries, pumped hydro, thermal and hydrogen.



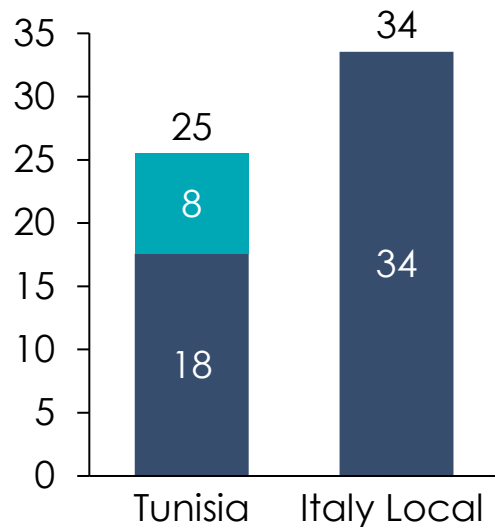
Case study: Tunisia-Italy

Cost of power generation, cross-border transmission, battery storage and all duration storage for Tunisia and Italy

\$/MWh, real 2022 prices, 2050 LCOEs

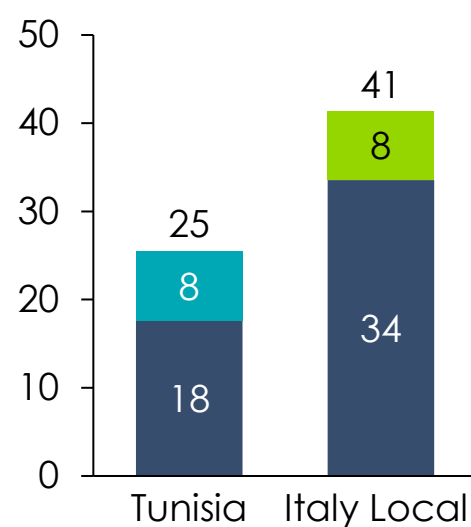
■ Transmission ■ All Storage
■ Batteries ■ Clean Generation

A Generation



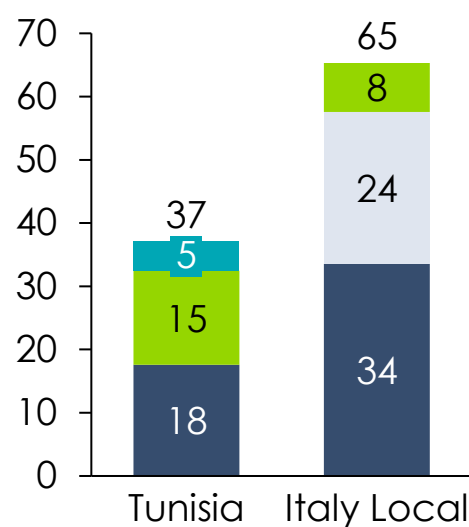
Tunisia-Italy cross-border transmission could be cost competitive

B 1 Balancing



Tunisia-Italy cross-border transmission could be cost competitive vs local Italy generation plus battery energy storage (short duration balancing)

B 2 Balancing



Tunisia-Italy cross-border transmission could also be more cost competitive than local Italy generation plus all duration storage

Key takeaway; due to Tunisia's excess solar power, and the short transmission distance, this case study remains cost effective across all examples



Source: Systemiq analysis for ETC; BNEF (2023) 2H 2023 LCOE: Data Viewer Tool. Note: Transmission calculations vary based on an assumed utilization rate of 1) 50% for lines without batteries and 2) 85% for lines featuring batteries. As a result, the former is more costly at \$9.9/(MWh * 1000km) and the latter less at \$5.83/(MWh * 1000km). LCOS calculations include variables that differ by market on the basis that balancing requirements across different markets vary, with a higher short duration requirement in tropical regions than the northern hemisphere. Long duration storage (LDES) forecast for Italy includes a 2050 split between LDES technologies including lithium-ion batteries, flow batteries, pumped hydro, thermal and hydrogen with a stronger weighting towards a longer-duration market split due to the balancing requirements between North-South.



A note on 2-way flow “interconnection” and balancing

- This analysis has primarily focused on the role of **1 –way flow “Long distance transmission”, including with additional storage** to provide balancing needs in the import market, as part of the continuous one-way flow.
- However, as noted earlier, **“2 way flow interconnection”** over short and long distances can also provide balancing function, likely operating at lower utilisation given there wouldn't be a continuous flow requirement.
- The economics of **“2 way flow interconnection”** for balancing will therefore be different. Lower utilisation will increase the costs per kWh per km, but these should be covered by the arbitrage opportunities, the value of supplying electricity at peak times, when prices are high.



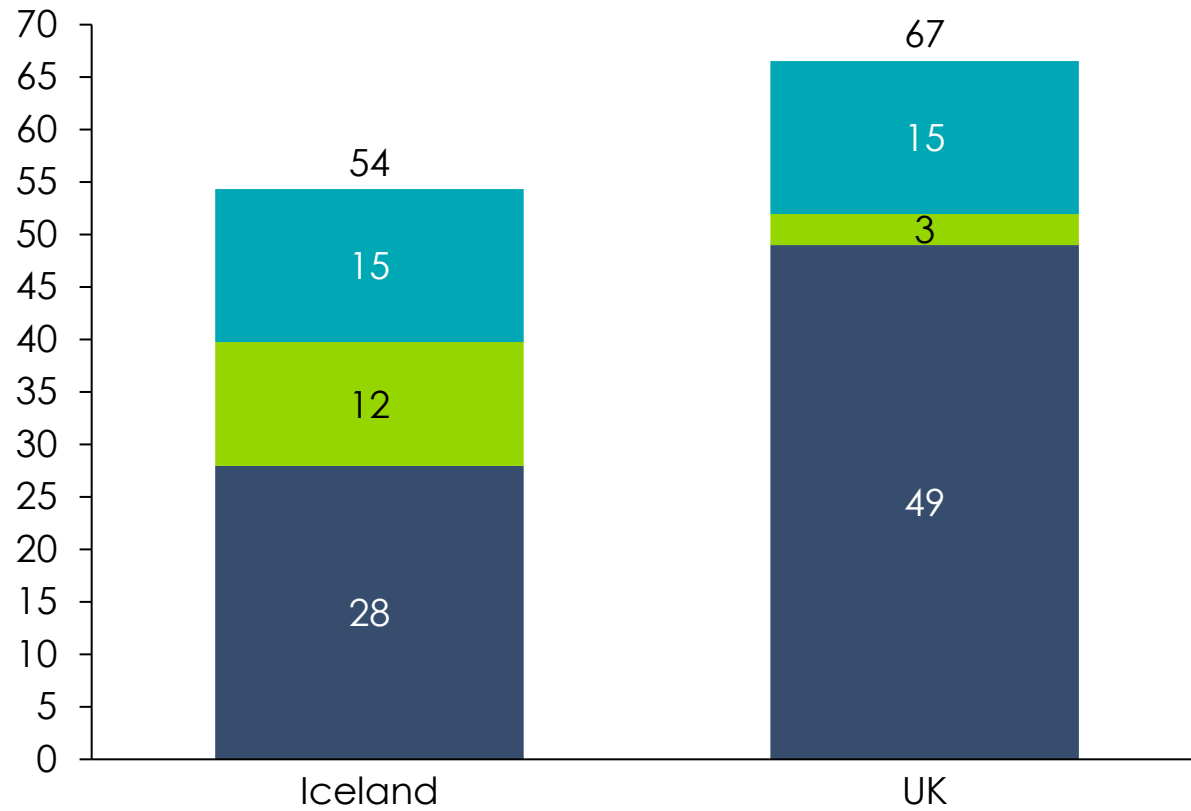
Case study: UK-Iceland, which could also operate as 2-way

Cost of power generation, cross-border transmission and battery storage for Iceland and UK

\$/MWh, real 2022 prices, 2050 LCOEs

Transmission Clean Generation Batteries

B 1 Balancing



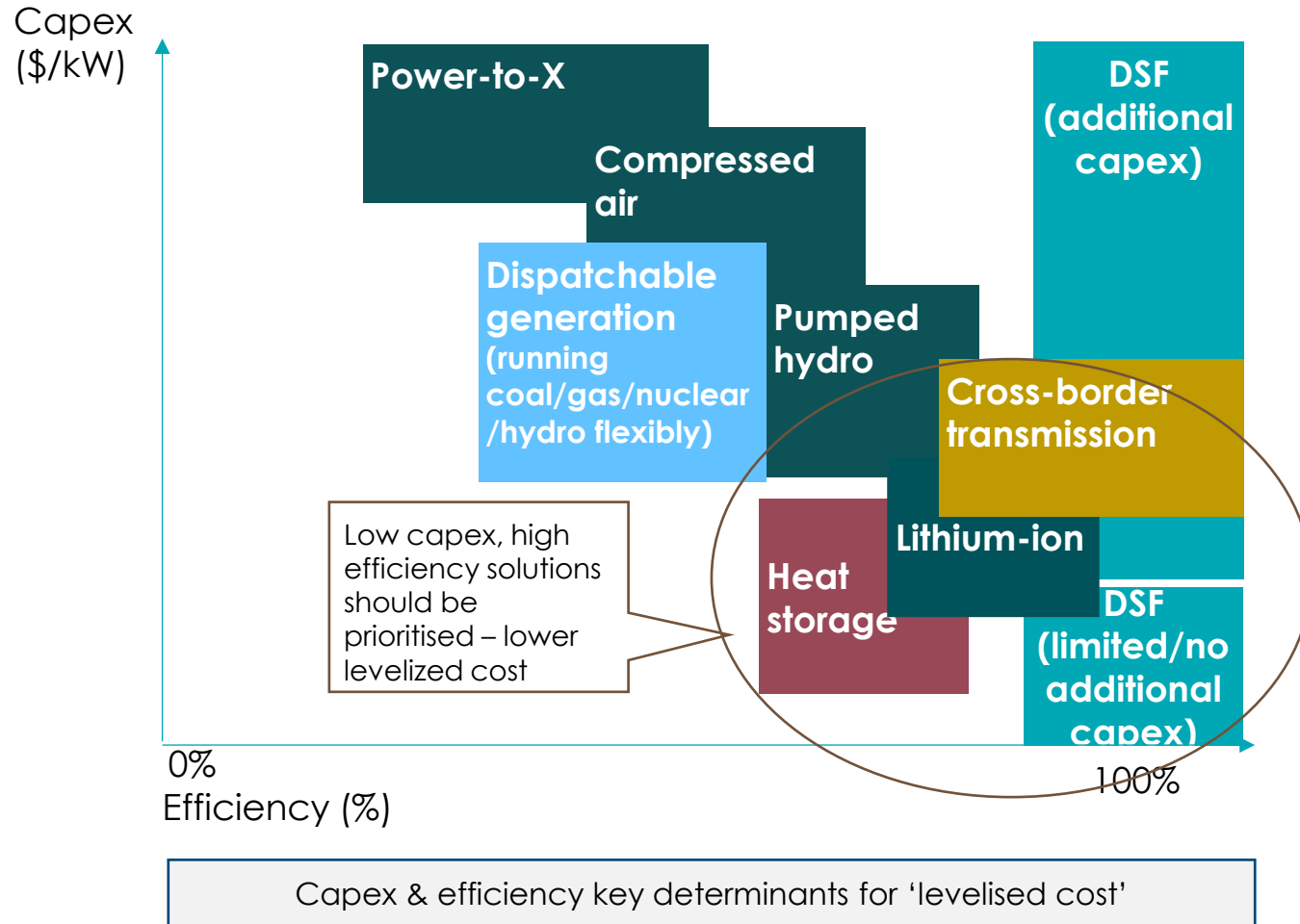
Key takeaway; on the basis of this project being an example of **two-way interconnection**, we can see that the project is cost competitive on the Iceland > UK exchange, but not in the reverse



Source: Systemiq analysis for ETC; BNEF (2023) 2H 2023 LCOE: Data Viewer Tool. Note: Transmission calculations vary based on an assumed utilization rate of 1) 50% for lines without batteries and 2) 85% for lines featuring batteries. As a result, the former is more costly at \$9.9/(MWh * 1000km) and the latter less at \$5.83/(MWh * 1000km). UK LCOE is based on the generation assumption for the UK that is 100% offshore wind, as this project (Icelink) is based on the scenario that Iceland would be sent excess wind.

Daily balancing: given option set available, low capex, high efficiency solutions should be prioritised

Illustrative view of selected flexibility technologies



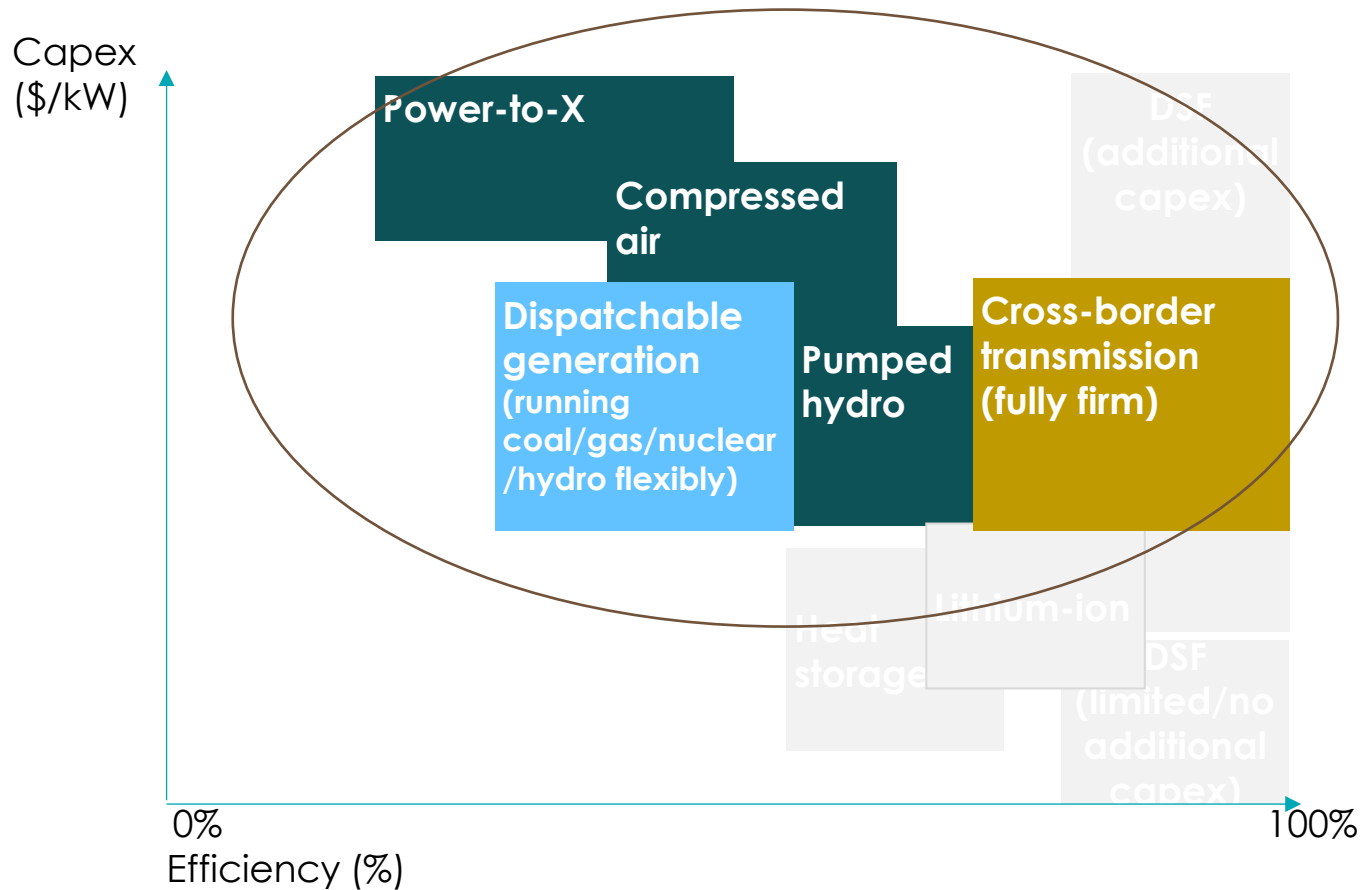
Cross border transmission (97% efficiency) could play a competitive role in short duration balancing

DSF definitions

Demand side flexibility (limited/no additional capex)	<ul style="list-style-type: none"> • EV smart charging • Pre-heating • Smart appliances • Shifting data centre demand geographically
Demand side flexibility (additional capex)	<ul style="list-style-type: none"> • Water tanks in homes • Industrial load management (e.g. for alu electrolysis)

Medium, long duration balancing: reduced option set to meet these needs

Illustrative view of selected flexibility technologies



Cross border transmission (98% efficiency) with firm (e.g. batteries at export, which would add some capex) could play a competitive role in longer duration balancing

Capex & efficiency key determinants for 'levelised cost'

4) What is the global potential for cross-border transmission?



ETC analysis will focus on several key questions



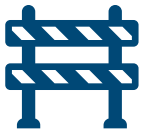
What drives the case for 1-way long distance transmission links in high variable renewable systems?

- Generation
- Balancing



What are the global top cable opportunities in high variable renewable systems?

- Modelling matching demand & supply profiles for each country to outline the locations of top new cables
- Results will demonstrate the most impactful new cables against a range of key criteria (e.g. highest volume, highest cost savings, emissions mitigated, land constraints overcome)
- Final view of the most impactful transmission 'megaprojects'



What are some of the key barriers and enablers to cross border links?



This approach brings forward new analysis to the landscape, building on existing work by Transition Zero

Existing analysis – ‘Cables to change the world’



Key question: What are the top 10 cables that save the most money by 2040?

- Assessed how much new generation, storage, and transmission infrastructure is needed to achieve net-zero in the power sector in 2040 under scenarios:
 1. No international transmission build
 2. Allowing expansion of new and existing transmission capacity
- Identified top 10 cables with largest impact, and overall benefits of \$3 trillion in 2040 in scenario 2.

Quantifies savings from long distance transmission links + key opportunities

New analysis – ‘Potential For long-distance interconnection’



Key question: What are the top lines by key criteria, and most impactful ‘megaprojects’ in a high variable renewable system?

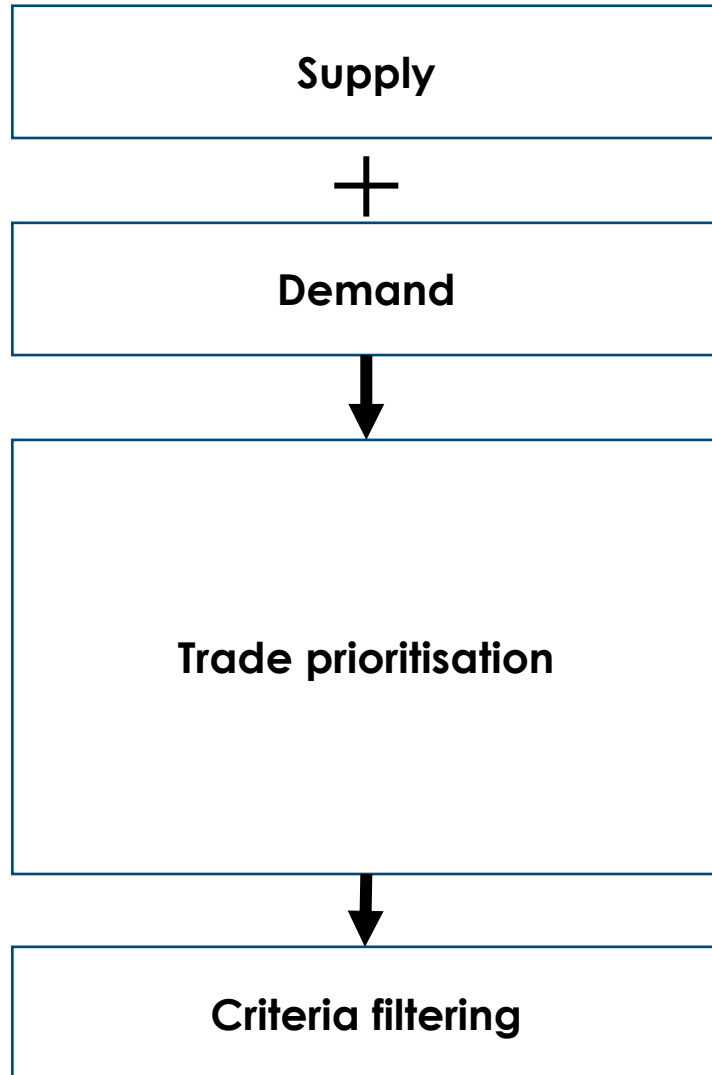
Lines connecting countries potential wind and solar assets assessed against key criteria:

- Total volume traded
- Cost effectiveness
- Daily and seasonal balancing
- Emissions reduction
- Overcome land constraints

Identifies in-depth resource complementarity across regions + key opportunities



Methodology – How to identify the most impactful transmission megaprojects?



1. Estimate total 2050 potential wind and solar supply for each country
2. Forecast 2050 demand for each country
3. Estimate 2050 LCOE data for wind and solar for each country
4. Establish costs of transmitting power between countries
5. 'Solve' for a long list of top interconnectors by highest traded value over time
6. Filter by key criteria to establish a useable set of results



The model's output top 100 lines by size will be filtered across key criteria

Criteria

Methodology

Total volume traded

The largest feasible transmission lines by total volume traded (i.e. the cables with the highest annual traded volume in TWh)

Cost-effectiveness

The lines with largest cost differential between importing, or sink country, LCOE (wind or solar if land is available, offshore wind if no land is available); minus exporting, or source country, LCOE (weighted average of wind and solar utilised); minus transmission costs.

Daily and seasonal balancing

The lines which provide the receiving country with the largest balancing benefits i.e. connections to countries who can provide power most consistently throughout the hours on a daily basis, and throughout the weeks on a seasonal basis

Emissions reduction

The lines which would provide the largest carbon emissions reductions based on difference between the new clean power source (assumed to be 0) and 2022 grid emissivity levels multiplied by the annual power which could be sent

Overcome land constraints

The lines that provide power to the smallest sink countries with substantial power demand (in terms of land available for renewables)



LCOE estimates were taken from BNEF wherever possible, however some data gaps had to be addressed

1. Source Directly from BNEF

- BNEF central estimates for 2050 for Solar PV, onshore and offshore wind
- Example countries where this was applied
 - UK
 - Australia
 - USA
 - China
 - South Africa

2. Make informed judgements on countries where BNEF forecasts not available

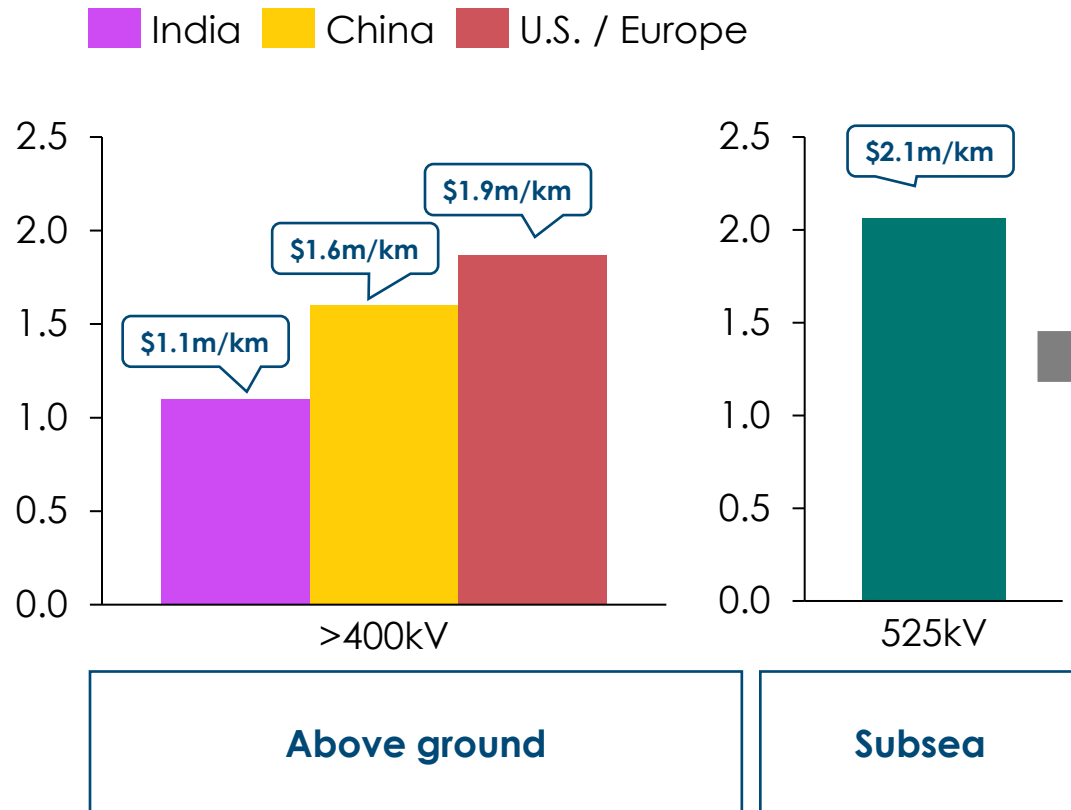
- Informed by ETC judgement, closest country values used wherever possible
- Example of countries where this was applied:
 - Western Europe solar = German values
 - Latin America onshore = Chile values
 - East Asia offshore = Japanese values
- Where directly applying other values doesn't accurately reflect risk, additional risk factor applied, i.e. Onshore wind in Libya and Sudan = closest values (Spanish) *1.5



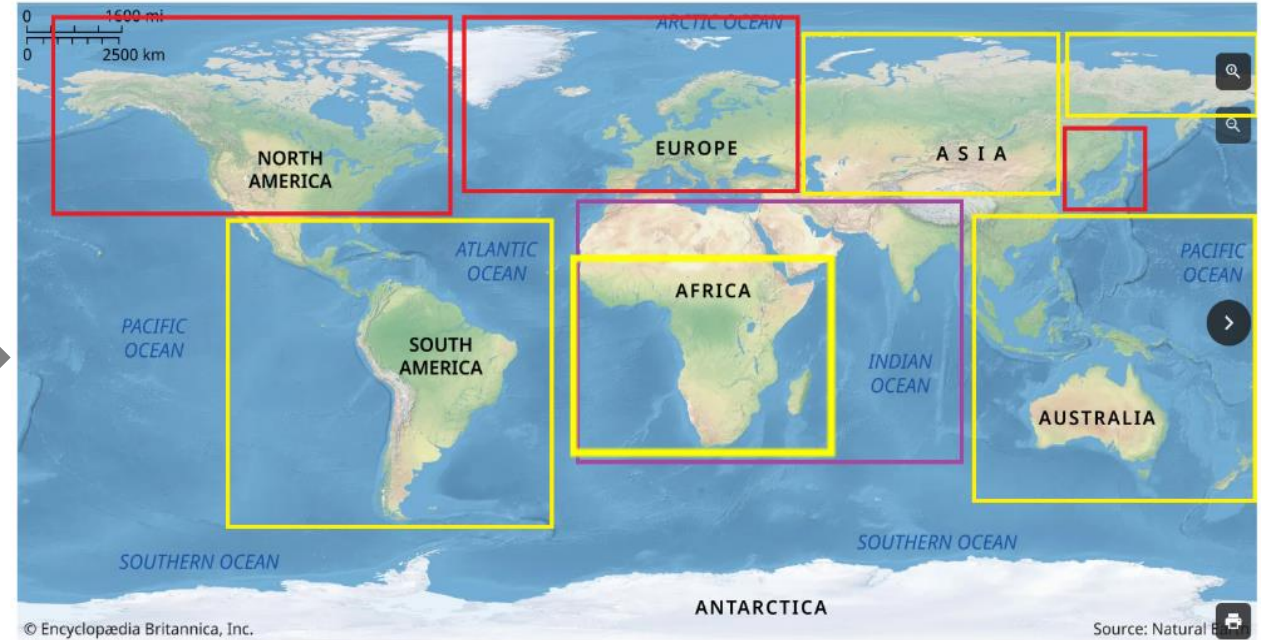
Interconnector costs vary across regions, with new US/European transmission most expensive and cheapest in India

Cost of constructing power lines

\$ m/km 4 GW, 4000 km, 2024 nominal costs



Transferring costs from BNEF to regions across the interconnection model

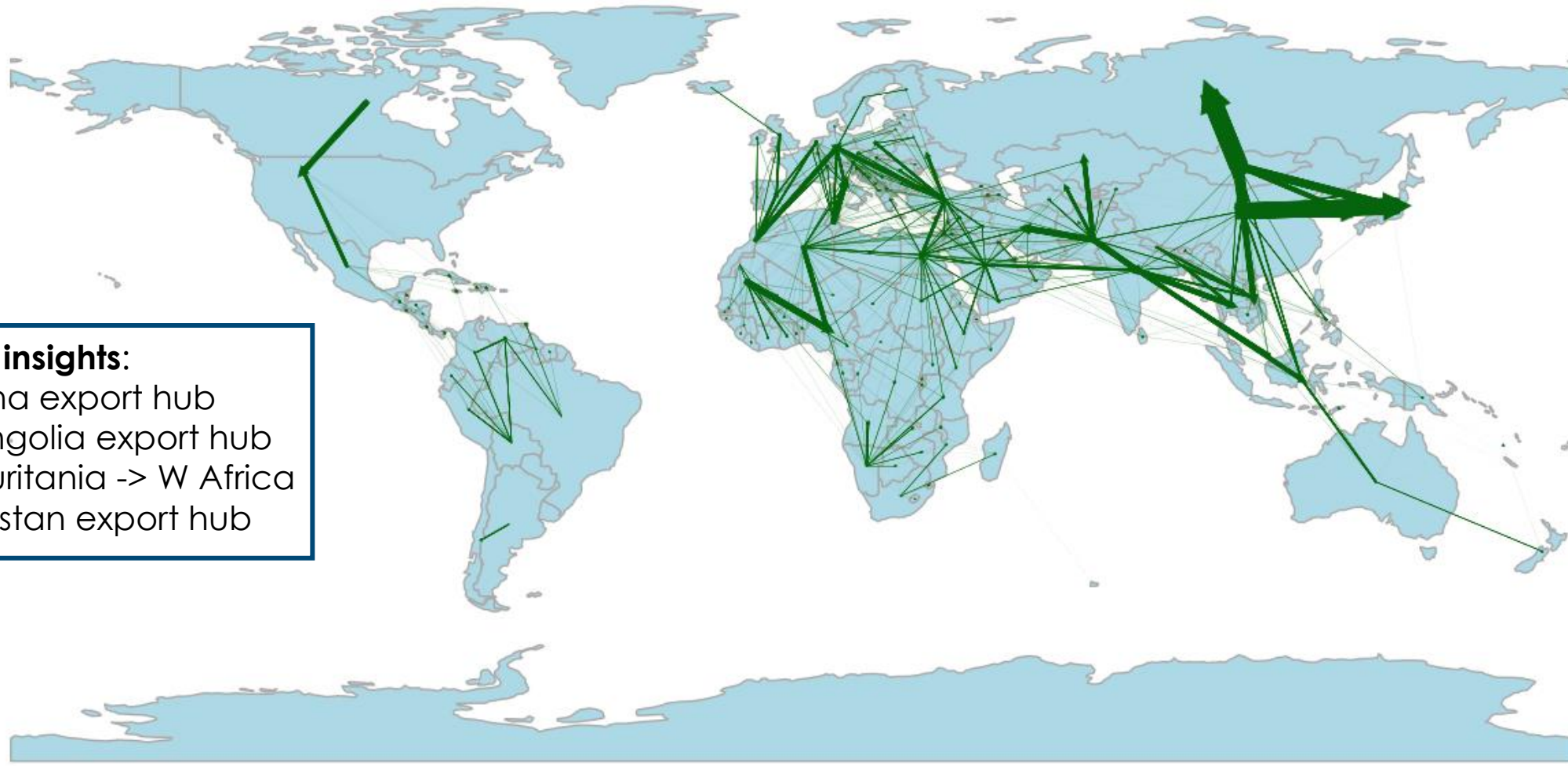


Cost per MWh per 1000km

- Subsea \$5.83/(MWh*1000km)
- Red (Europe/US) \$5.30/(MWh*1000km)
- Yellow (China equivalent) \$4.45/(MWh*1000km)
- Pink (India equivalent) \$3.04/MWh*1000km

Note: Representative grid costs based on BNEF's GridVal model, based upon 4000 km projects with MW capacities 2,000 for wires at voltage levels of ~500 kV. Included HVDC converter station costs at \$1.1bn per pair, and financing costs at 5% paid off over a 10-year period.. Average of US and European costs used.
 Source: Systemiq analysis for the ETC; BNEF (2024), *Grid Capex Cost Model (GridVal V1.0)*; conversations with expert stakeholders.

First results: The default solution suggests heaviest trade between China and neighbours as well as between MENA and Europe (before criteria filtering)



Key insights:

- 1 China export hub
- 2 Mongolia export hub
- 3 Mauritania -> W Africa
- 4 Pakistan export hub

This image shows all interconnectors of the solution, where arrow thickness is proportionate to trade volume

Key insights and are they realistic?

Key insights

- 1 **China as an export hub**
- 2 **Mongolia as an export hub** (particularly to Russia and China)
- 3 **Mauritania big role exporting to West Africa**
- 4 **Pakistan as export hub**

Feasibility

- **Not feasible:** Top importers on paper not politically allied with China (i.e. Japan and South Korea)
- **Not feasible:** Russia not committed to clean power; other transmission lines would have to pass through China who may prefer to export directly
- **Somewhat feasible:** ample space for deployment, but transmission lines may have to run through countries which don't have comprehensive transmission (i.e. Mali, Niger)
- **Somewhat feasible:** May be some role in balancing export to India, but neighbours like Iran and Afghanistan will not seek Pakistan's clean power



Political feasibility must be taken into account



The politically feasible scenario is based on two core principles

- 1) Would the countries be willing to trade power with each other?** (i.e. China and Japan not likely to trade)
- 2) Does the transmission line cross borders which might be problematic?** (i.e. China not happy to host transmission lines sending power from Pakistan to South Korea)



Top 10 lines across each key criteria

Total volume traded

Source country	Sink country	TWh
Mongolia	Russia	895
Mongolia	China	475
Mauritania	Nigeria	305
Saudi Arabia	India	300
Norway	UK	295
Tunisia	Italy	285
Canada	USA	275
Morocco	Germany	225
Pakistan	Kazakhstan	225
Algeria	Nigeria	220
Total TWh		3480

Cost-effectiveness

Source country	Sink country	Saving per MWh
India	Bangladesh	\$75
Saudi Arabia	Egypt	\$73
Pakistan	Bangladesh	\$72
Pakistan	Kazakhstan	\$70
India	Thailand	\$68
India	Malaysia	\$65
India	Viet Nam	\$64
Tunisia	Italy	\$64
Australia	Indonesia	\$56
Australia	Singapore	\$60
Total TWh		1300
Total saving		\$90bn

Daily and seasonal balancing

Source country	Sink country	Balancing coefficient
Saudi Arabia	Egypt	0.94
Saudi Arabia	Sudan	0.92
Saudi Arabia	Ethiopia	0.91
Australia	Indonesia	0.77
Pakistan	Bangladesh	0.76
India	Malaysia	0.75
India	Bangladesh	0.74
Turkey	Czechia	0.62
Canada	USA	0.61
Turkey	Germany	0.60
Total TWh		930

Emissions reductions

Source country	Sink country	Emissions saving (CO2)
Mongolia	Russia	391
Mongolia	China	278
Pakistan	Kazakhstan	187
Pakistan	Uzbekistan	179
Mauritania	Nigeria	157
India	Thailand	148
India	Indonesia	146
Algeria	Nigeria	114
Tunisia	Italy	108
Canada	USA	106
Total TWh		3315
Total MtCO2		1810

Overcome land constraints

Source country	Sink country	Sink land availability (km²)
Sri Lanka	Singapore	100
Morocco	Belgium	1,350
Morocco	Netherlands	2,100
Norway	Denmark	3,500
Turkey	Czechia	3,700
Morocco	Switzerland	3,800
Turkey	Hungary	5,500
Turkey	Bulgaria	9,100
Qatar	Kuwait	10,800
Egypt	Greece	11,700
Total TWh		480



15% of global power generation today



4% of global power generation costs today



6% of global power flexibility needs

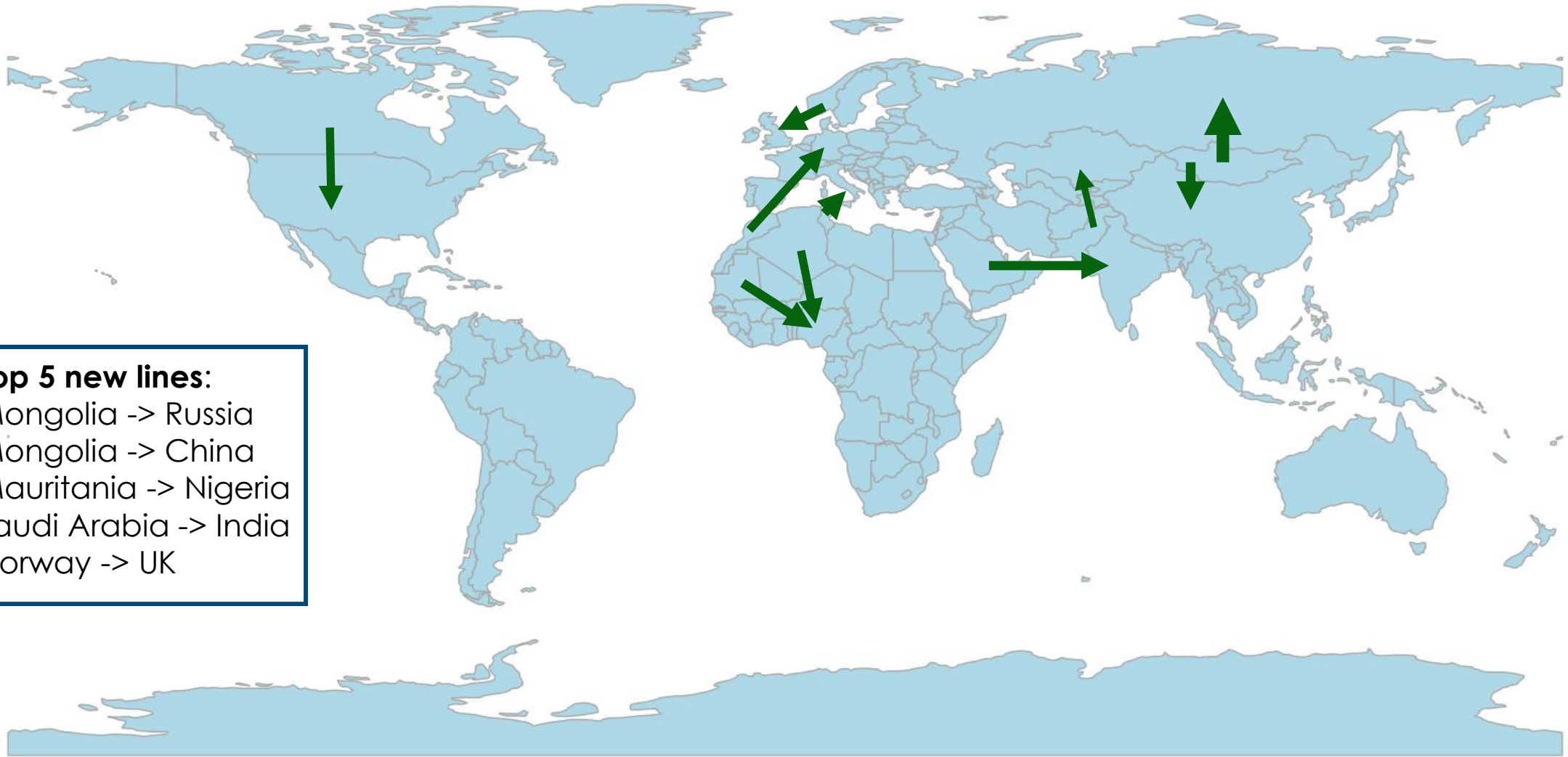


13% of global power sector emissions



Land constrained countries gain access to clean power

Traded volume: top 10 lines are dispersed across the globe

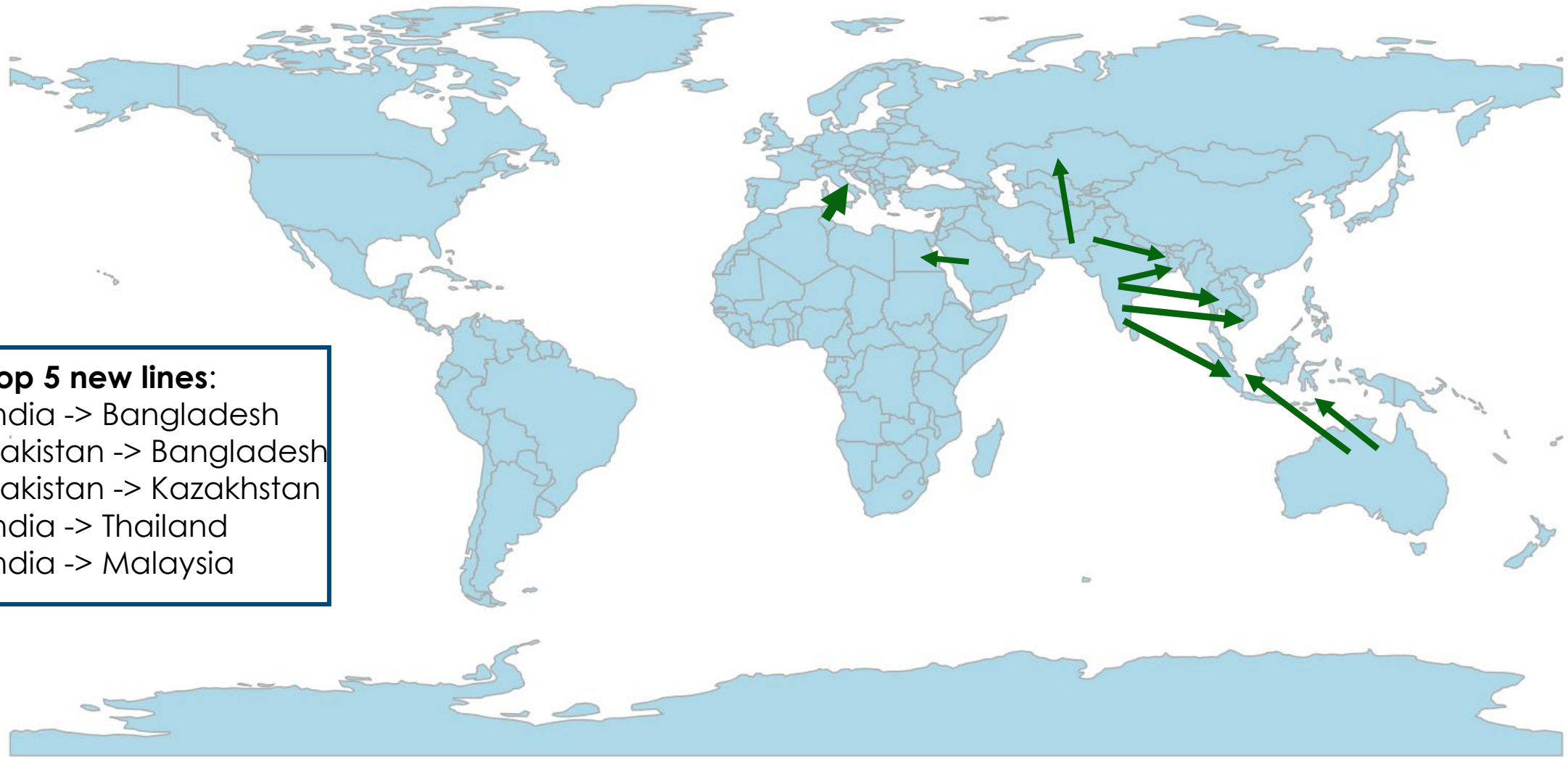


Top 5 new lines:

- 1 Mongolia -> Russia
- 2 Mongolia -> China
- 3 Mauritania -> Nigeria
- 4 Saudi Arabia -> India
- 5 Norway -> UK

Notes: Top 10 lines based on modelling results for total annual volume traded. Largest line shown = Mongolia to Russia, at 900 TWh; smallest shown Algeria to Nigeria at 220 TWh. Source: Systemiq analysis for the ETC.

Cost differential: Interconnectors from solar-rich countries to land constrained countries that would otherwise have to use nascent offshore wind dominate

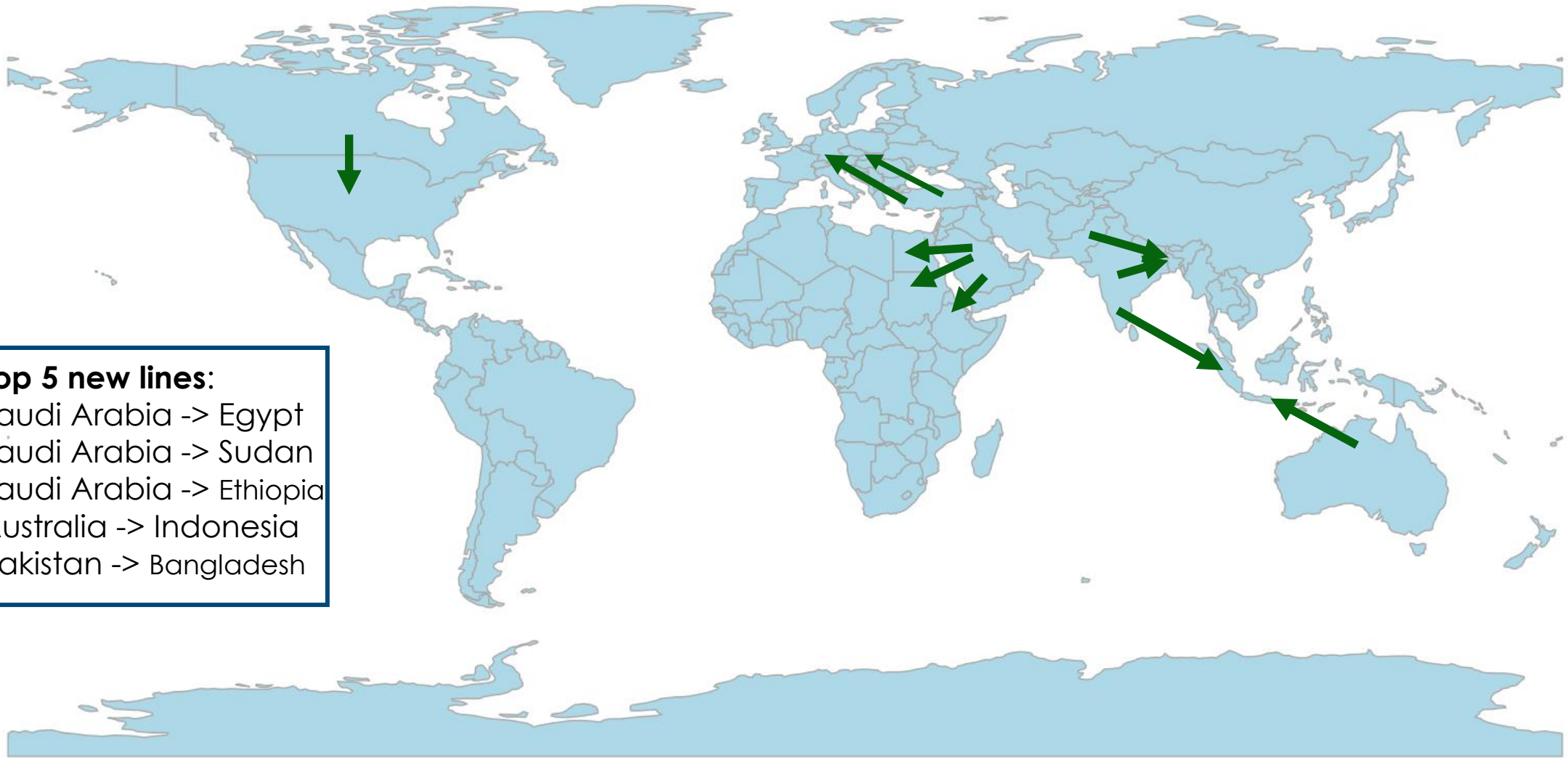


- Top 5 new lines:**
- 1 India -> Bangladesh
 - 2 Pakistan -> Bangladesh
 - 3 Pakistan -> Kazakhstan
 - 4 India -> Thailand
 - 5 India -> Malaysia



Notes: Top 10 lines based on modelling results for cost effectiveness – difference between source country LCOE and sink country LCOE (not accounting for amount of power traded). Largest line shown = Tunisia to Italy at 285 TWh; smallest shown Australia to Singapore at 10 TWh.
Source: Systemiq analysis for the ETC.

Balancing potential: Lines from larger countries such as Saudi Arabia and India to nearby countries with less renewable potential dominate



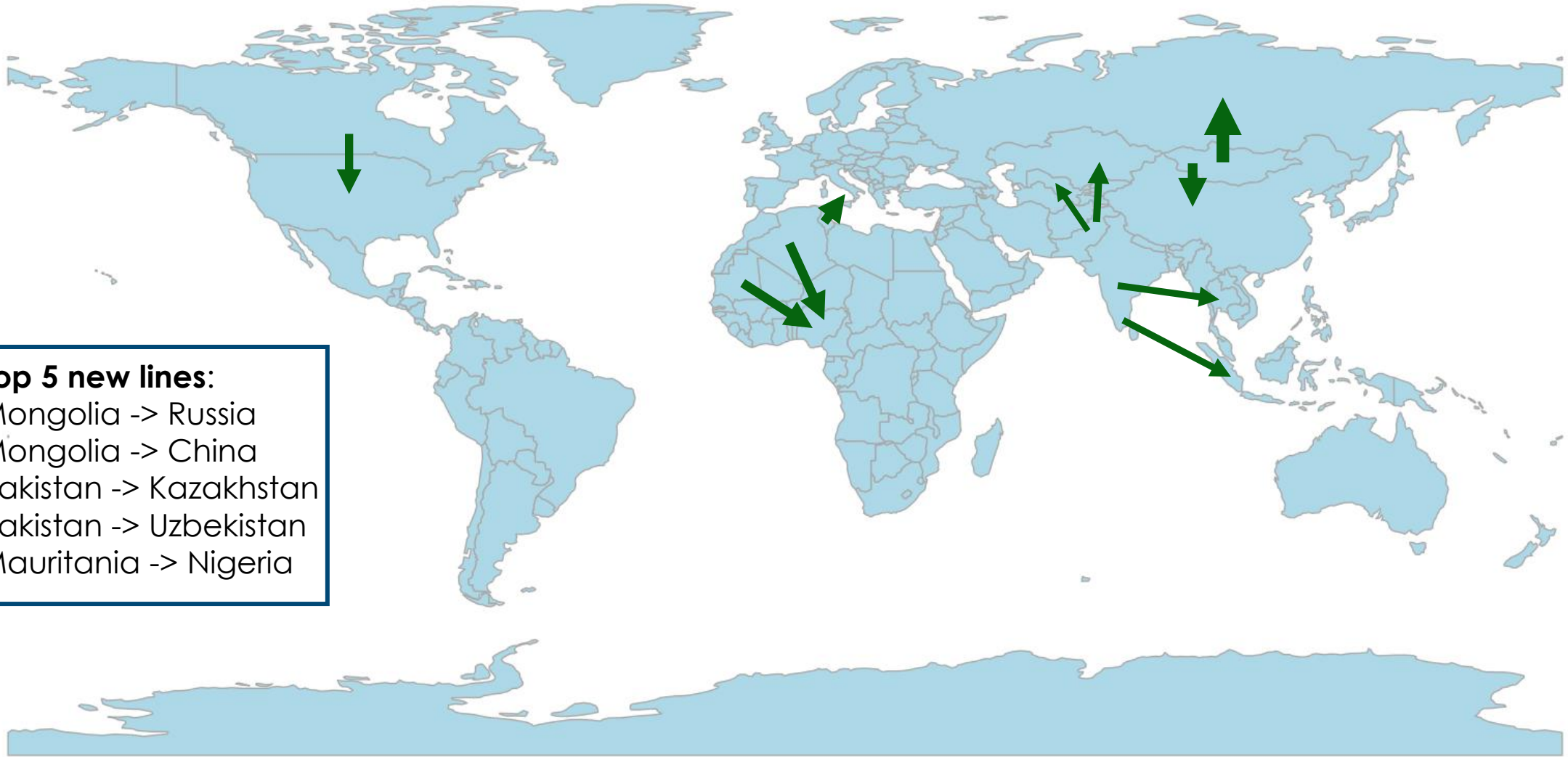
Top 5 new lines:

- 1 Saudi Arabia -> Egypt
- 2 Saudi Arabia -> Sudan
- 3 Saudi Arabia -> Ethiopia
- 4 Australia -> Indonesia
- 5 Pakistan -> Bangladesh

Notes: Top 10 lines based on modelling results for balancing potential – complementarity between generation at times of demand for sink country and supply at source country. Largest line shown = Canada to USA, at 275 TWh; smallest shown Turkey to Czechia at 40 TWh.
Source: Systemiq analysis for the ETC.



Emissions reduction: Sending clean power to the largest emitters such as Russia and Uzbekistan help most with reducing emissions

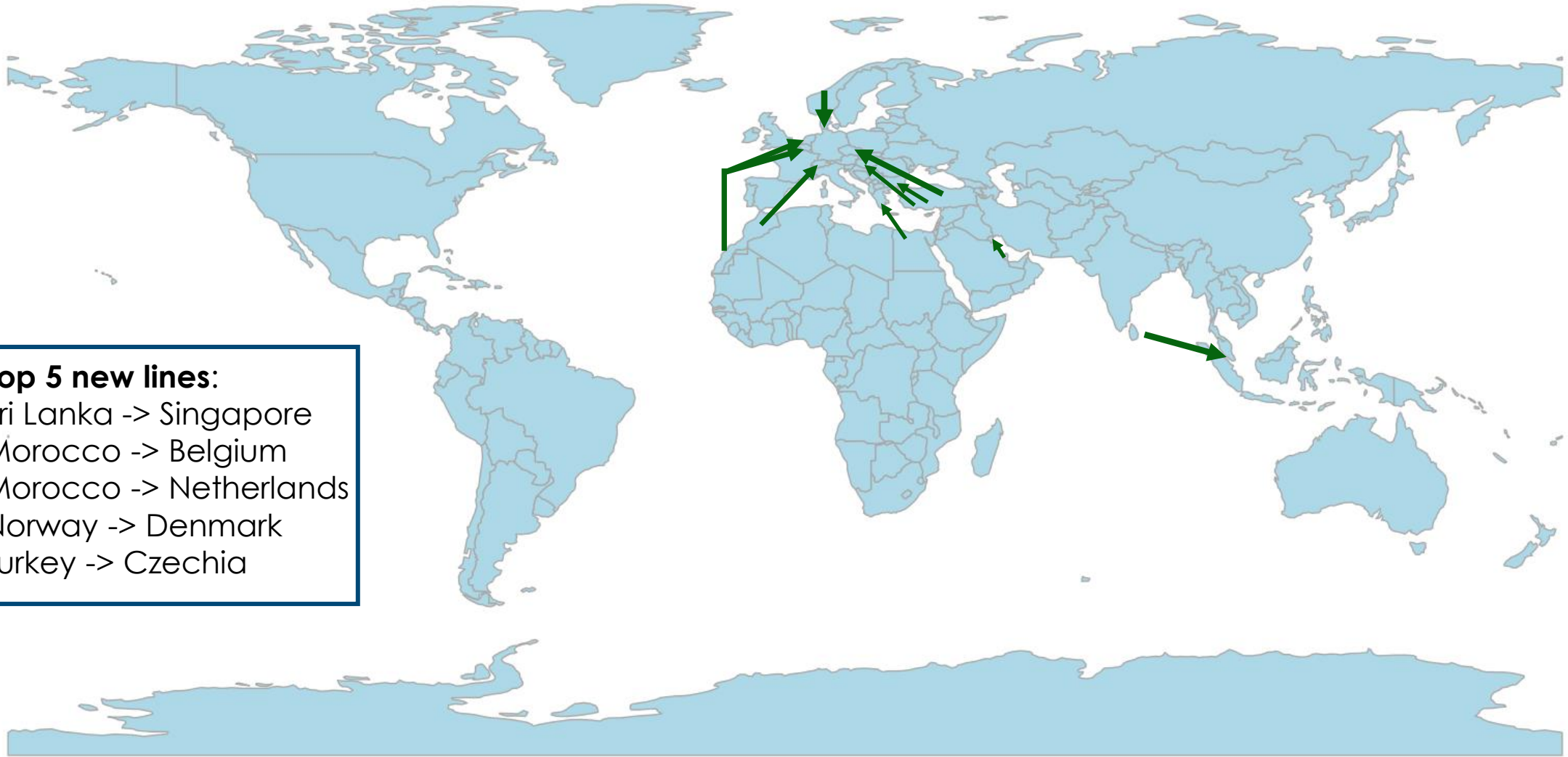


- Top 5 new lines:**
- 1 Mongolia -> Russia
 - 2 Mongolia -> China
 - 3 Pakistan -> Kazakhstan
 - 4 Pakistan -> Uzbekistan
 - 5 Mauritania -> Nigeria

Notes: Top 10 lines based on modelling results for balancing potential – complementarity between generation at times of demand for sink country and supply at source country. Largest line shown = Mongolia to Russia at 895 TWh; smallest shown Pakistan to Uzbekistan at 120 TWh.
Source: Systemiq analysis for the ETC.



Land constraints: Central and Eastern European countries require most assistance from larger neighbours



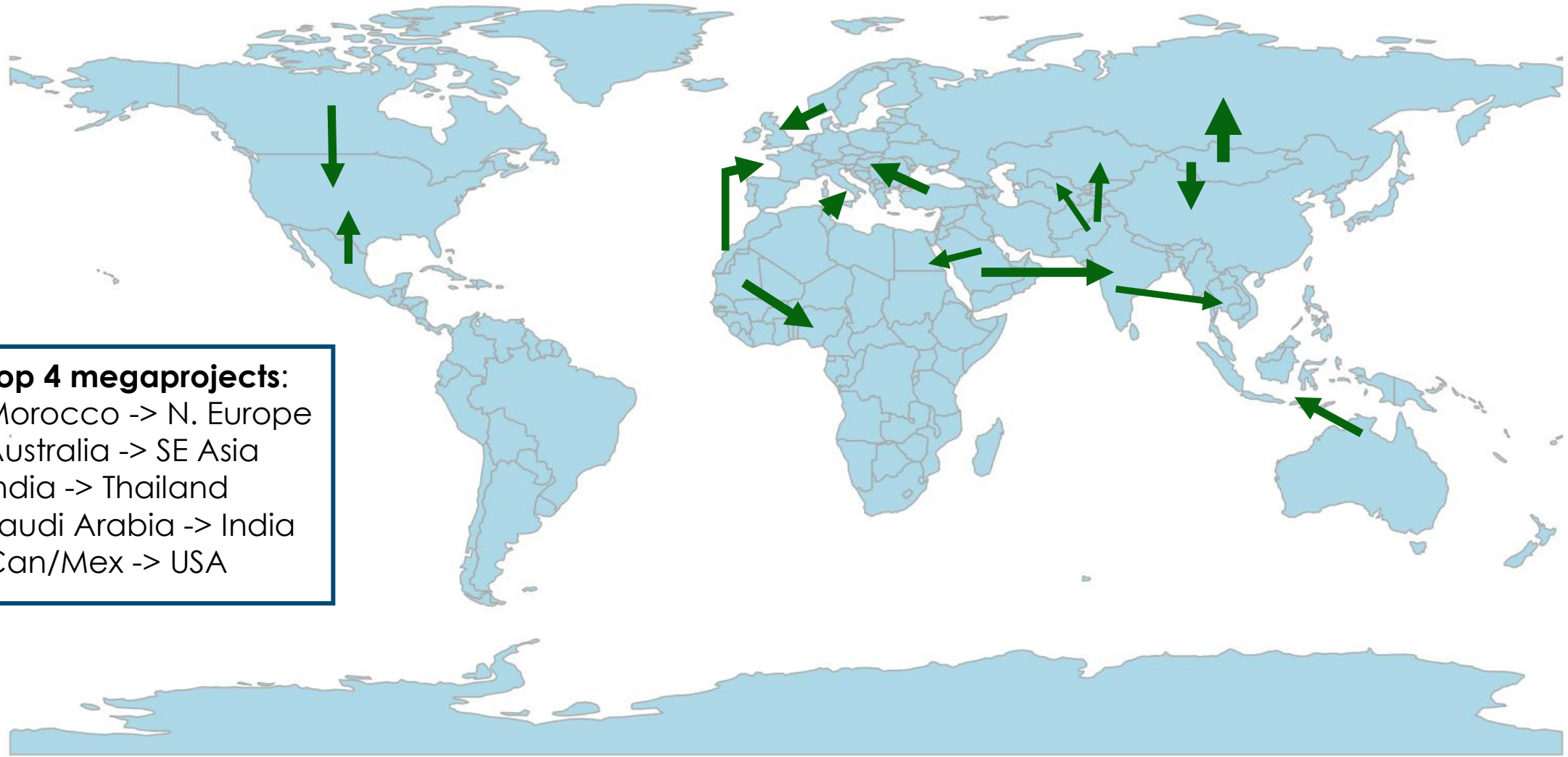
Top 5 new lines:

- 1 Sri Lanka -> Singapore
- 2 Morocco -> Belgium
- 3 Morocco -> Netherlands
- 4 Norway -> Denmark
- 5 Turkey -> Czechia

Notes: Top 10 lines based on modelling results for balancing potential – complementarity between generation at times of demand for sink country and supply at source country. Largest line shown = Morocco to the Netherlands, at 90 TWh; smallest shown Egypt to Greece at 30 TWh.
Source: Systemiq analysis for the ETC.



Overall results: top 15 lines show potential for network 'megaprojects' such as Morocco and Australia as export hubs



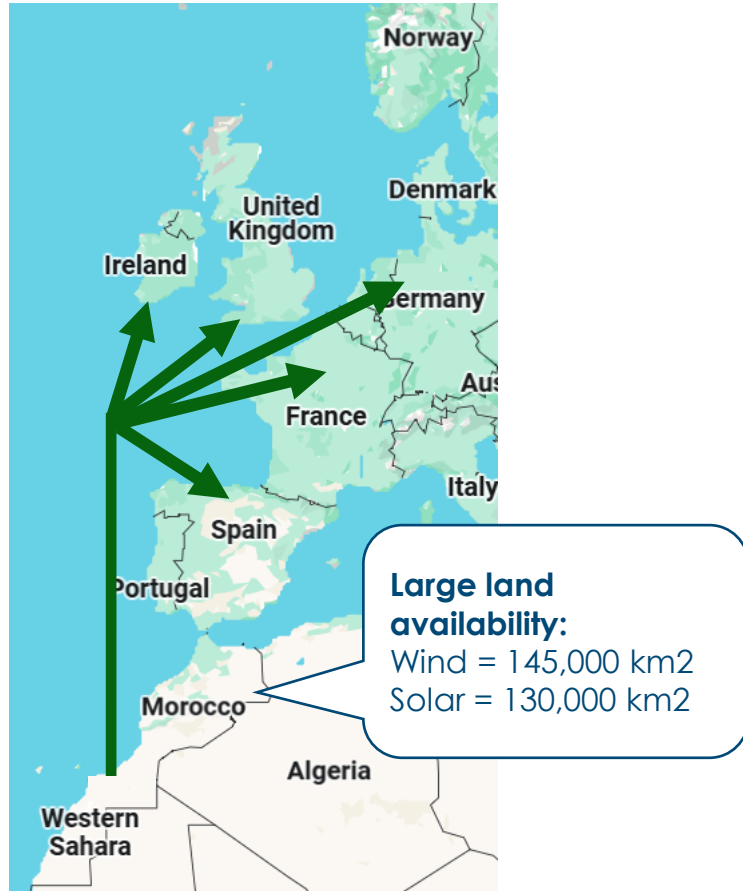
- Top 4 megaprojects:**
- 1 Morocco -> N. Europe
 - 2 Australia -> SE Asia
 - 3 India -> Thailand
 - 3 Saudi Arabia -> India
 - 4 Can/Mex -> USA

Notes: Top 10 lines based on results across all metrics, amended for political feasibility (trading power between allied nations, not crossing excessive country borders). Largest line shown = India to Thailand, at 480 TWh; smallest shown Mexico to USA at 170 TWh.
Source: Systemiq analysis for the ETC.



Megaproject 1 – Morocco as an export hub to North Europe

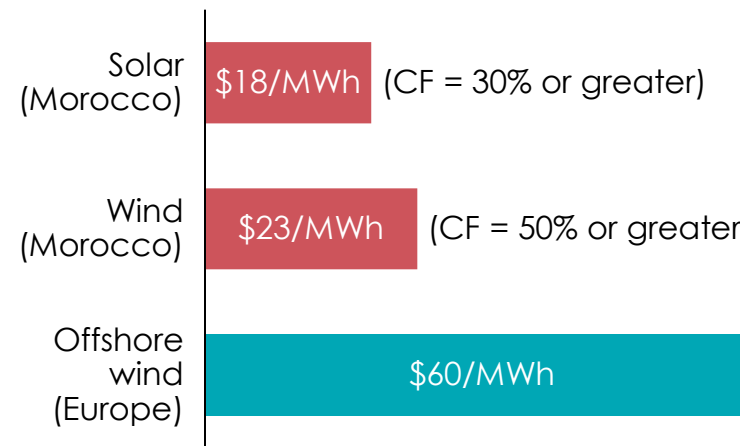
High potential links from Morocco



Morocco export is cost-effective

- Morocco has vast potential as export hub to Northern Europe, with the model suggesting a **cost-effective export potential of over 900 TWh**
- **More competitive LCOEs than Northern Europe** (due to high-capacity factors and cheaper land)

Project LCOEs in 2050



Demonstrator project



- **Commissioning date ~2030**
- **3.6 GW 4,000km** HVDC sub-sea cable link from Morocco->UK
- **11.5 GW** of zero carbon energy generation, backed with onsite battery storage of **22.5 GWh/5 GW**
- Will send power for **19+ hours per day**, bringing clean power to **over 7 million homes** and supplying **8% of GB demand**

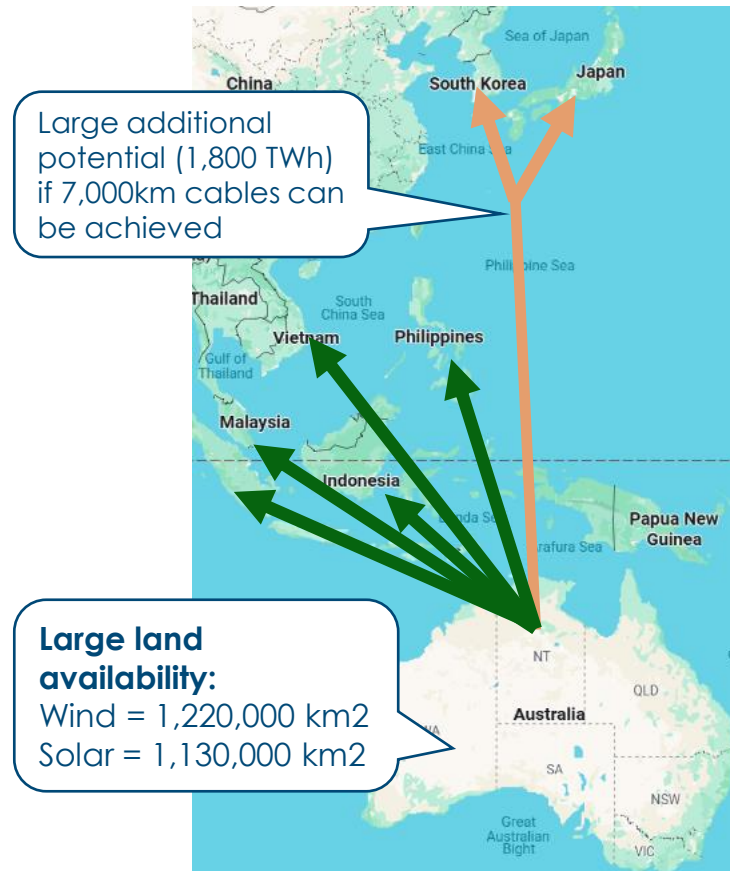
If the project is successful there may be a large role for further export, particularly to Germany, the Netherlands and Belgium

Notes: Importing countries include France, Germany, Spain, Netherlands, Belgium, Switzerland, Ireland, UK, Portugal. BNEF mid scenarios for Spain in 2050 used as the closest available country to Morocco.

Source: BNEF (2024), 2024 LCOE Forecast; Systemiq analysis for the ETC.

Megaproject 2 – Australia as an export hub to SE Asia

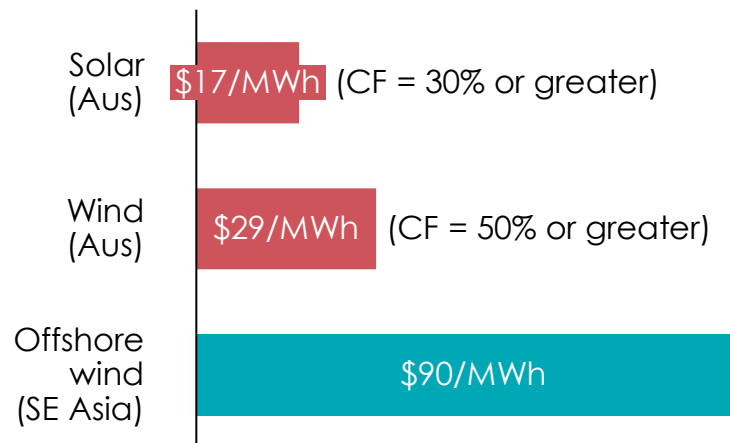
High potential links from Australia



Australia export is cost-effective

- Australia has vast potential as an export hub to SE Asia, with the model suggesting **cost effective export potential of over 300 TWh**
- **More competitive LCOEs than SE Asia** (due to high-capacity factors and cheaper land)

Project LCOEs in 2050



Demonstrator project



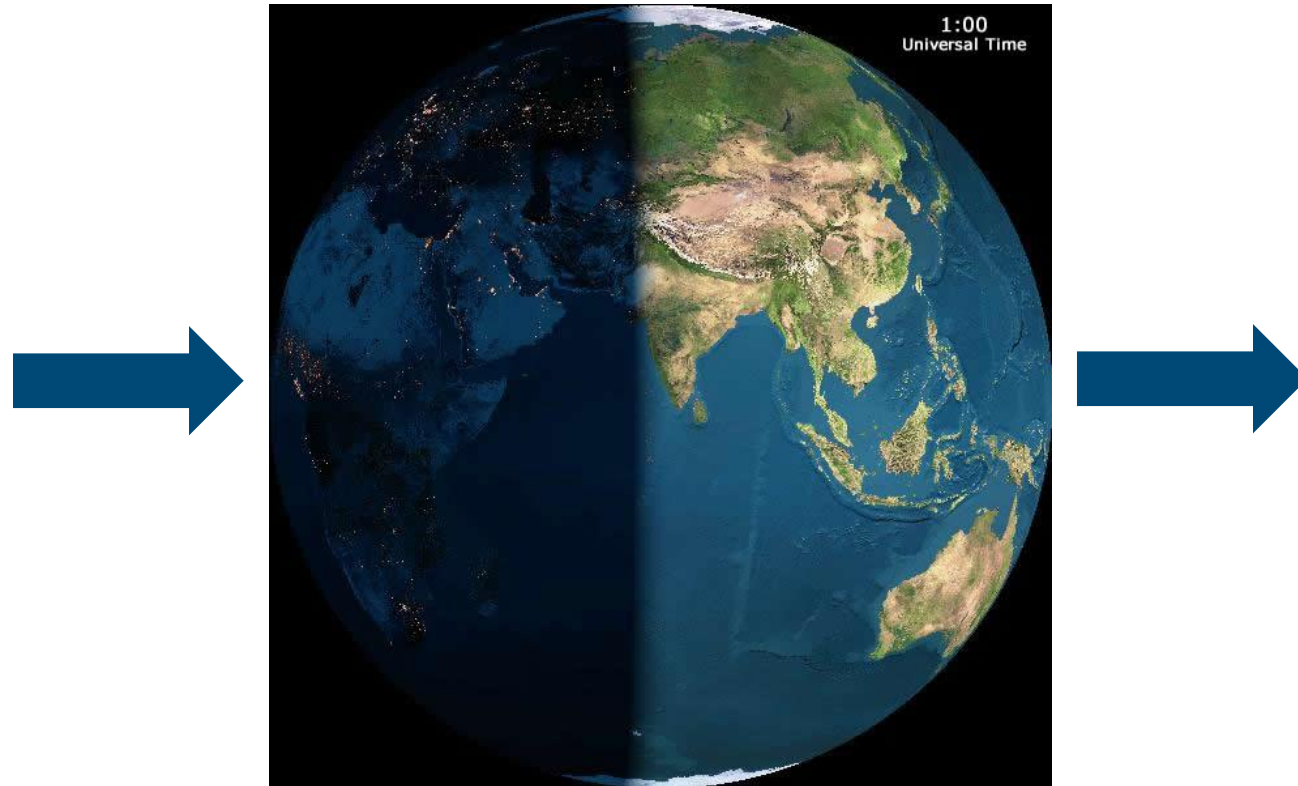
- **Commissioning date ~2035**
- Will harness solar and wind from Australia's Northern territories, stored in batteries and sent to demand centres in:
 - **Darwin 800km** away, **4 GW** constant supply to industry
 - **Singapore, 4,300km** away, **2 GW** cable providing 24/7 flat load of 1.75 GW, **15%** of Singapore's energy demand

Aus export potential could be 1,000 TWh higher than ETC model shows if results were based on speed of delivery

Notes: Importing countries include France, Germany, Spain, Netherlands, Belgium, Switzerland, Ireland, UK, Portugal. BNEF mid scenario LCOEs drop to highlighted values in 2050. Could be a significant role for more ASEAN cross-border trade as part of ASEAN 'Super-grid'.
Source: BNEF (2024), 2024 LCOE Forecast; Systemiq analysis for the ETC.

Megaproject ③ – ‘OSOWOG’ starting from India, which has high potential to export East and import West as the sun rises and sets

An interconnected grid on which the sun never sets



Key insight: Potential for ‘One-Sun-One-World-One-Grid’ with countries horizontally interconnected and can always access clean solar power

India has great potential exporting to countries to the East (i.e. Thailand, Vietnam, Indonesia, etc.)

Source	Sink	TWh potential	Utilisation
India	Thailand	540	54%
India	Viet Nam	480	64%
India	Indonesia	290	22%
India	South Korea	250	28%
India	Malaysia	100	33%

High potential lines exporting to India from the West, with lower utilisation (i.e. Saudi Arabia)

Source	Sink	TWh potential	Utilisation
Saudi Arabia	India	300	10%



Megaproject 4 – US importing power from Canada and Mexico

High potential for vertical links from Canada and Mexico to USA



Can/Mex export is effective for balancing & overcoming land issues

- Vast wind available in Canadian provinces which can send power to the US when the sun isn't shining or wind isn't blowing to the south.
 - Model suggests potential of **275 TWh**, but this could be much greater if hydro also included.
- Strong solar potential in Mexico closer to the equator that can provide clean energy boost to US grid.
 - Model suggests potential of **170 TWh**, but if US struggles further with permitting issues, importing even more power from Mexico could be beneficial

Demonstrator project



- **Commissioning date 2026**
- Will harness connect hydro and wind resources from Quebec, Canada to deliver power to New York, USA.
- The **550km, 1.25 GW** line cost **\$6bn**, and will provide 'always-on' power for customers in the New York Metro area.
- The line will be **buried underground and underwater** in various sections to minimise environmental impact
- **Expected to save homes and businesses \$17.3bn** over 30 years through wholesale electricity costs.



Other interesting links could have strong potential, but come with drawbacks

Source Country	Sink Country	TWh
Mongolia	Russia & China	1,370
Turkey	Central and Eastern Europe	720
Mauritania	W Africa	440
Pakistan	Kazakhstan & Uzbekistan	380
Saudi Arabia	NE Africa	180

The 'West African Power Pool' has started work to improve cross-border flows



Reason	Drawback
Big TWh potential & emissions savings	Russia and China may not like to import power
Overcome European land and permitting constraints	Requires stronger European transmission network
Growing power demand and strong emission reductions	Longer links must go through countries with some energy access needs themselves
Big emissions savings	Must go through Afghanistan
Provide consistent power (balancing)	Potential unreliable offtake (e.g. Sudan)



Central and Eastern Europe includes: Germany, Ukraine, Poland, Romania, Czechia, Hungary, Bulgaria, Belarus, Slovakia, North Macedonia, Italy. West Africa includes: Nigeria, Ghana, Cote d'Ivoire, Cameroon, Senegal, Mali. NE Africa includes: Egypt, Ethiopia, Sudan.

Key takeaways

- **Massive global interconnection potential, a small number of high potential links could deliver:**
 - **15%** of global power demand
 - **1.8 Gt** per annum carbon reductions (**13%** of global power sector emissions)
 - **\$90bn** dollars of savings per year
- **Interconnection is a cost-effective way of meeting generation and balancing challenges**
 - Generation – many opportunities where generation in Country A plus transmission is cheaper than generation in Country B
 - Short term balancing – differences in generation and demand profiles can be utilised to assist with balancing
 - Multiple balancing challenges – more complex projects with additional storage can provide ‘clean firm’ & flexible power
- **Some projects should be acted on now to deliver immediate benefits and derisk future projects**
 - Morocco to UK; Australia to Southeast Asia; Canada to USA
- **Some projects may need more time before full benefits can be realised**
 - India may need more domestic build before export; West African grid may need more reinforcement
- **Political feasibility a critical barrier and may result in a much lower uptake than modelling results suggest**



5) Key blockers and enablers



ETC analysis will focus on several key questions



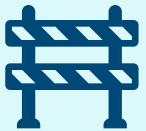
What drives the case for 1-way long distance transmission links in high variable renewable systems?

- Generation
- Balancing



What are the global top cable opportunities in high variable renewable systems?

- Modelling matching demand & supply profiles for each country to outline the locations of top new cables
- Results will demonstrate the most impactful new cables against a range of key criteria (e.g. highest volume, highest cost savings, emissions mitigated, land constraints overcome)
- Final view of the most impactful transmission 'megaprojects'



What are some of the key barriers and enablers to cross border links?



Key enablers covers all types of cross-border transmission links

Primarily 2-way flow “Interconnection”

Short or Long

- Most existing links today are 2-way, short distance
- Not a continuous flow (can have lower utilization); flow of electricity driven by market signals
- Based on **arbitraging S/T price variations** across markets (e.g. UK<>Europe), can help with **balancing**.
- In some interconnectors, flow tends to be in one direction primarily (e.g. Norway <> UK is primarily from Norway, given the hydro resource)
- Can be built with high TSO involvement, or private

1 –way flow “transmission”

Long

- Some existing or proposed links today (e.g. across China, Xlinks)
- Likely to be a continuous flow of electricity (high utilization rates), based on one-way cost arbitrage
- Based on **structural resource complementarity** across markets, e.g. lower costs/higher energy output (e.g. Western China has better wind and solar resources), can also help with **balancing**
- International links would typically be privately-owned



Several blockers can slow the uptake of cross-border cables

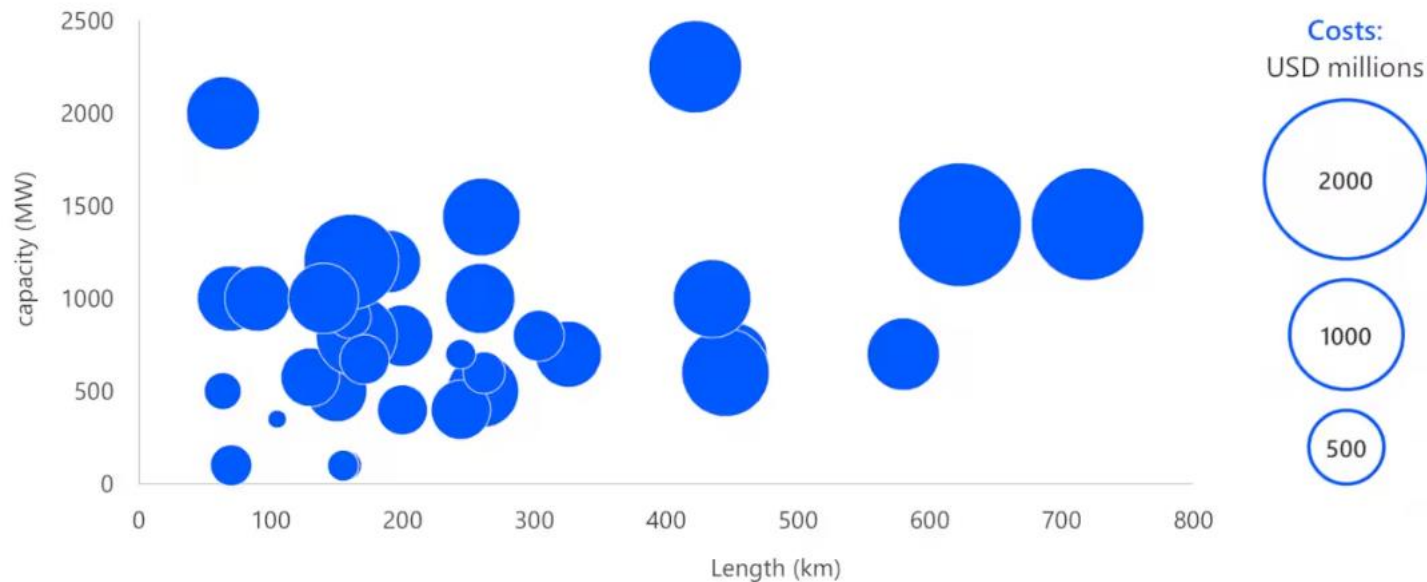
Blocker	Key challenge	Key enabler	Severity
Finance <i>Deep dive on next slides</i>	Hard to agree funding and revenue mechanisms between parties	Many options can be utilised for different projects (see next slide)	Fairly severe
Political feasibility	Hard to make agreements between countries trading power + those where lines cross borders, & ensuring consumers feel benefits of new lines	Unallied countries may never be able to agree – some quid pro quo may need to be offered to allies to increase acceptance; need to ensure no price distortion for consumers	Severe
Supply chain constraints	Limited short-to-medium-term supply of cables, transformers and vessels	Long-term planning provides clarity to OEMs to scale up, some scaling up and self-producing underway (i.e. XLCC)	Fairly severe (short-term)
Technical	Can be technical issues linking up grids on different frequencies (i.e. 50 vs 60 Hz used in different ASEAN countries)	Can be overcome; Europe is connected by 400 interconnectors, whilst Japan's East (50 Hz) and West (60 Hz) grids are connected via HVDC and trade power	Not severe
Lack of demonstrators	Lack of very long-distance demonstrators to prove that power can be sent over 2000km+	China already have interconnectors over up to 2,200km (Hami-Zhengzhou UHVDC); X-Links developing 4,000km subsea cable	Some valid concerns (short-term)
Geopolitical & Energy security challenges	Hesitancy for countries to commit to importing large % of power from neighbours, concerns about security of cables	Countries will likely prefer some diversity, but power interconnectors not necessarily less secure than very common gas interconnectors	Some valid concerns



Interconnector projects represents a sizeable investment over a number of years

Reported cost of European HVDC commissioned projects, 2005-2022

Capacity (MW), length (km) and cost (\$ million)



Costs of interconnection are significant

- The Viking Link between the UK and Denmark was commissioned in December 2023. It cost **~€2.4bn** for 1.4 GW over 760km.
- The Neuconnect interconnector is planned between the UK and Germany to commission in 2028, with similar dimensions (1.4 GW, 725 km) and cost **~€2.4bn**.

Time horizon also a key factor

- **12 years for development and construction process of the North Sea Link** interconnector between **Norway and the UK**, commissioned in 2021, with feasibility study conducted in 2009 and construction starting in 2015.

Given scale of finance required and timescale of project development, **sufficiently attractive rates of return** are required alongside **revenue streams during construction** to make the project viable to investors.



There are traditionally two ways to finance primarily short-term trade-based interconnectors

In general, there are two main business models for interconnectors:

1) 'Regulated model' – via cap and floor and capacity market payments

Interconnectors sponsored by Transmission System Operators (TSOs) or utilities, (most common). Usually **finance interconnectors through balance sheets** as part of their ongoing business and receive a rate of return subject to a 'cap and floor mechanism' and receive capacity market payments. The prime responsibility of a TSO is to **ensure proper functioning of the power grid**, so this group doesn't necessarily need to make a profit on the interconnector. There is some room to make a profit through congestion rents.

2) 'Merchant model'

Where **arbitrage via congestion rents is the key revenue stream** that is driving increasing interest from privately sponsored interconnector projects, which are often owned by a collection of partners.

- **The more interconnectors that are added to the system, the more congestion rents will shrink in the long run (they will cannibalise rents).** This will apply to all interconnectors (both owned by TSOs and private investors), which is a reason for the low number of merchant model interconnectors in place.
- **Interconnectors therefore typically require subsidies or other forms of support to reduce or eliminate the associated long-term risks.**



For longer distance links, there are three emerging financing routes

1) State procurement

Where the state facilitates all required investments to bring the project online. This is frequently the case in China, including for the Hami <> Zhengzhou 8 GW, 2,200 km above ground UHVDC link commissioned in 2019, capable of transmitting +/- 800kV back and forth between provinces.

2) Contracts for Difference

A relatively new mechanism for transmission projects, e.g. advocated for the Morocco -> UK X-Links project. Here the company seeks to arrange a constant price to provide power for 19+ hours a day at a rate that reflects the cost of their installing onshore wind, solar PV and batteries in Morocco, and building a transmission cable connecting the two countries.

3) Power Purchase Agreements

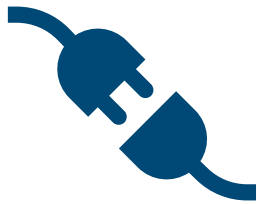
Similar to a CfD in terms of being a contract to deliver power, PPAs are agreements generally between two private parties to build a transmission line to carry power from one region to another. The Champlain Hudson Power Express HVDC Canada->USA line is being financed via a PPA, which began construction in 2022 and is due to commission in 2026.



Notes: with the CFD, if wholesale market prices are above the strike price X-Links will pay back to the Government, if they are below the strike price, the Government will top-up X-Links the difference.

Case study, derisking interconnectors: Germany <> UK Neuconnect

NeuConnect



- Current submarine power cable under construction since 2023 between the Isle of Grain, England and Wilhelmshaven Germany, expected to operate in 2028.
- Set up as a special purpose vehicle (SPV) by a group of institutional investors: Meridiam, Allianz Capital Partners, Kansai Electric Power, and TEPCO.
- The investors applied for all available permitting revenue guarantees (which can be seen as a kind of subsidy) with authorities in Germany and the UK.



In **Germany**, the **TSO** will in effect **pay Neuconnect a fixed tariff per megawatt hour transmitted.**



In the **UK**, the **project's revenues are subject to a cap and floor mechanism guaranteed for 25 years by Ofgem.** This model assures the SPV a steady income interval for the 25-year period.

In essence, revenues from this project are guaranteed by the two countries via local regulators and TSOs. The result is a highly de-risked business model with a higher chance of bankability. But it also means that the merchant risk is thus taken by the TSOs or, in the end, the tax payers.



Finance mechanisms have evolved over the years, with emerging options for new types of projects

Type of cable

Financing mechanism

Primarily 2-way flow
“Interconnection”
Short distance
(existing)

Merchant – Private companies collaborate to group funding to build an interconnector to make profit from **arbitrage via congestion rents**, selling power from a country where the power price is low, to a country where the price is high.

Cap and floor mechanisms – provide a degree of price certainty for investors. A cap sets a max price for electricity transmission, while a floor establishes a minimum. This mitigates some market risk inherent in merchant models.

Capacity market payments – provide a stable income stream for interconnectors by compensating for contribution to system security and reliability. payments typically made by SOs or governments, ensuring a steady revenue flow.

1 –way flow
“transmission”
Long distance
(emerging)

State procurement – Funds provided directly by the state, i.e. for the rollout of China’s extensive domestic long-distance HVDC network.

Contracts for difference – Government backed contract paying a fixed amount per MWh for a near constant supply of power i.e. X-Links Morocco->UK agreement with UK Government on behalf of taxpayers

Power Purchase Agreements – Private contract paying fixed amount per MWh for a near constant supply of power i.e. Champlain Hudson Power Express Canada->USA agreement between ‘transmission developers’ and New York State

Mutli-purpose
interconnectors
(hybrid)*

Being established – Current regulatory frameworks traditionally support either development of generators or interconnectors, rather than encouraging assets which use both (i.e. hybrids). As a result, there isn’t a mechanism to ensure costs are shared out an borne by all parties and countries which benefit from them. Work is currently ongoing to establish business models which work for all parties and can encourage investment (likely form of cap and floor).



Notes: *combining offshore wind with interconnectors forms a hybrid interconnector.

Political feasibility – transnational collaboration required to ensure geopolitical alignment as highlighted by previous energy collaboration efforts

Previous/Pre-existing energy initiatives built to secure transnational energy projects

1 NSCOGI/NSEC



North Seas Energy Cooperation

Purpose

- To facilitate **coordinated development of a North Seas offshore grid**, integrating offshore wind energy and **enhancing interconnections between North Seas countries**

Output

- Key foundational work for cross-border transmission (e.g. **North Sea Link**)
- Has produced several **reports** and **studies** to guide the development of the offshore grid
- The initiative's work has been **integrated** into the Political Declaration on energy **cooperation between the North Seas Countries**

2 GEIDCO



Global Energy Interconnection Development and Cooperation Organization
全球能源互联网发展合作组织

Purpose

- To **promote the establishment of a Global Energy Interconnection (GEI) system**, to meet global power demand with clean and green alternatives, to implement the United Nations "Sustainable Energy for All" and climate change initiatives

Output

- Conducted **in-depth studies** on the economic and social development, energy resources, and electricity supply and demand of over 100 countries
- Proposed the **GEI Backbone Grid plan**, focusing on accelerating GEI development and building a modern energy system dominated by clean energy

3 TERAMed



Purpose

- Launched during the Cairo Sustainable Energy Week in 2024, aims to set a common target of 1 terawatt of renewable energy capacity in the Mediterranean region by 2030

Output

- Organized high-level panels and discussions at international forums, such as COP29, to promote the initiative and encourage official commitments from regional governments

Development of new energy pathways bring new geopolitical and security challenges

1

Geopolitical Risks: Subsea cables can cross multiple jurisdictions, exposing them to **geopolitical tensions**, disputes, or unilateral actions by transit countries. Could result in geopolitical sabotage or limitation of infrastructure.



Case Study 1

1

- 1) Severing of **four** subsea telecommunications cables in the **Baltic Sea** in November 2024 in an incident that appears to be **politically motivated**
- 2) Severing of subsea cables in **Red Sea** affecting 25% of data traffic flowing between Asia and Europe

3

Dependence on Imports: Relying on subsea cables for electricity imports creates a dependency on external energy sources, potentially compromising domestic energy security during disruptions.

2

Physical Vulnerability: Cables are susceptible to damage from **natural disasters** (e.g., earthquakes, underwater landslides), and **human activities** (e.g., fishing, anchoring).



2

Case Study

- 1) **Seismic** activity causes damage to four subsea cables in West Africa, **disconnecting** 7 countries from internet connection

4

Repair and Maintenance Challenges: Repairing subsea cables is **time-consuming** and **costly**, requiring specialized ships and equipment, leading to prolonged outages in case of damage.



Recommendations for faster rollout

- 1) **Cross-border transmission to be placed on the global action agenda, including via the COP process and through key global actors such as MDBs, global grids initiatives**
- 2) **Within and across regions, key countries must consider cross-border transmission as part of a strategic vision for network expansion**
- 3) **Implementation will be on decadal timescales, requiring sustained political will starting now**
 - Support & derisking mechanisms for cost effective demonstrator projects to be realised
 - Detailed cost-benefit analyses for longer-term projects must strongly consider impacts on consumer bills to increase political acceptance
 - Introduce business models and begin or advance political cooperation processes
- 4) **Address skills, components (e.g. HVDC cables) and materials gaps**



Next steps for the workstream

- **Standalone paper on the potential for Cross-border transmission will be published in 2025** – alongside integrated Power systems transformation report
- **Final workshop on Power systems transformation (key enablers) to be held early next year**



Upcoming workshops

Grid build challenge

Briefing note published in September 2024

March 26th

Key technologies to balance the system: *dispatchable generation, energy storage, heat storage*

June 18th

Key technologies to balance the system: *demand side flexibility*

Blog published in November 2024

Oct 9th

Sizing the system balancing challenge

Oct 24th

Potential of cross-border transmission

End 2024

Key enablers

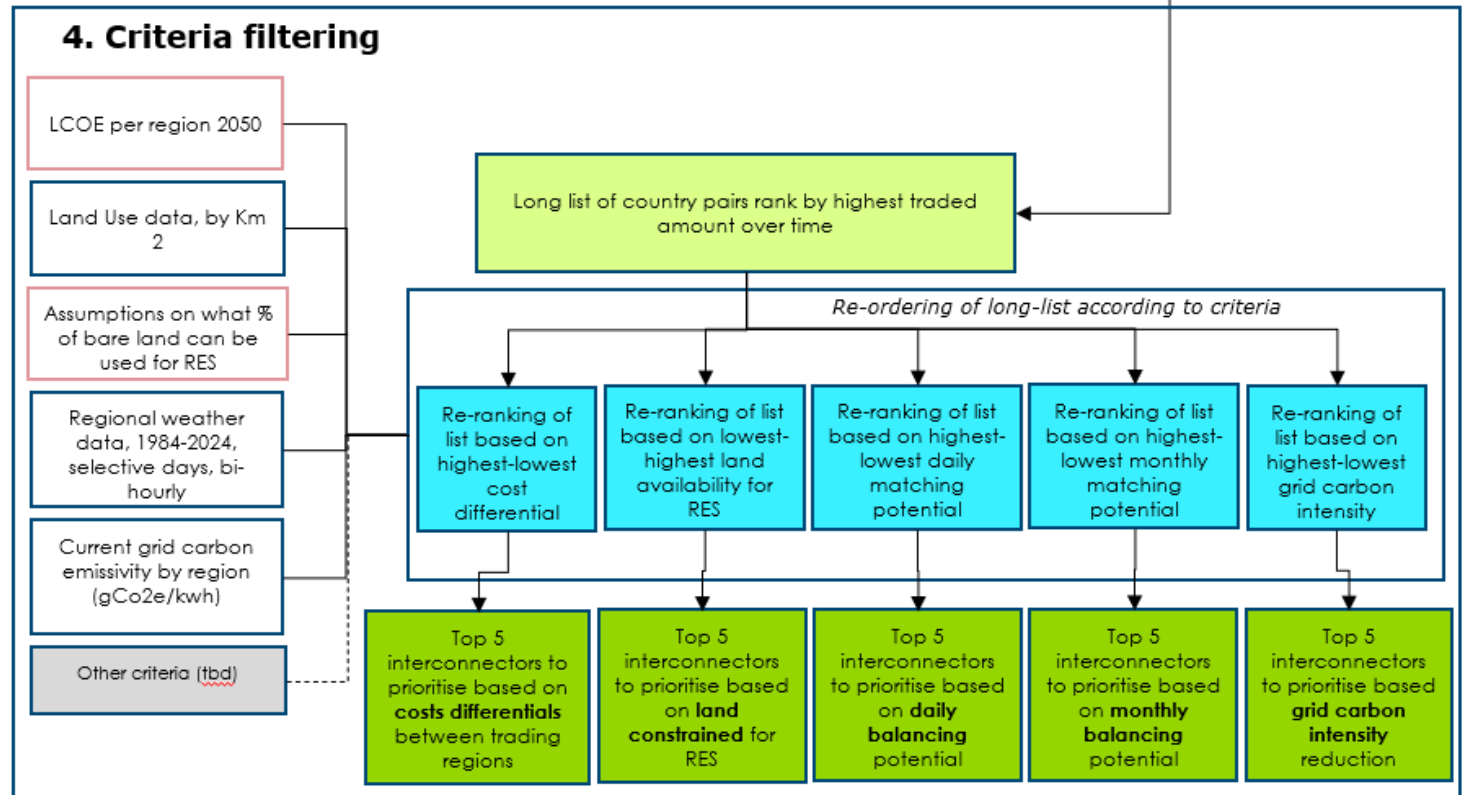
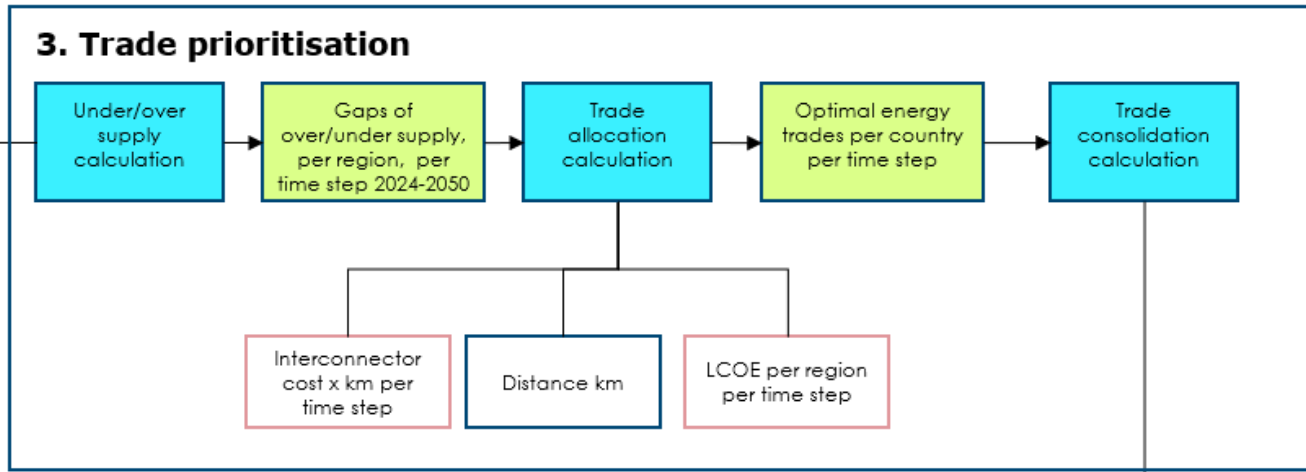
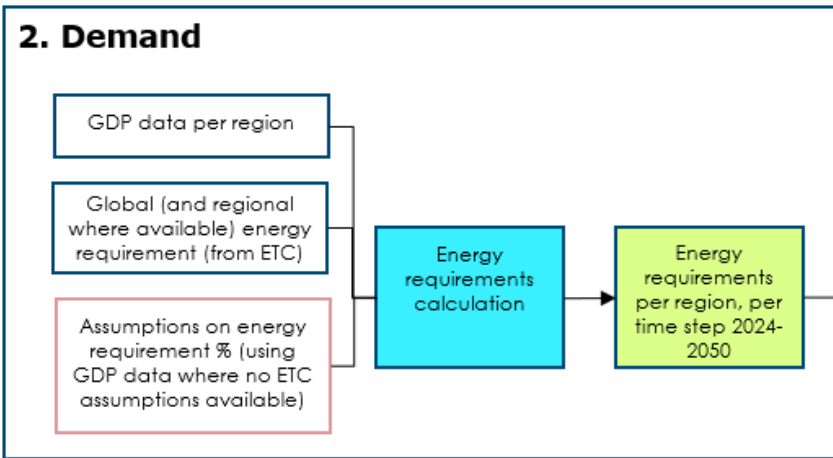
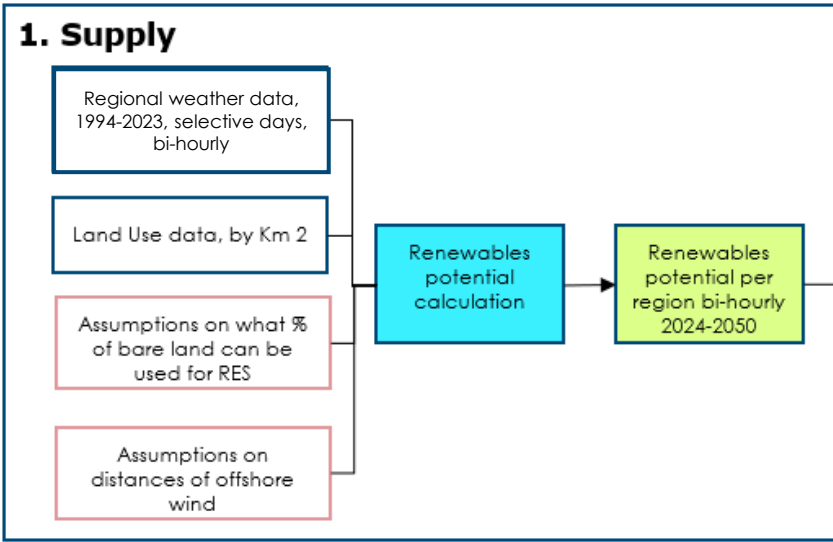
Early 2025



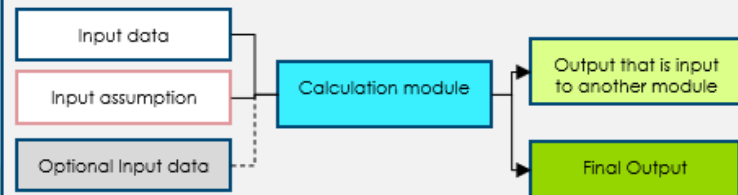
Technical Annex



Model outline – we created a model to bring together global demand and potential supply



Legend



Methodology – Estimating supply potential

Supply

+

Demand



Trade prioritisation



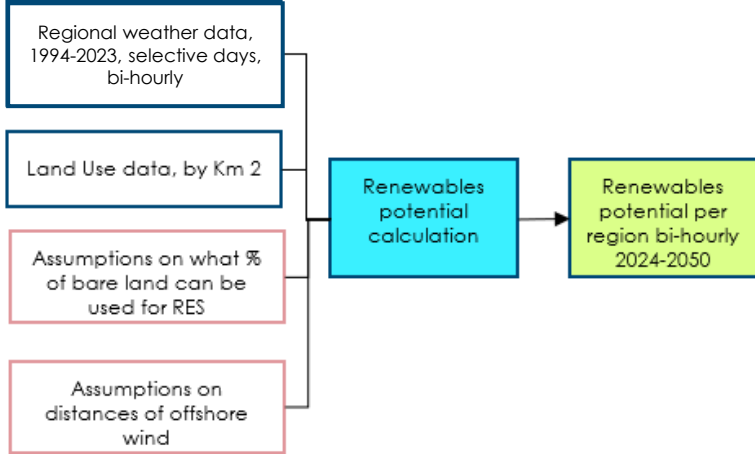
Criteria filtering

1. Estimate total 2050 potential wind and solar supply for each country
2. Forecast 2050 demand for each country
3. Estimate 2050 LCOE data for wind and solar for each country
4. Establish costs of transmitting power between countries
5. 'Solve' for a long list of top interconnectors by highest traded value over time
6. Filter by key criteria to establish a useable set of results

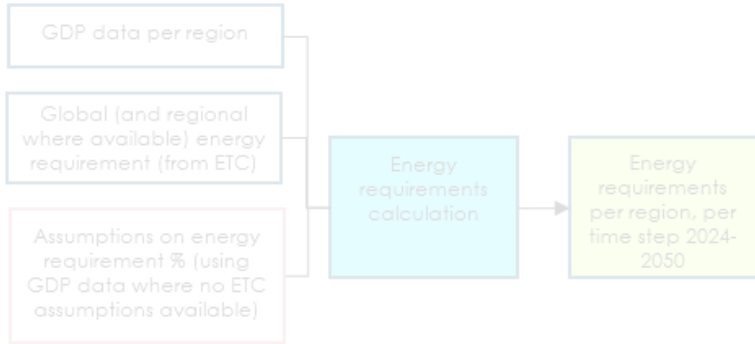


Model outline – focus on supply inputs

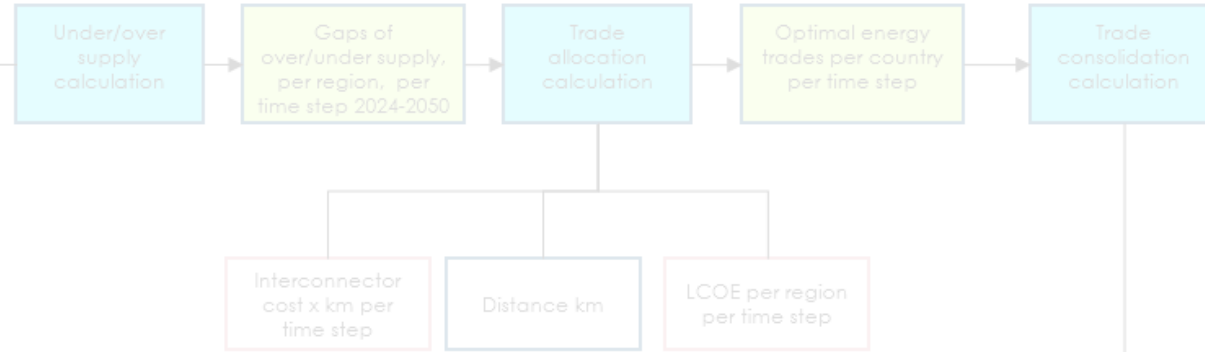
1. Supply



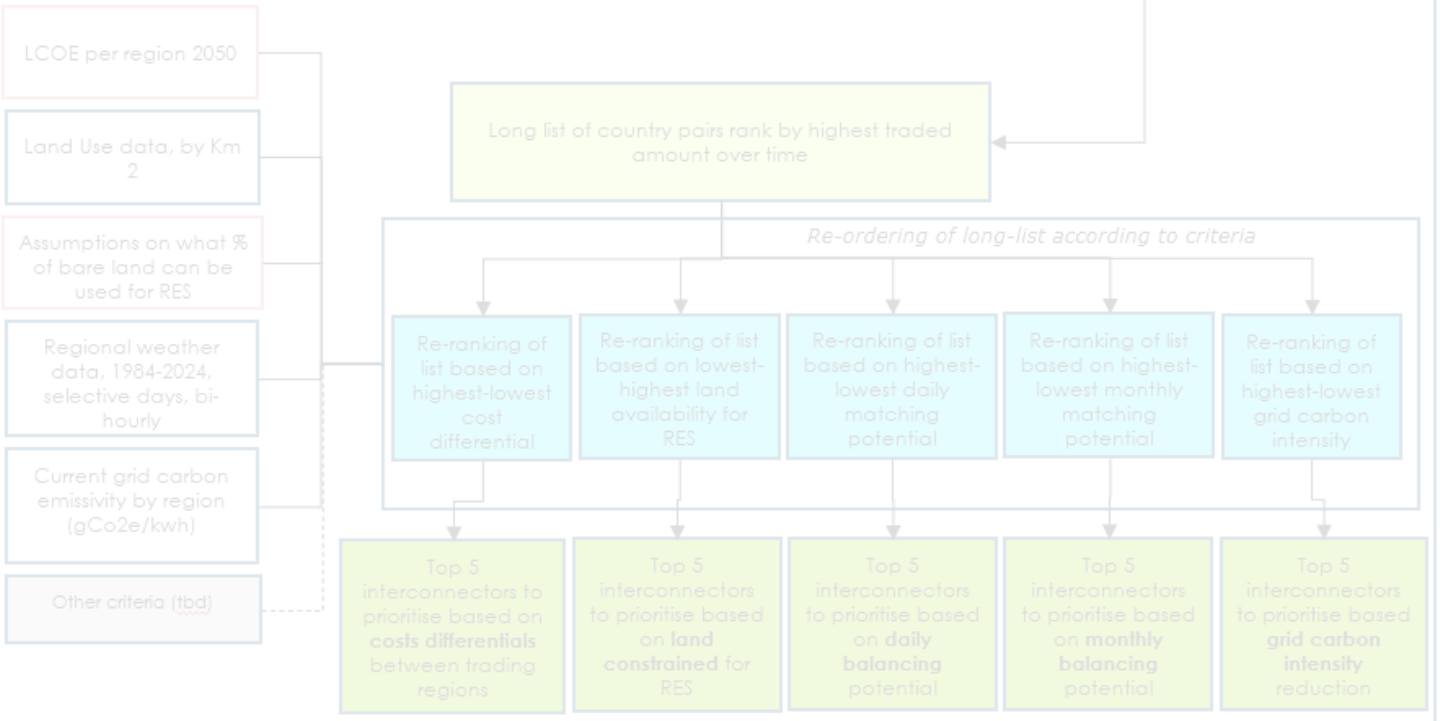
2. Demand



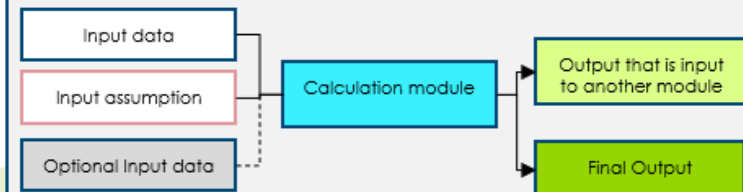
3. Trade prioritisation



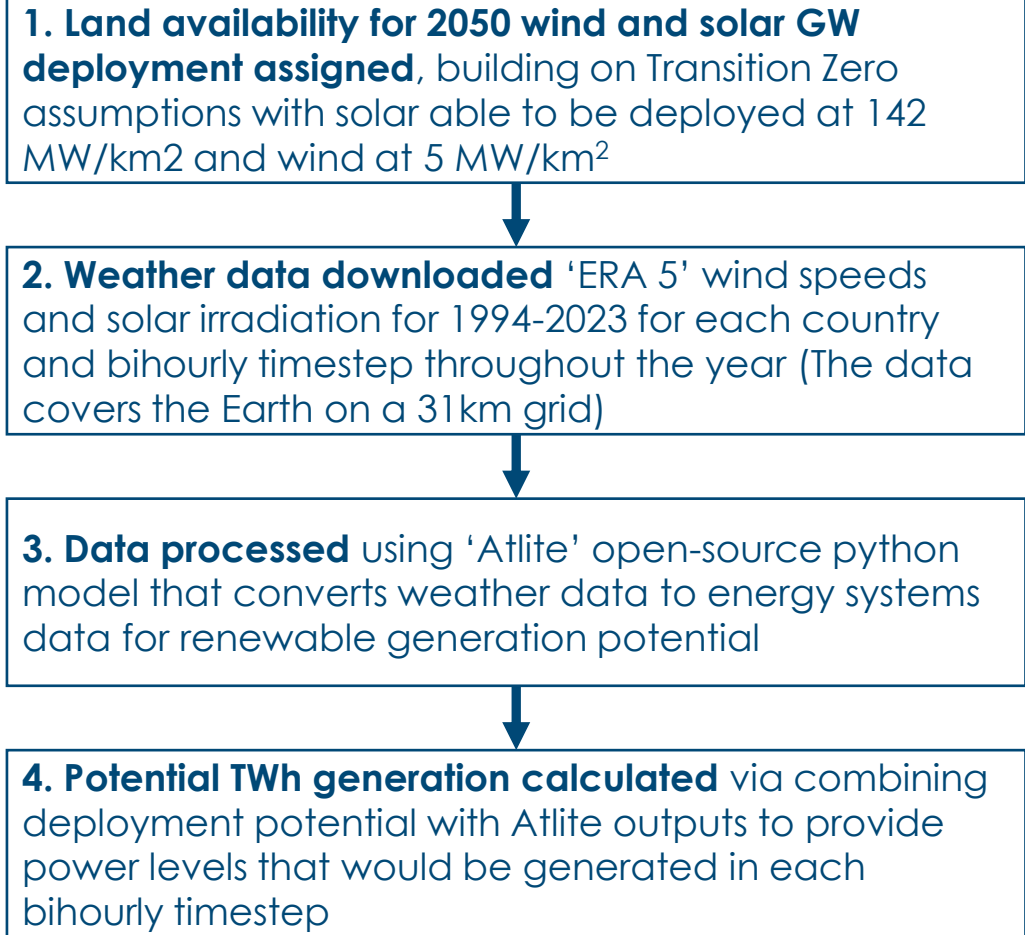
4. Criteria filtering



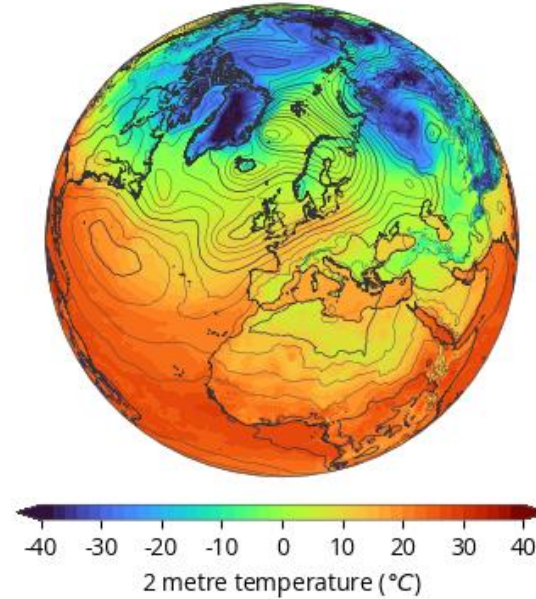
Legend



Weather data and supply side modelling: key steps



ERA5 2 metre temperature and Mean sea level pressure
1 January 2023 at 00:00 UTC



Assumptions on available land to deploy wind and solar were sourced and adapted from Transition Zero's analysis

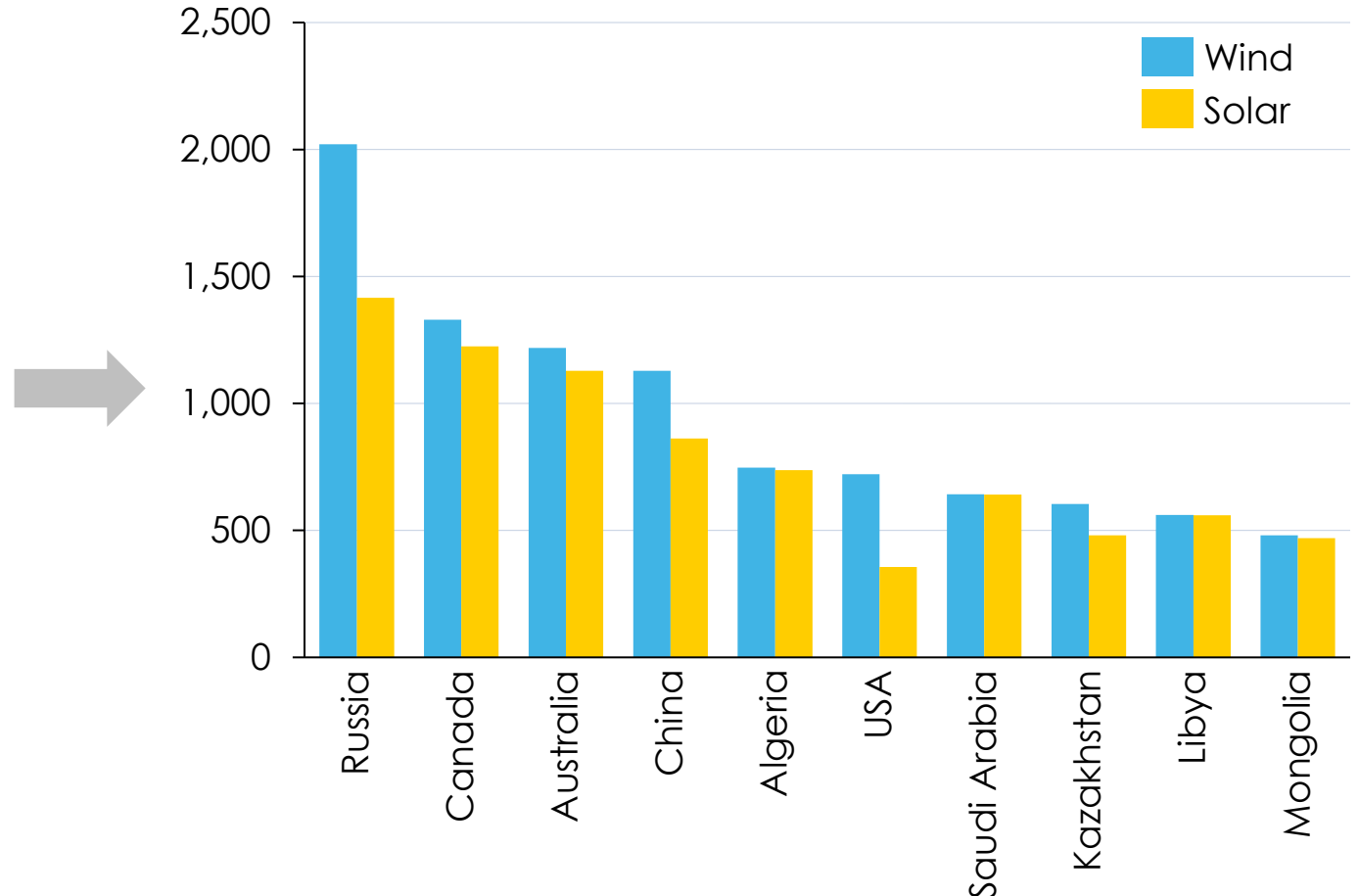
Inputs for land availability

% available for renewable deployment by land type

Land Type	Solar Usable Land (%)	Onshore Wind Usable Land (%)
Urban	1.2	0
Cropland	1	15
Shrubs and vegetation	1	15
Bare	17	33
Water, wetland, moss and ice	0	0
Protected Areas	0	0
Forest	0	0
Installed capacities per area assumptions	142 MW/km ²	5 MW/km ²

Top 10 countries with high wind and solar land availability

000's km² available land for wind and solar



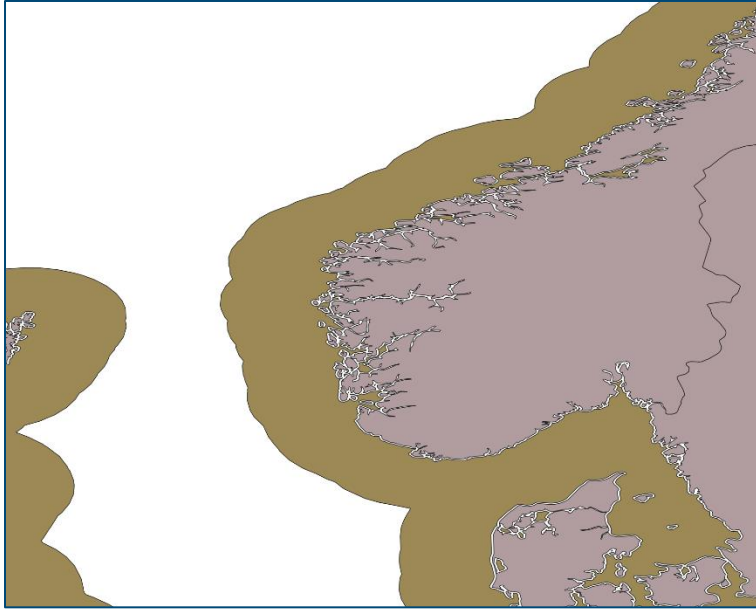
Notes: Percentage of useable land for each type amended from Transition Zero's report. In some instances % of useable land is increased i.e. 0.03% -> 1% for solar on cropland to reflect potential of 'agrisolar', and 3% -> 15% for wind on cropland to reflect lower perceived barriers between turbines and crops. Conservative assumption of 5 MW/ km² used for wind so as not to create an overabundance given higher percentages of available land.

Source: Systemiq analysis for the ETC; Transition Zero (2023), *Cables to change the world*.



Potential offshore wind farm locations was calculated by overlaying multiple sets of data

Area available for offshore wind from shoreline



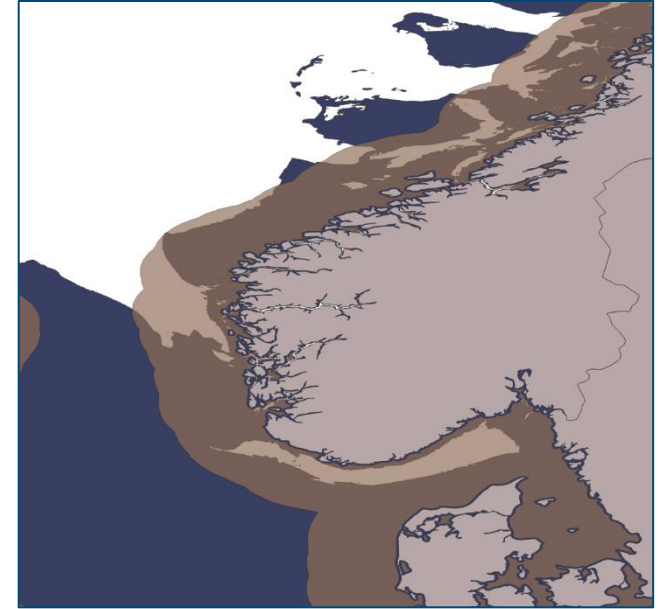
Offshore wind farms can only be placed between **5 km and 200 km** away from shore

Area with allowable depth for offshore wind



They can only be placed in waters less than **300 meters** deep (dark blue)

Area available for offshore wind capacity



Overlaying the data layers provides the areas where offshore wind can be placed. We assume 20% of this space can be used

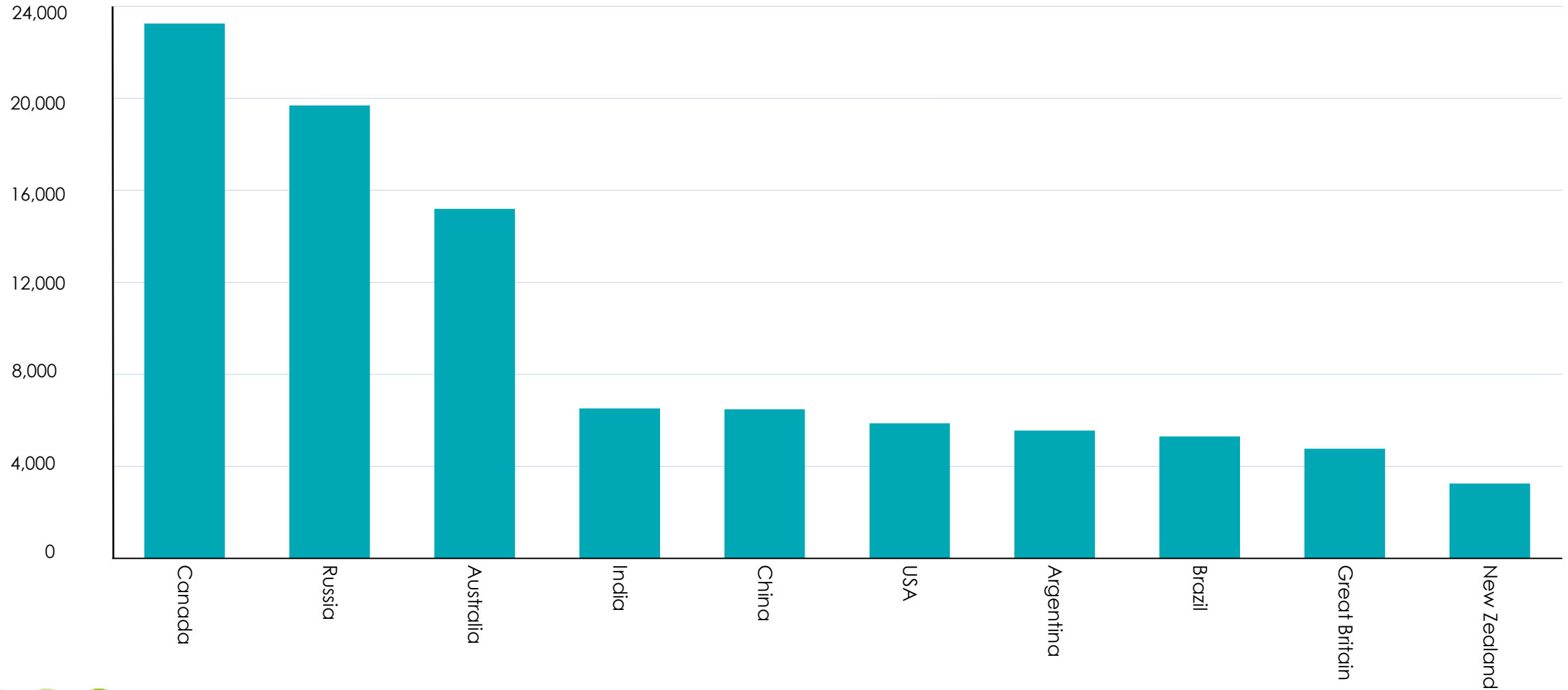


Notes: The remaining 80% of sea space may in reality be utilised by other needs, such as military zones, areas of nature preservation, fisheries, etc.
Source: Systemiq analysis for the ETC;

Canada, Russia and Australia have the largest potential for offshore wind generation

Top 10 countries for offshore wind potential

Annual offshore wind TWh potential



Source: Systemiq analysis for the ETC

Methodology – Estimating 2050 demand

Supply

+

Demand



Trade prioritisation



Criteria filtering

1. Estimate total 2050 potential wind and solar supply for each country

2. Forecast 2050 demand for each country

3. Estimate 2050 LCOE data for wind and solar for each country

4. Establish costs of transmitting power between countries

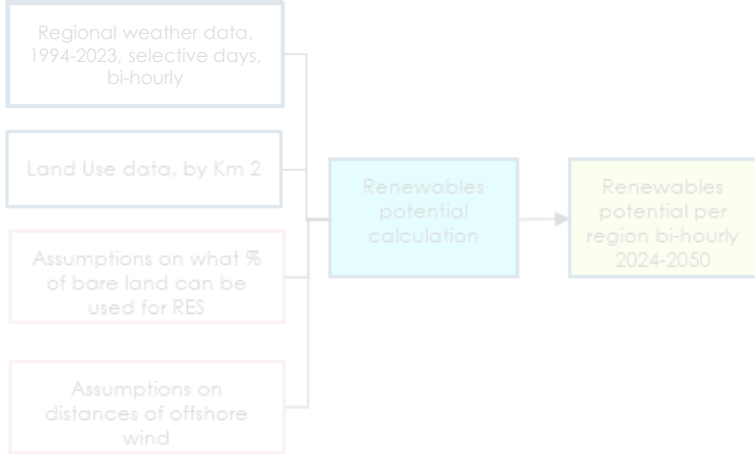
5. 'Solve' for a long list of top interconnectors by highest traded value over time

6. Filter by key criteria to establish a useable set of results

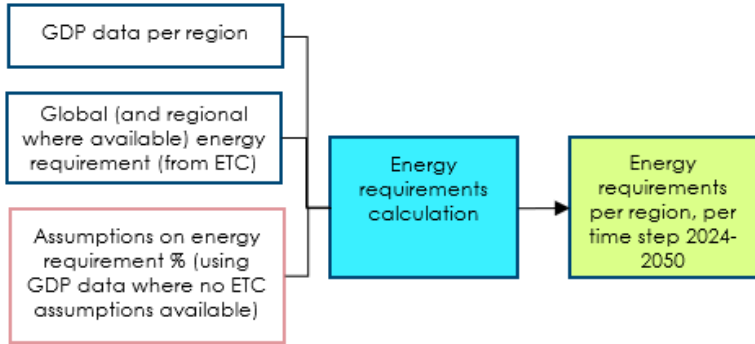


Model outline – Demand inputs

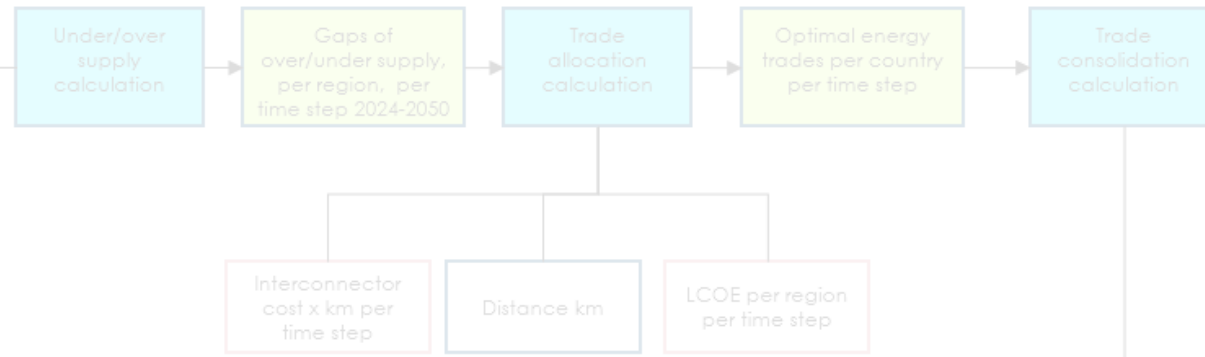
1. Supply



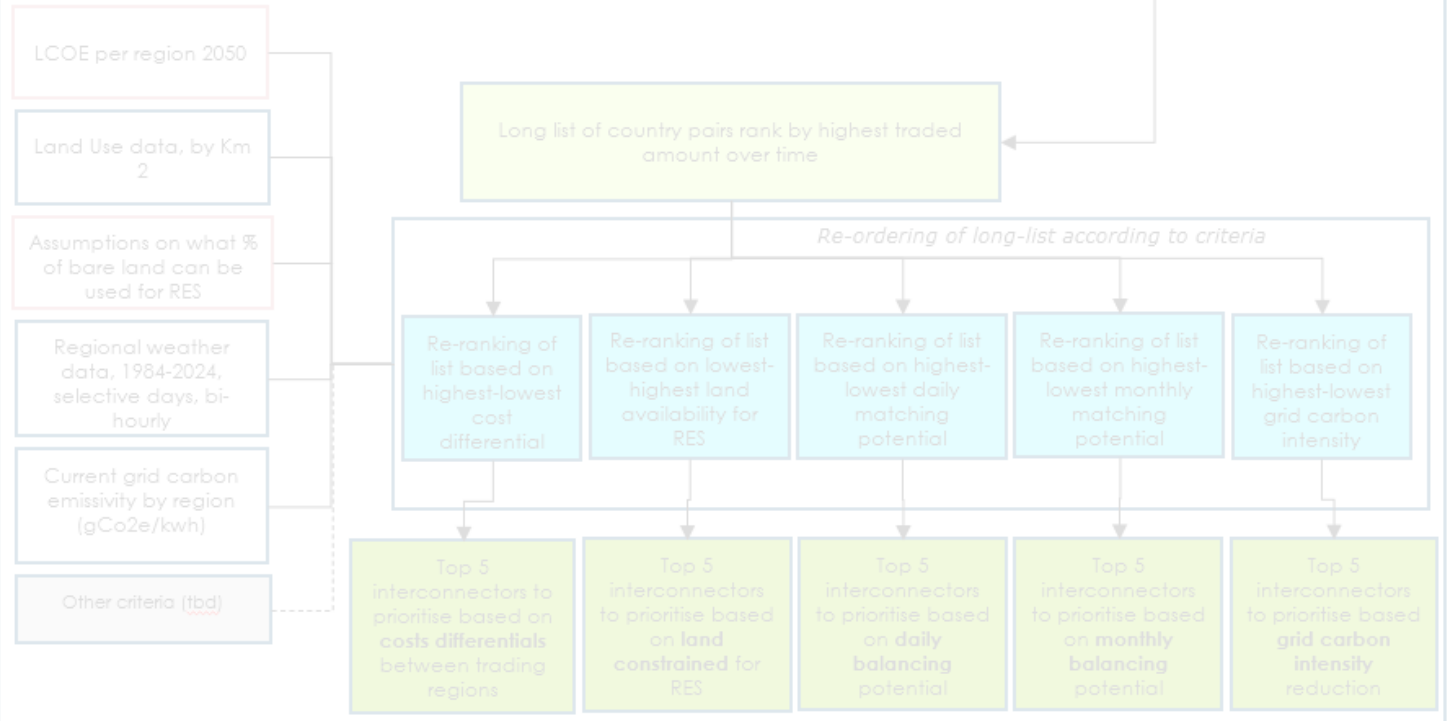
2. Demand



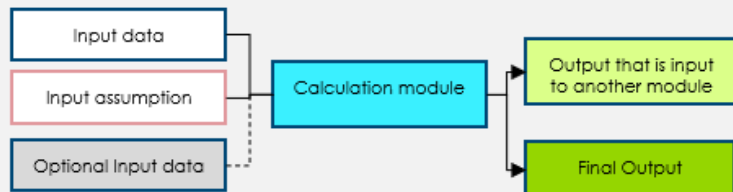
3. Trade prioritisation



4. Criteria filtering



Legend

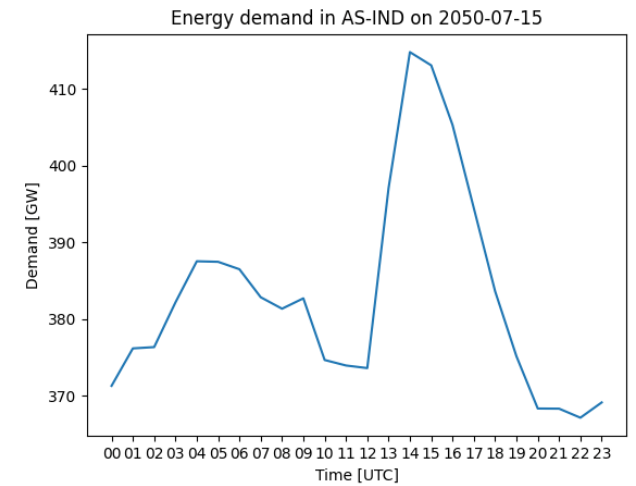
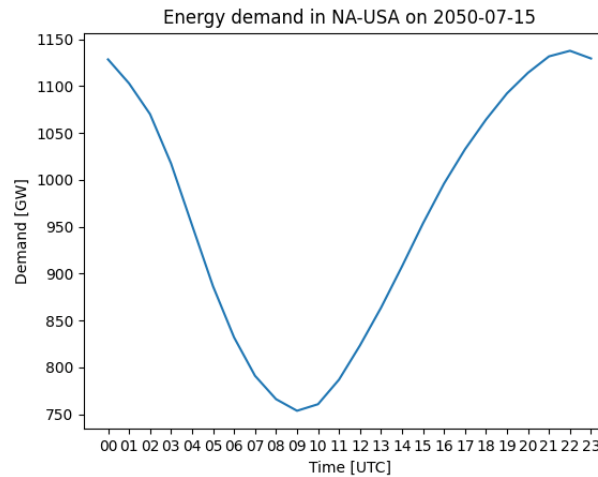
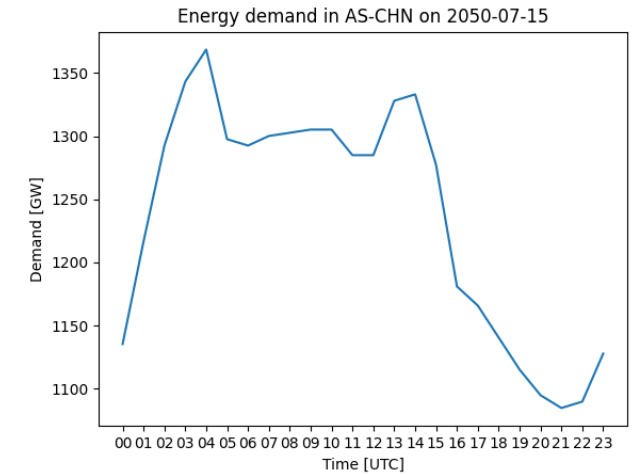
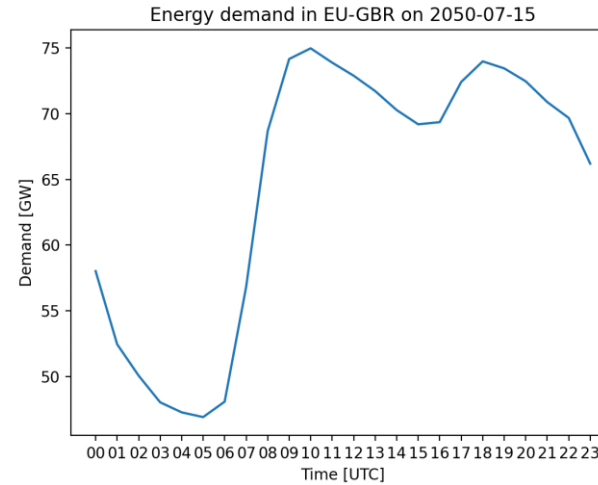


Demand side needs calculated on a bi-hourly basis, using PLEXOS 2015 demand curves scaled up to ETC and BNEF NZS 2050 projections

1. Hourly demand curves obtained via the PLEXOS 2015 for every country for 2015

2. Scaled 2015 curves to projected 2050 demand levels, based on ETC Fossil Fuels in Transition Possible But Stretching targets, and BNEF Net Zero Scenario projections

3. Averaged between original PLEXOS curves and fully scaled projections for more accurate peak demands, as direct scaling led to overly high peak demands (representing some implicit demand side flexibility)



Methodology – Prioritising trade between countries

Supply

+

Demand



Trade prioritisation



Criteria filtering

1. Estimate total 2050 potential wind and solar supply for each country

2. Forecast 2050 demand for each country

3. Estimate 2050 LCOE data for wind and solar for each country

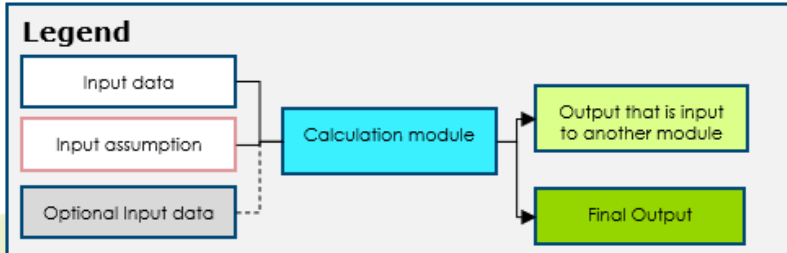
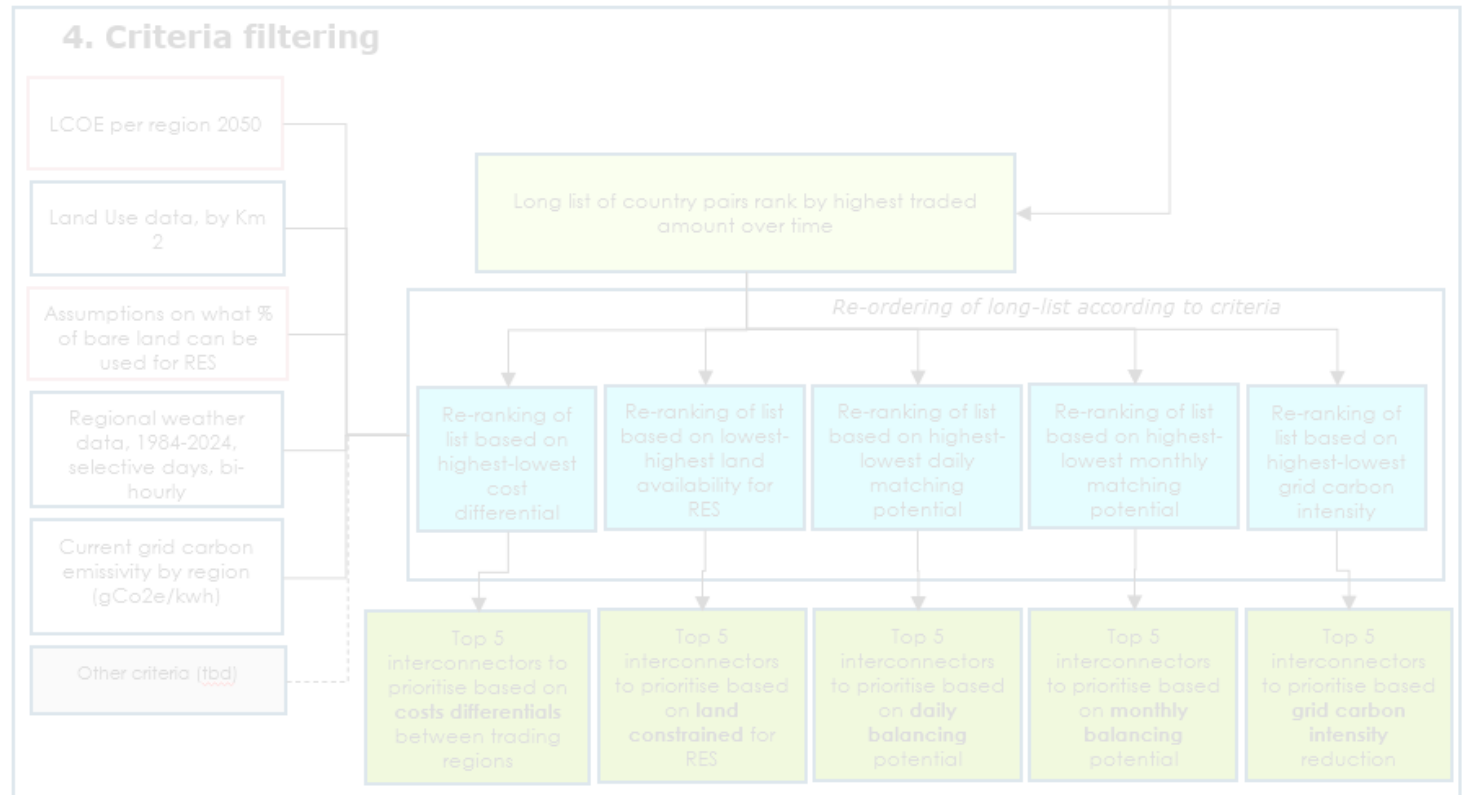
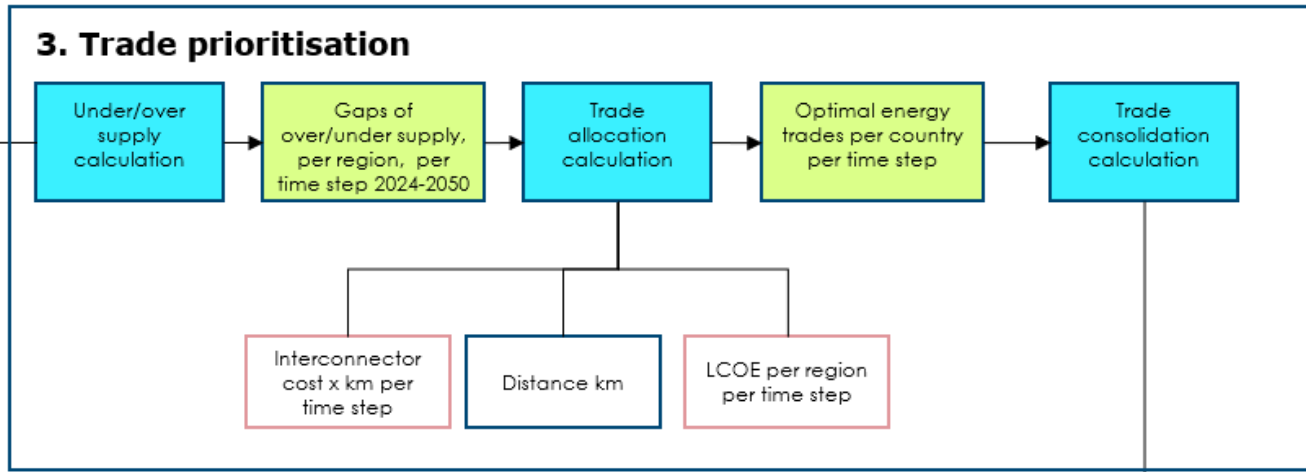
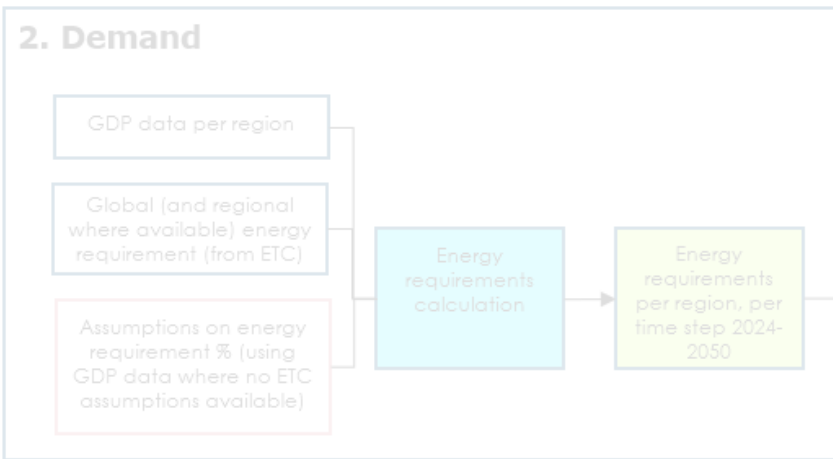
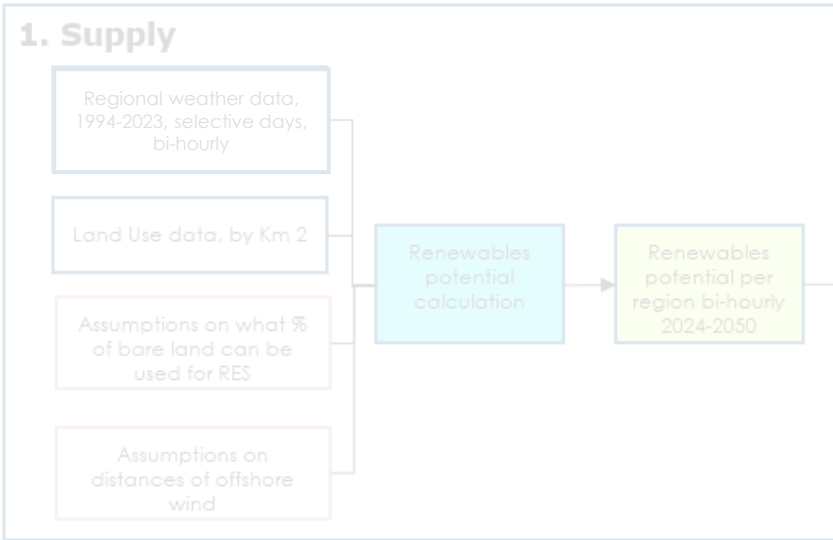
4. Establish costs of transmitting power between countries

5. 'Solve' for a long list of top interconnectors by highest traded value over time

6. Filter by key criteria to establish a useable set of results



Model outline – Trade prioritisation



Cost-optimised trade prioritisation: key steps

1. BNEF 2050 Levelised Costs of Electricity assigned to each country for solar, onshore and offshore wind



2. Transmission costs assigned to each region based on representative 2023 BNEF costs, splitting the globe into 3 regions



3. Where there is geographic potential for renewables to be deployed (i.e. land availability) the model **optimises for deployment of wind, solar and transmission** starting from a base of no generation or transmission installed



LCOE estimates were taken from BNEF wherever possible, however some data gaps had to be addressed

1. Source Directly from BNEF

- BNEF central estimates for 2050 for Solar PV, onshore and offshore wind
- Example countries where this was applied
 - UK
 - Australia
 - USA
 - China
 - South Africa

2. Make informed judgements on countries where BNEF forecasts not available

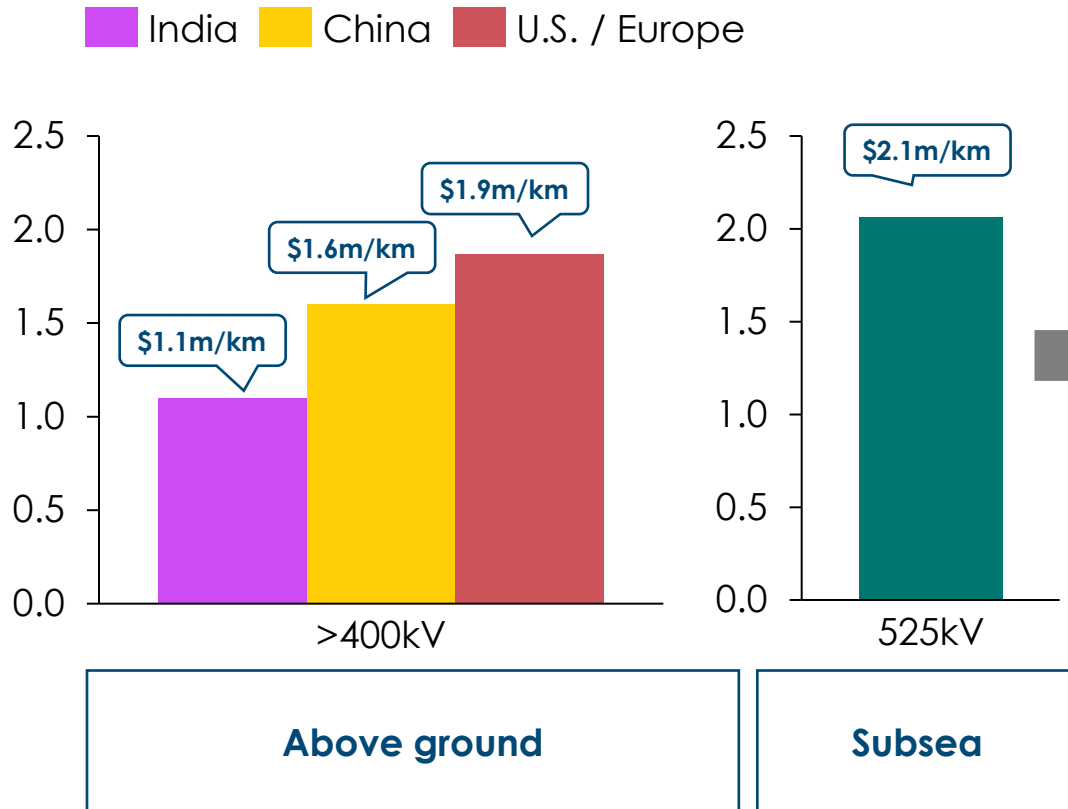
- Informed by ETC judgement, closest country values used wherever possible
- Example of countries where this was applied:
 - Western Europe solar = German values
 - Latin America onshore = Chile values
 - East Asia offshore = Japanese values
- Where directly applying other values doesn't accurately reflect risk, additional risk factor applied, i.e. Onshore wind in Libya and Sudan = closest values (Spanish) *1.5



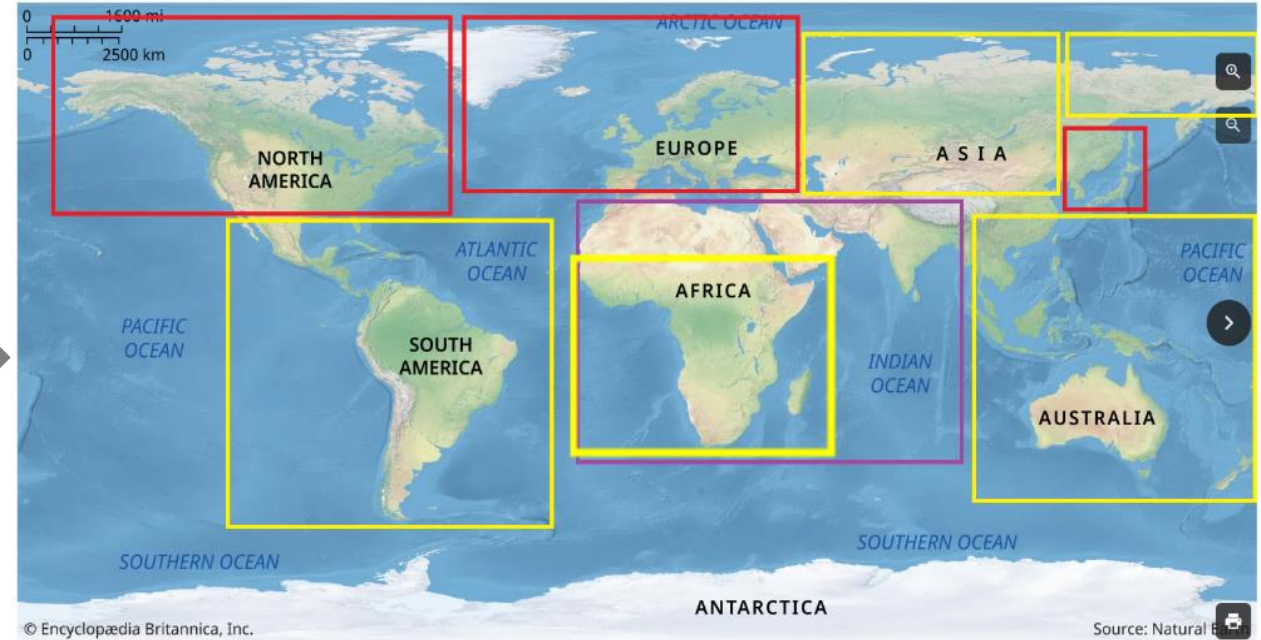
Interconnector costs vary across regions, with new US/European transmission most expensive and cheapest in India

Cost of constructing power lines

\$ m/km 4 GW, 4000 km, 2024 nominal costs



Transferring costs from BNEF to regions across the interconnection model

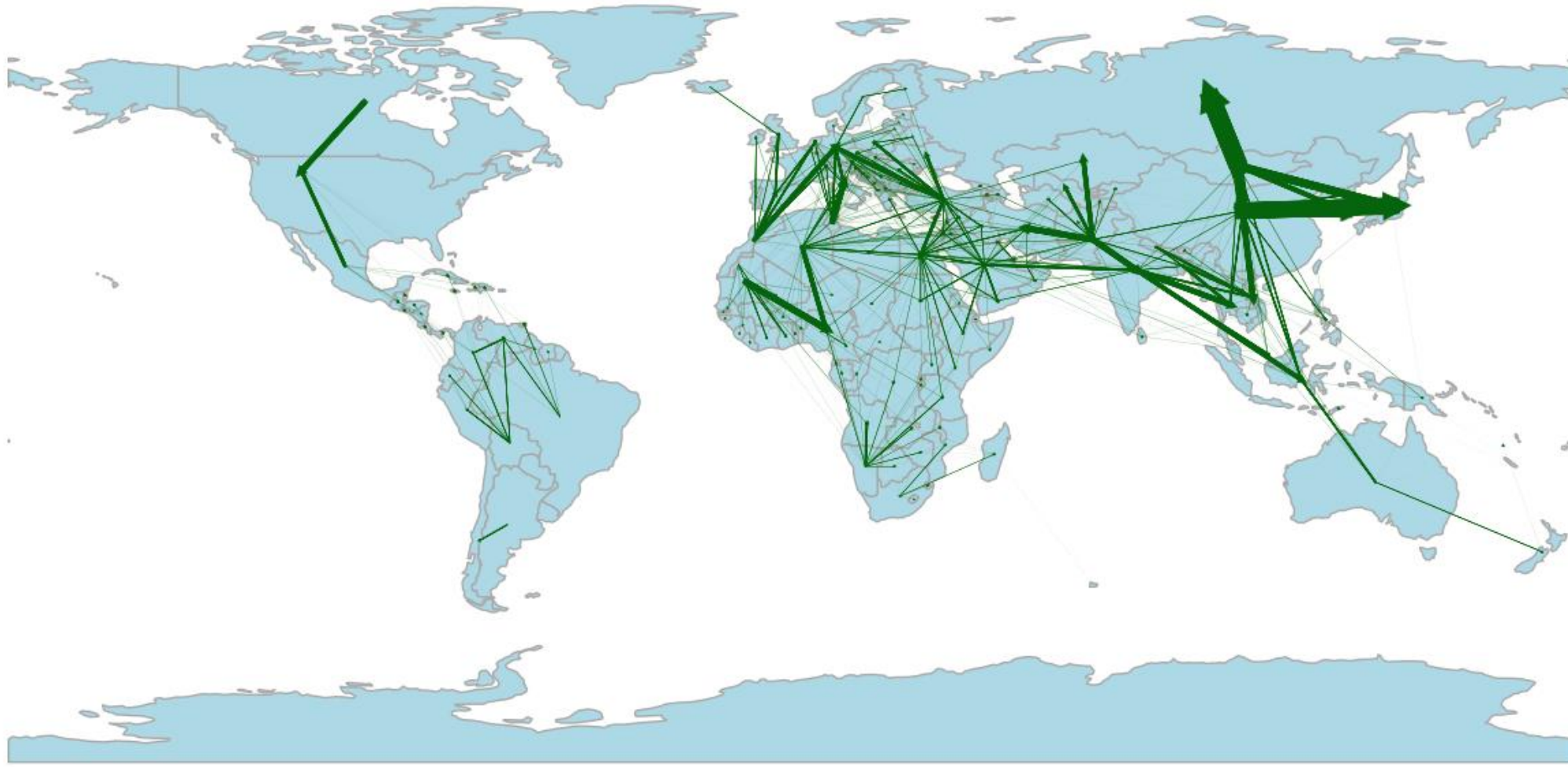


Cost per MWh per 1000km

- Subsea \$5.83/(MWh*1000km)
- Red (Europe/US) \$5.30/(MWh*1000km)
- Yellow (China equivalent) \$4.45/(MWh*1000km)
- Pink (India equivalent) \$3.04/MWh*1000km

Note: Representative grid costs based on BNEF's GridVal model, based upon 4000 km projects with MW capacities 2,000 for wires at voltage levels of ~500 kV. Included HVDC converter station costs at \$1.1bn per pair, and financing costs at 5% paid off over a 10-year period.. Average of US and European costs used.
 Source: Systemiq analysis for the ETC; BNEF (2024), *Grid Capex Cost Model (GridVal V1.0)*; conversations with expert stakeholders.

First results: The default solution suggests heaviest trade between China and neighbours as well as between MENA and Europe (before criteria filtering)



This image shows all interconnectors of the solution, where arrow thickness is proportionate to trade volume

Methodology – Prioritising trade between countries

Supply

+

Demand



Trade prioritisation

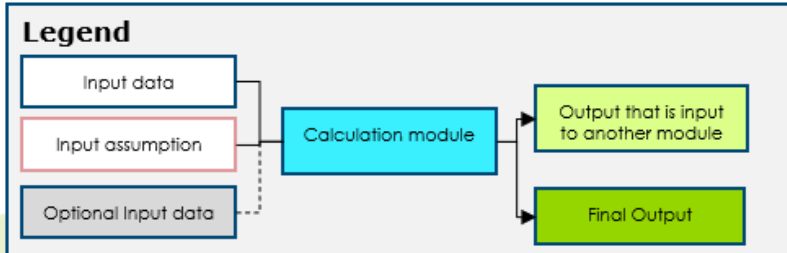
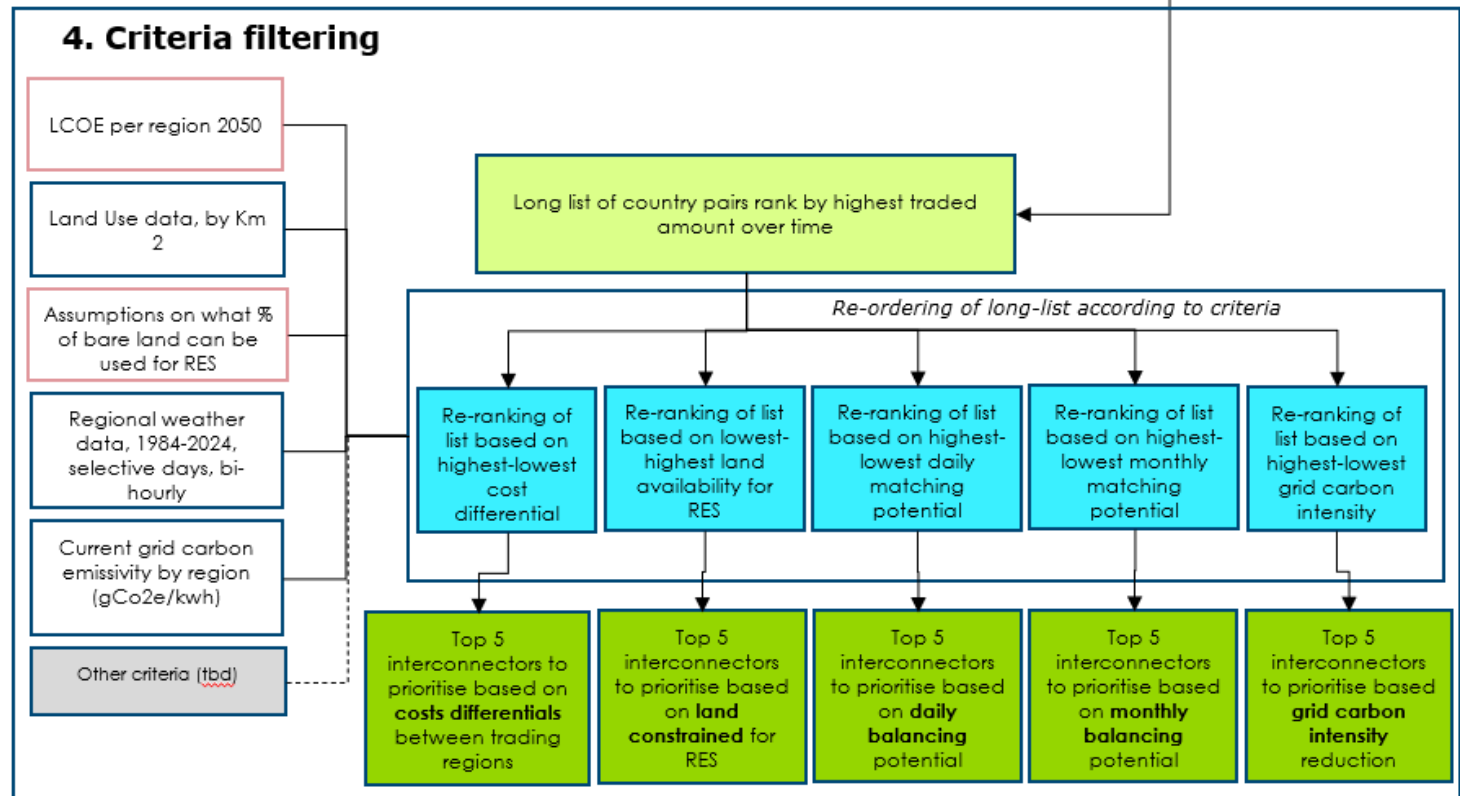
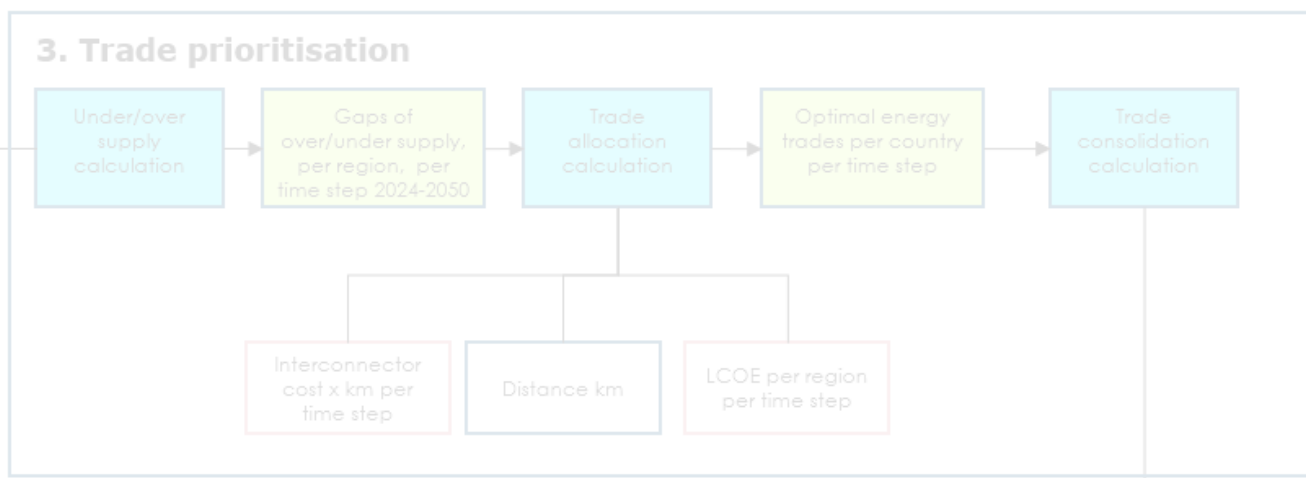
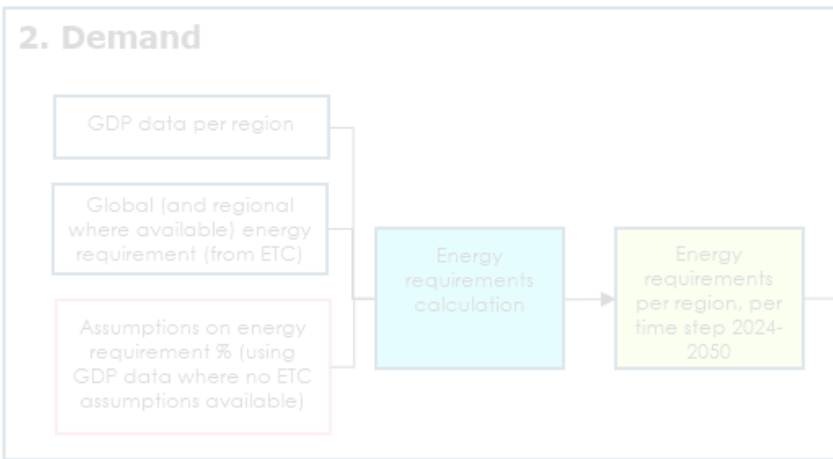
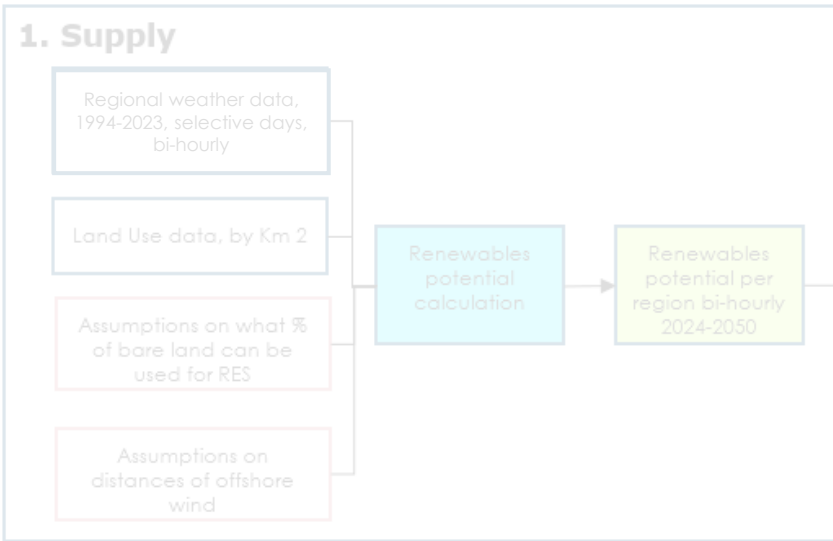


Criteria filtering

1. Estimate total 2050 potential wind and solar supply for each country
2. Forecast 2050 demand for each country
3. Estimate 2050 LCOE data for wind and solar for each country
4. Establish costs of transmitting power between countries
5. 'Solve' for a long list of top interconnectors by highest traded value over time
6. Filter by key criteria to establish a useable set of results



Model outline – Trade prioritisation



The model's output top 100 lines by size will be filtered across key criteria

Criteria

Methodology

Total volume traded

The largest feasible transmission lines by total volume traded (i.e. the cables with the highest annual traded volume in TWh)

Cost-effectiveness

The lines with largest cost differential between importing, or sink country, LCOE (wind or solar if land is available, offshore wind if no land is available); minus exporting, or source country, LCOE (weighted average of wind and solar utilised); minus transmission costs.

Daily and seasonal balancing

The lines which provide the receiving country with the largest balancing benefits i.e. connections to countries who can provide power most consistently throughout the hours on a daily basis, and throughout the weeks on a seasonal basis

Emissions reduction

The lines which would provide the largest carbon emissions reductions based on difference between the new clean power source (assumed to be 0) and 2022 grid emissivity levels multiplied by the annual power which could be sent

Overcome land constraints

The lines that provide power to the smallest sink countries with substantial power demand (in terms of land available for renewables)



**What are the top
interconnectors
across key criteria?**



Top 10 lines across each key criteria (Calculation steps)

Total volume traded

Source country	Sink country	TWh
Mongolia	Russia	895
Mongolia	China	475
Mauritania	Nigeria	305
Saudi Arabia	India	300
Norway	UK	295
Tunisia	Italy	285
Canada	USA	275
Morocco	Germany	225
Pakistan	Kazakhstan	225
Algeria	Nigeria	220
	Total TWh	3480

Cost-effectiveness

Source country	Sink country	Saving per MWh
India	Bangladesh	\$75
Saudi Arabia	Egypt	\$73
Pakistan	Bangladesh	\$72
Pakistan	Kazakhstan	\$70
India	Thailand	\$68
India	Malaysia	\$65
India	Viet Nam	\$64
Tunisia	Italy	\$64
Australia	Indonesia	\$56
Australia	Singapore	\$50
	Total TWh	1300
	Total saving	\$90bn

Daily and seasonal balancing

Source country	Sink country	Balancing coefficient
Saudi Arabia	Egypt	0.94
Saudi Arabia	Sudan	0.92
Saudi Arabia	Ethiopia	0.91
Australia	Indonesia	0.77
Pakistan	Bangladesh	0.76
India	Malaysia	0.75
India	Bangladesh	0.74
Turkey	Czechia	0.62
Canada	USA	0.61
Turkey	Germany	0.60
	Total TWh	930

Emissions reductions

Source country	Sink country	Emissions saving (CO2)
Mongolia	Russia	391
Mongolia	China	278
Pakistan	Kazakhstan	187
Pakistan	Uzbekistan	179
Mauritania	Nigeria	157
India	Thailand	148
India	Indonesia	146
Algeria	Nigeria	114
Tunisia	Italy	108
Canada	USA	106
	Total TWh	3315
	Total MtCO2	1810

Overcome land constraints

Source country	Sink country	Sink land availability (km²)
Sri Lanka	Singapore	100
Morocco	Belgium	1,350
Morocco	Netherlands	2,100
Norway	Denmark	3,500
Turkey	Czechia	3,700
Morocco	Switzerland	3,800
Turkey	Hungary	5,500
Turkey	Bulgaria	9,100
Qatar	Kuwait	10,800
Egypt	Greece	11,700
	Total TWh	480

Calculation steps:

Calculated by taking the lines in terms of total annual potential of TWh traded where supply in the source country can cost-effectively meet demand in the sink country.

Calculated by taking the difference between the sink countries LCOE of available generation – weighted average of source country LCOE – interconnector cost. Total saving calculated by multiplying average saving by total TWh.

Calculated by ranking daily and seasonal balancing metrics (total amount of excess power available in source country at required time period compared to need in sink country) for top 100 interconnectors, combining rankings and dividing by 2.

Calculated by multiplying the total potential annual TWh by the 2023 grid emissivity levels in gCO2/kWh.

Calculated by assessing available land for solar PV or onshore wind deployment, countries only shown which rank in top 100 interconnectors for total volume.