EXECUTIVE SUMMARY

EVOLUTION OF ENERGY NETWORKS:
Decarbonizing the Global Energy Trade

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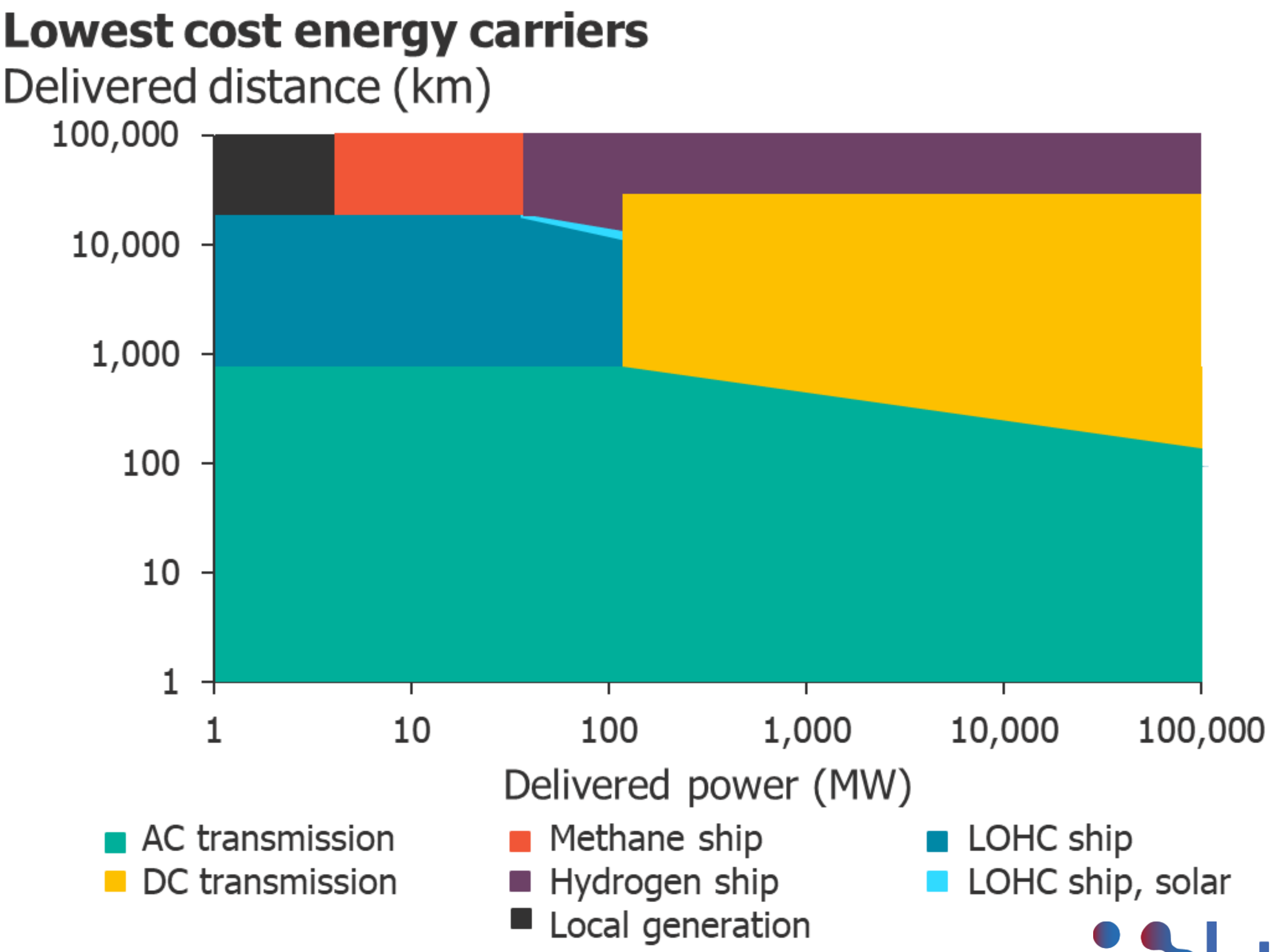
The future global renewable energy trade will be electric

Not every country in the world can satisfy its demand for energy with domestically produced renewable energy; some countries simply lack the land area and resource potential to power their energy-intensive economies. To achieve their decarbonization goals, these countries will need to find a way to import zero-carbon energy.

- **New electricity infrastructure using high-voltage AC or DC transmission lines** will be the primary means of importing low-cost solar energy from distant regions.
- **Power-to-gas technology using pipelines is limited**; shipping liquefied hydrogen, methane, or ammonia offers better economics, but only over long distances.
- Imported energy costs can be competitive against other zero-carbon technologies, but **no energy carrier can offer costs low enough to replace LNG or oil and offer a global renewable energy trade.**



Today's global economies are supported by a global energy trade – one built exclusively on fossil fuels

The growth of the global economy has also resulted in a greater demand for energy. However, not every country can meet its own energy demands through domestic production, and the global energy trade – notably coal, oil, and natural gas – is crucial for many countries to maintain a growing economy due to their limited domestic energy resources. Globally, 2,800 TWh per year is transported from resource-rich regions, such as the Middle East, to energy-intensive regions, such as Southeast Asia.

Not only is the demand for energy imports growing; it is also diversifying. New energy carriers like liquefied natural gas (LNG) tankers are supplementing, or in some cases substituting, the traditional oil and coal vessels that have largely made up the mix of energy imports to date.

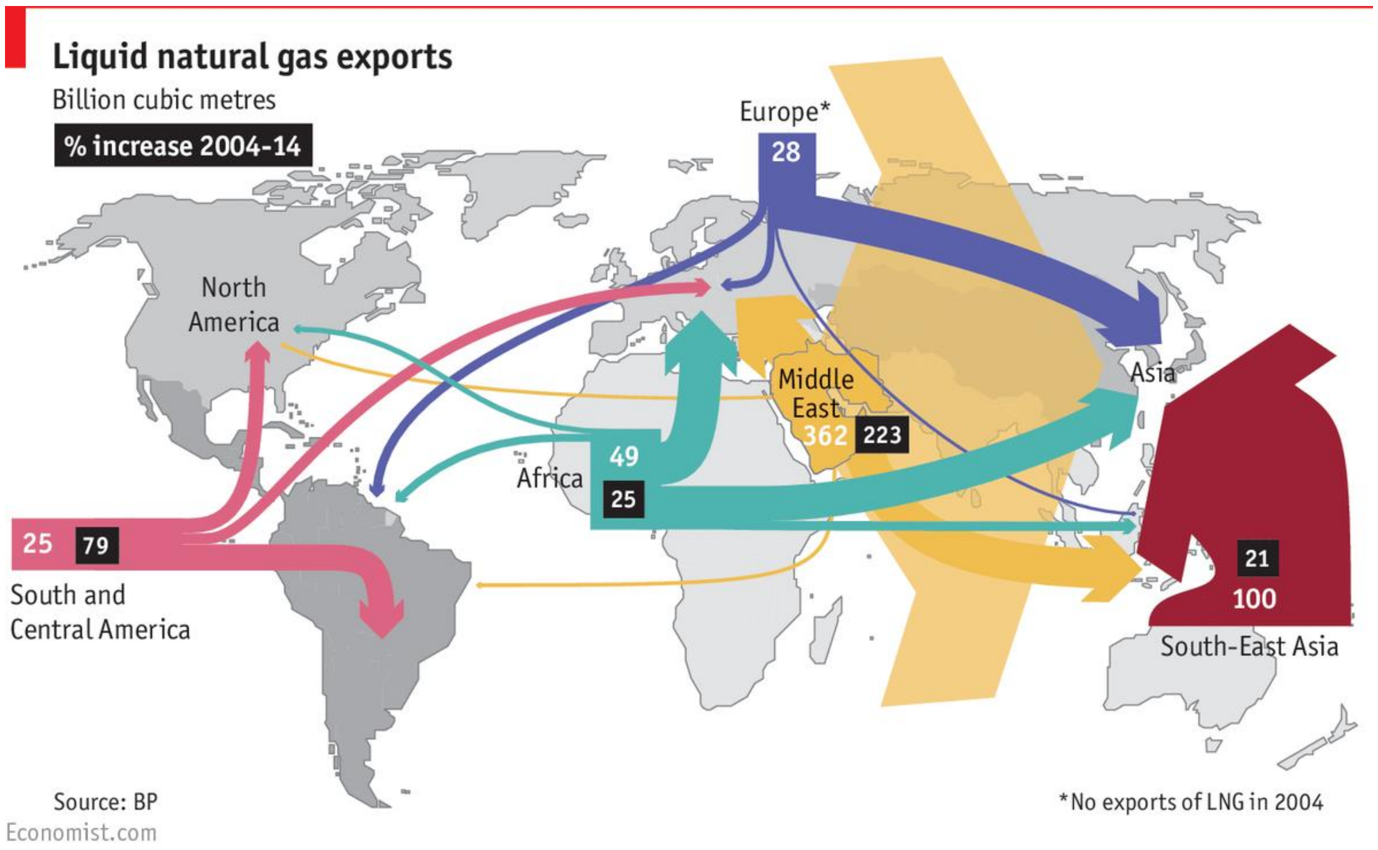


Image Source: The Economist

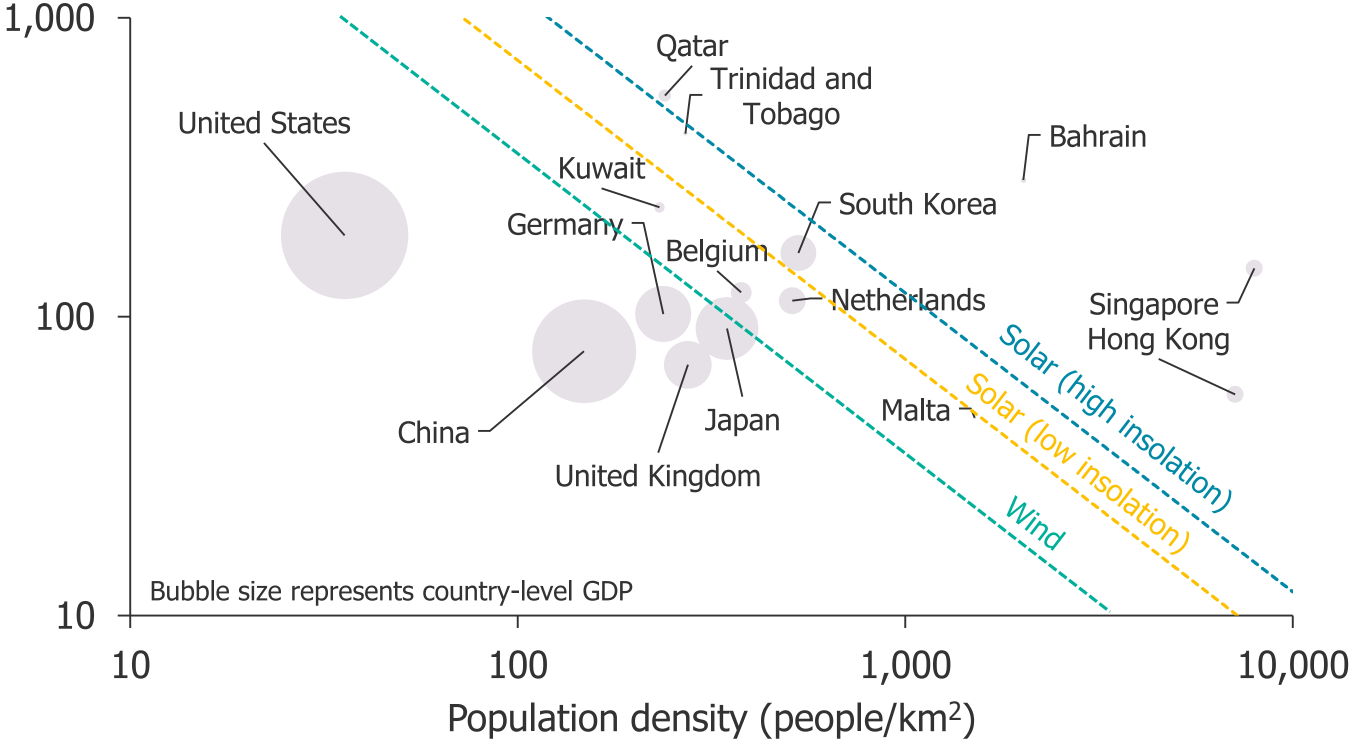
While harnessing the "unlimited" power of sun and wind, renewable energy has similar constraints

In the global push toward decarbonization, many countries are finding it difficult to replace their hydrocarbon-based energy imports with domestic renewables like wind and solar. These new energies also face their own resource limitations. In places like Singapore, Japan, and the Netherlands, energy demand is simply too high to be met with low-energy-density wind and solar alone.

David MacKay of Oxford University illustrated the challenges of meeting energy demand solely through domestic renewable energy. He analyzed population density and per capita energy demand, finding that the power used per unit area in some regions exceeded wind and solar production. Countries representing $9 trillion of global GPD would face difficulties in meeting energy demand with domestic renewable production alone, requiring the import of future energy carriers.

Country-level Energy Demand

Per capital energy demand (kWh/person-day)



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PRESENT AND FUTURE ENERGY CARRIERS

Electricity

Electricity is the sole means of transmitting renewable energy today. There are approximately 5 million kilometers of high-voltage power lines around the world, with roughly 200,000 km added each year. The majority of this transmission line growth is to support renewable energy capacity additions, with China as the leader in new transmission line building to support its wind and solar aspirations.

LUX TAKE

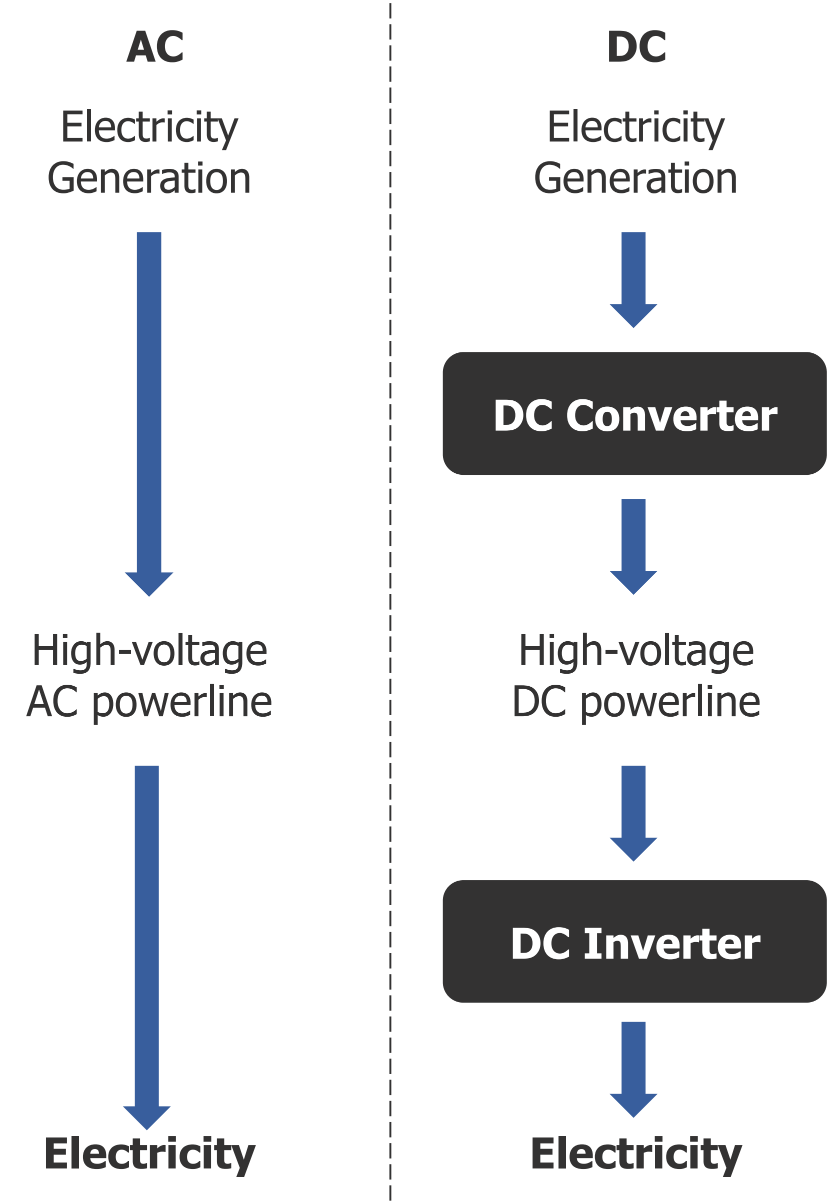
Challenges in the efficiency and cost of long-distance, high-capacity lines have driven regional transmission operators to look to new technologies like ultra-high-voltage AC power lines and high-voltage DC power lines. These higher-efficiency, longer-distance lines better connect remote renewable sources to population centers.

AC & DC Transmission

The only way to connect wind and solar generation to customers today

INTRODUCTION:
AC transmission requires no conversion between the source of electricity and the end customer – only stepping up and down voltage through transformers. Higher voltages can carry more power over longer distances with lower inductive and resistive losses but suffer from higher corona losses as air ionizes near the high-voltage lines.

CHALLENGES AND NEW DEVELOPMENTS:
New AC transmission line projects in China are now above 1,000 kV. These power lines required advances in shielding and insulation to reduce corona losses and improve safety. Other developers like Siemens and ABB are promoting high-voltage DC transmission, which eliminates inductive losses but requires AC-DC and DC-AC conversion through large thyristor or transistor halls.



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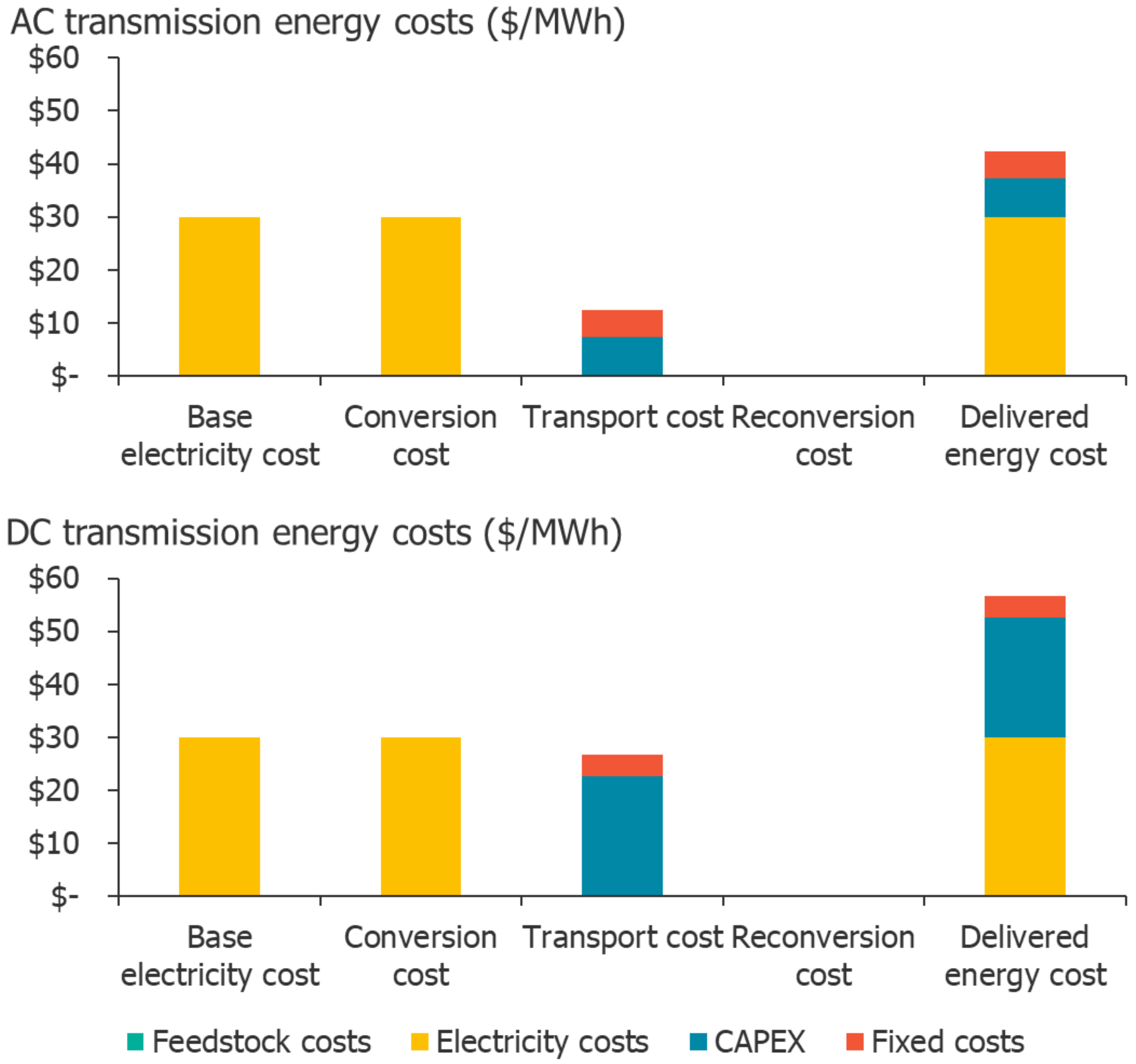
Electricity transmission: 300 MW, 500 km



AC & DC Transmission

For shorter distances or lower power, AC transmission wins out

Lux used a database of AC and DC power line projects to derive the costs of the electricity supply chain. The average power line length and capacity from that database was approximately 500 km and 300 MW – roughly consistent with the scale and distance from load of utility renewable projects. These values are used for the remainder of the analysis.

At 300 MW capacity and 500 km distance, AC lines are the lowest-cost option, adding just $10/MWh to base electricity compared to DC lines, which add $26/MWh. Both AC and DC power lines have less than 5% loss, so conversion costs are effectively base electricity costs. As renewable energy projects get larger and more distant from load centers, AC transmission lines become less compelling and DC transmission begins to be favored.

PRESENT AND FUTURE ENERGY CARRIERS

Pipelines

Pipelines have been used to deliver energy for 200 years, starting with coal gas for street lighting in London. Today, 2 million kilometers of pipelines deployed globally transport crude oil, natural gas, and petrochemicals in regional markets. Natural gas pipelines constitute 65% of total pipeline length, with crude oil pipelines making up an additional 20%. Most pipeline capacity is in the U.S. to support the country's growing oil and gas sector.

LUX TAKE

With the rise of renewable energy, crude oil and natural gas pipelines may quickly become stranded assets. Innovations in pipeline utilization largely come from Germany and Denmark, which have piloted power-to-gas technology to decarbonize their natural gas infrastructure and promote renewables integration.

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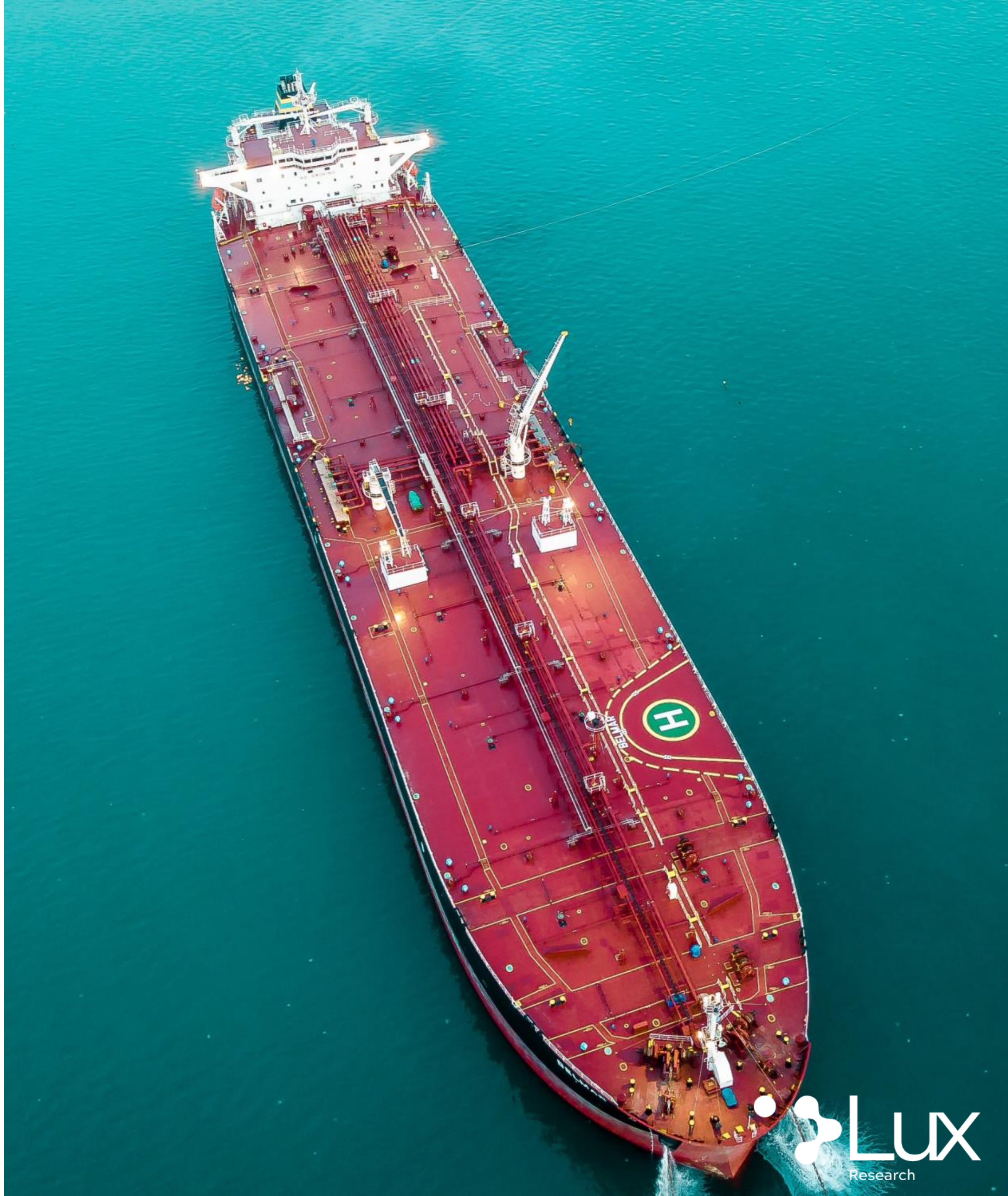
PRESENT AND FUTURE ENERGY CARRIERS

Ships

Ships have been central to importing energy for almost 300 years, starting with whaling in the 1700s. Today, more than 3.5 TW of crude oil, liquefied natural gas, and petroleum products are shipped around the world. Not limited to specific right of way like pipelines or power lines, these oil and gas ships have enabled a truly global energy market for energy products. Shipping today is being challenged by both the delivered product and the energy used in shipping to deliver that product.

LUX TAKE

As countries look to decarbonize their energy mix, they’re turning to lower-carbon fuels like LNG that require specialized cryogenic tankers. Some early adopters are even leveraging those designs to build liquefied hydrogen tankers. As the industry aims to reduce carbon emissions by 50% by 2050, the shipping industry must turn to entirely new energy carriers to decarbonize.



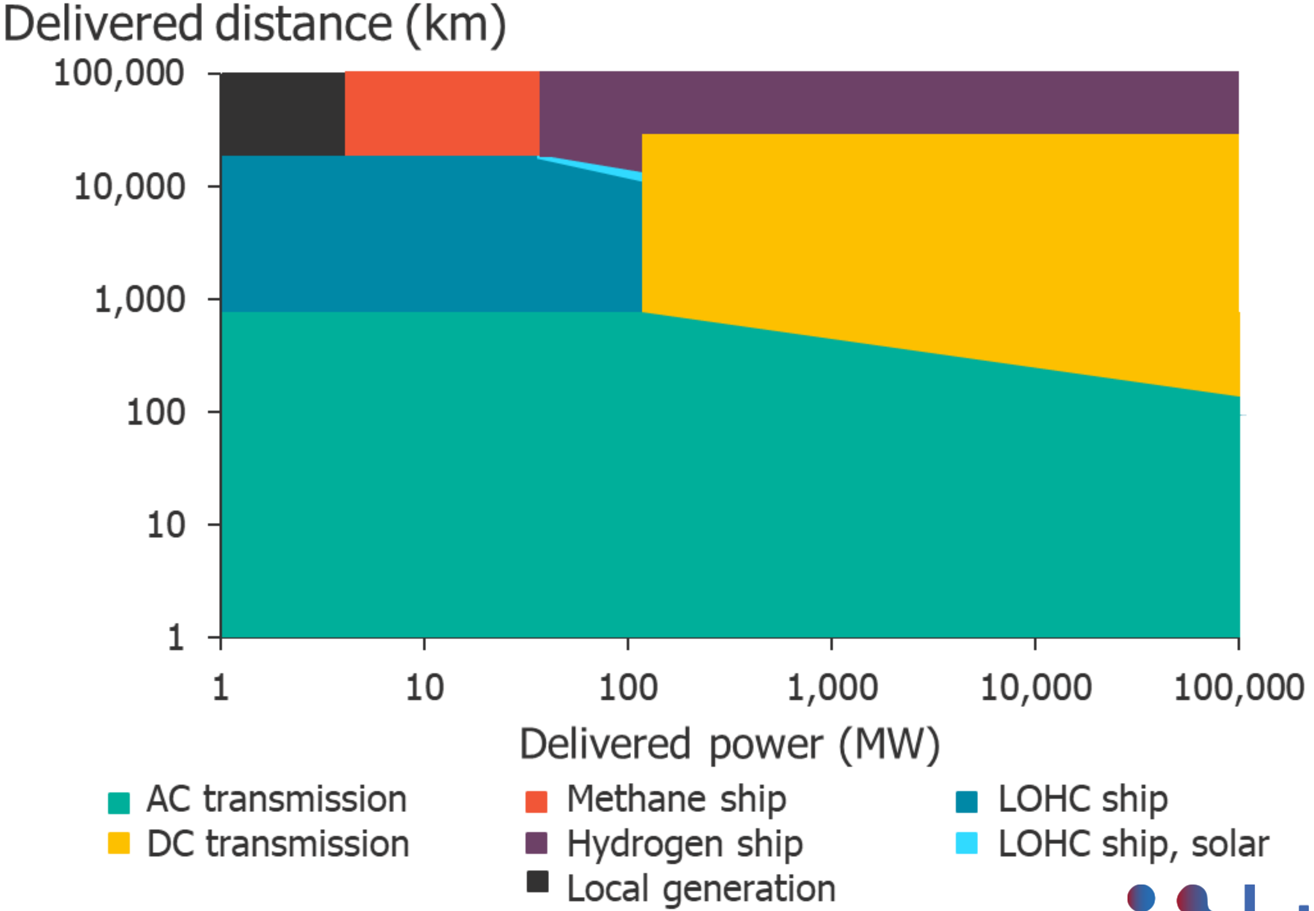
LOWEST-COST ENERGY CARRIERS

Where possible, the future of energy transmission is electric

When comparing all energy carriers across all powers and distances, AC and DC power lines will provide the lowest-cost solution to connecting remote solar power systems to customers. While this is good for energy costs – not converting electricity to fuels keeps electricity prices low – it limits the prospects of a worldwide renewable energy trade that can balance supply and demand and set prices globally.

Only at distances greater than 20,000 km when HVDC lines drop in efficiency, or greater than 1,000 km but less than 100 MW when HVAC lines drop in efficiency, does shipping appear competitive. The lower delivered power case for sea-based energy carriers will be to support small island communities, but the long-distance energy trade will be more limited – shipping journeys greater than 20,000 km are less than 0.2% of total journeys today.

Lowest cost energy carriers



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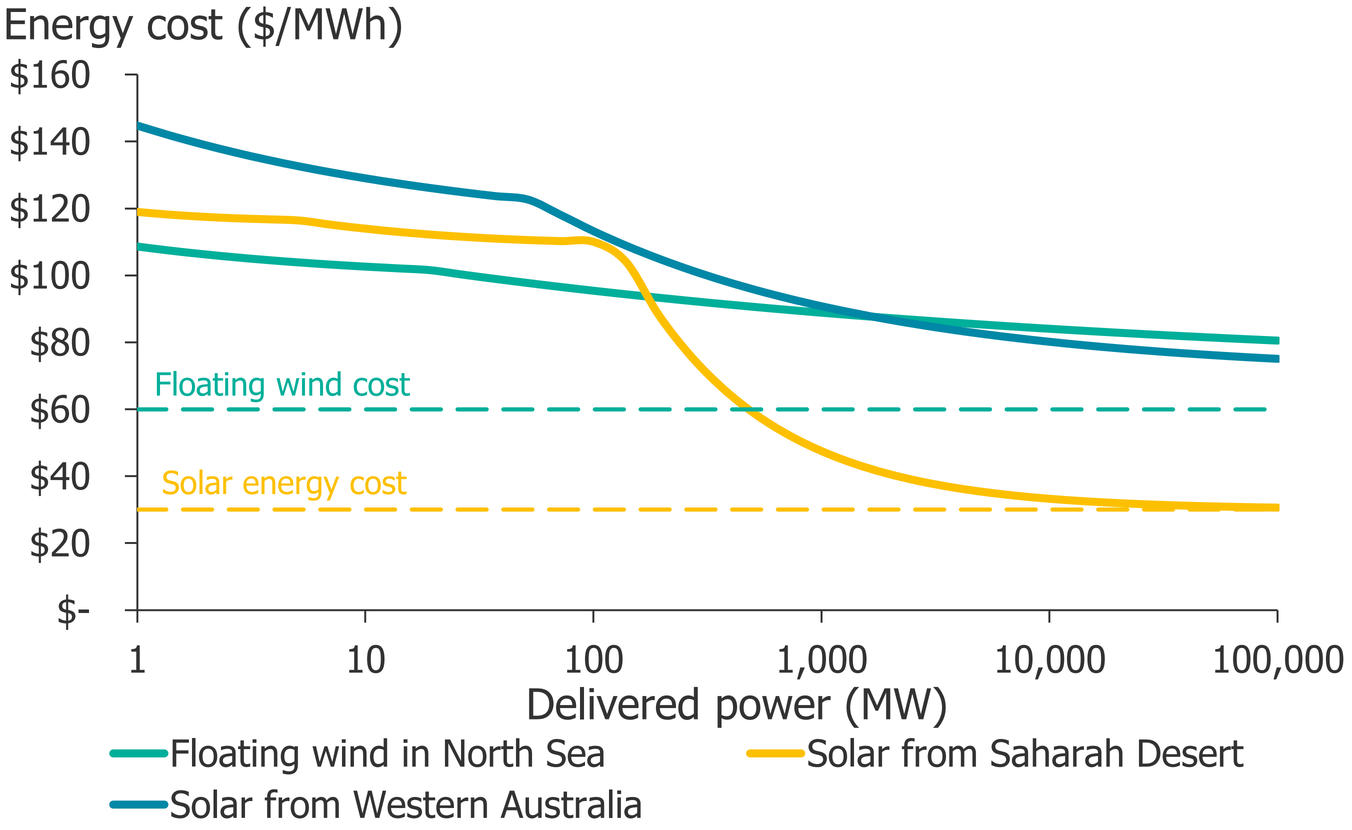
Evaluating energy carrier costs can yield valuable energy import strategies

While solar resources in places like Northern Europe might be poor, they do have access to local high wind resources like the North Sea. Floating wind turbines may have higher electricity costs – estimated at $60/MWh versus the modeled $30/MWh value for solar – but, depending on power delivery, may offer lower costs than importing renewable energy from farther away.

Here, Lux considers three cases for Northern Europe: importing via ship from more expensive floating wind turbines 50 km from the shore, importing via electrical transmission line or pipeline from low-cost solar in the Sahara Desert 2,500 km away, or importing via ship from low-cost solar in Western Australia 20,000 km away. Depending on power delivery, different carriers offer different costs.

Renewable energy in Northern Europe



Specific energy carriers will dramatically reshape how particular regions access low-cost renewable energy

Liquid organic hydrogen carriers, high-voltage DC transmission, and liquefied hydrogen will enable energy-intensive economies to reach their CO_2 targets starting in 2030.

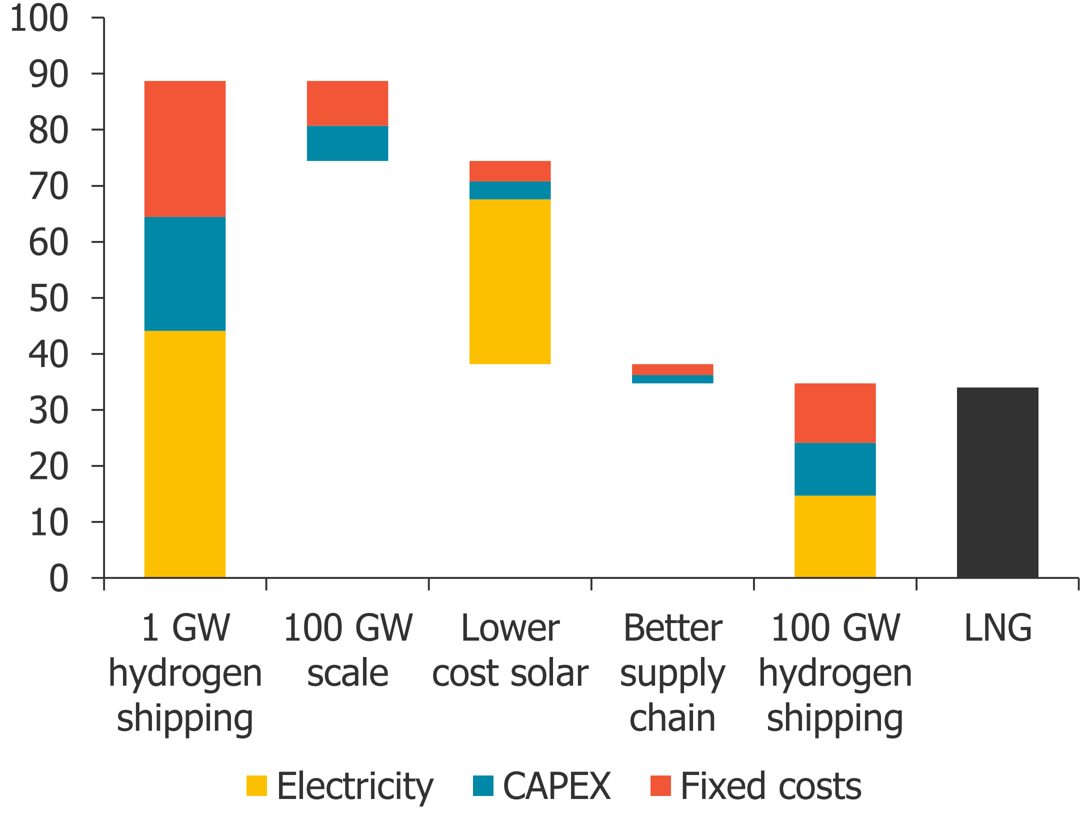
- **Successful projects will target multiple high-value applications; industry consortia will be key**
  Focusing on difficult-to-decarbonize sectors like chemicals, heavy transportation, and heat will make better use of energy carriers. These sectors intersect around industry; partnerships among industry, logistics, and renewable power will be essential.

- **New infrastructure projects are not cheap**
  Consortia are critical for another reason – cost. These renewable energy carrier projects will cost of billions of dollars each. Costs won't be borne by industry alone; governments also have a role.

- **A global renewable energy trade is unlikely**
  Even with highly favorable conditions, high-volume energy carriers can only just match LNG prices today. If renewable energy displaces hydrocarbons, though, future LNG prices will be lower as demand drops.

Pathway to LNG parity

Delivered energy cost ($/MWh)



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