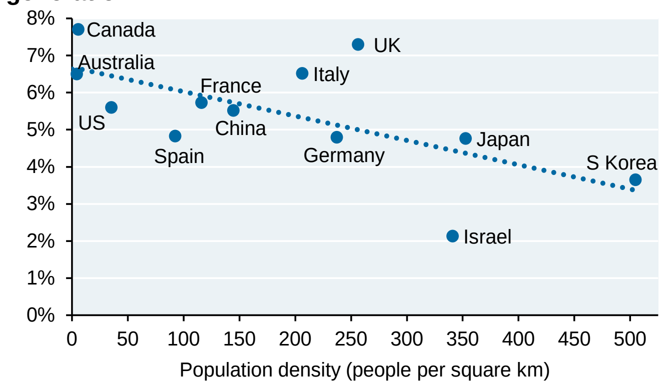
[2] High voltage direct current lines: China leads, US lags

In China, the US, Brazil, India and Australia, there are long distances between wind/solar/hydro facilities and major population centers. How this power is transmitted is an important part of grid efficiency and renewable energy integration. Using standard AC transmission lines, longer distances tend to result in larger transmission losses and also in greater involuntary curtailment of wind/solar power (i.e., power that could have been generated but which wasn't consumed).

Transmission and distribution losses as a % of total generation



Source: IEA Energy Technology Systems Analysis Programme, 2014.

Involuntary curtailment ratios

Country	Obs Year	Wind/Solar Curtailment
Denmark	2014	0.0%
Germany	2013	0.2%
Ireland	2013	3.8%
Italy	2014	0.3%
Portugal	2014	0.0%
Spain	2013	1.6%
US-ERCOT	2014	0.5%
US-MISO	2014	5.5%
China	2012	17.1%
China	2013	10.7%
China	2016	17.0%

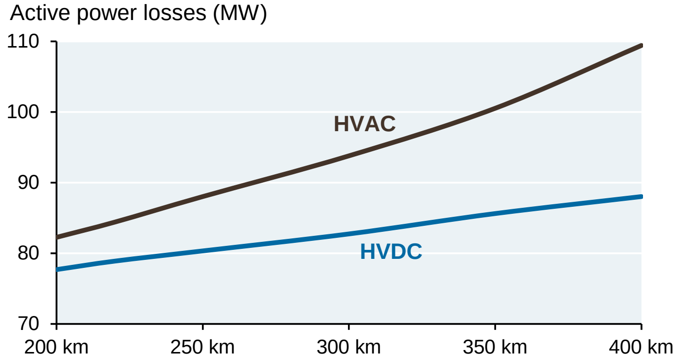
Source: 2015 Wind Integration Workshop, Kansai University (Japan), NRDC.

While AC lines are usually best for short and medium distances, **high voltage direct current lines** (HVDC) can be more economic for longer distances. The tradeoffs involve the following:

- higher upfront capital costs for DC terminals given the need for voltage conversion equipment
- lower per km line costs for DC due to fewer conductors, less metal for towers and lower land costs (a 3-conductor 500 kV AC tower is ~1.5 times larger than a 2-conductor 500 kV DC tower)
- fewer transmission losses for DC lines over the project's life as distances increase (see chart, left)

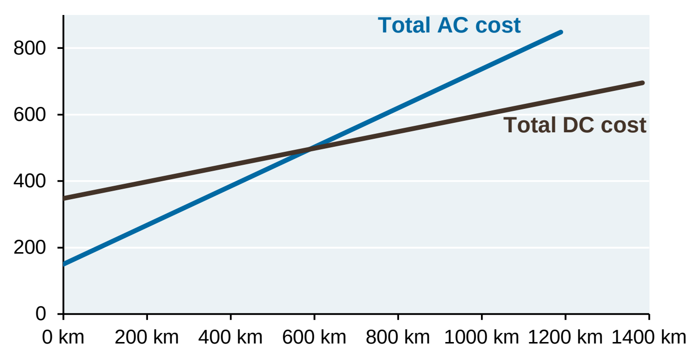
The chart on the right from the IEA puts all the pieces together: DC lines are usually cheaper once distances exceed 600-700 km[10]. Siemens and ABB report similar breakeven distances (both are working on the world's first 1,100 kV HVDC transformers for use in Guquan, China).

Transmission losses: HVAC vs HVDC
Active power losses (MW)



Source: "*Power loss evaluations for long distance transmission lines*", Nguyen and Saha (University of Queensland), 2009.

Comparison of HVAC and HVDC lifetime system costs
Cost

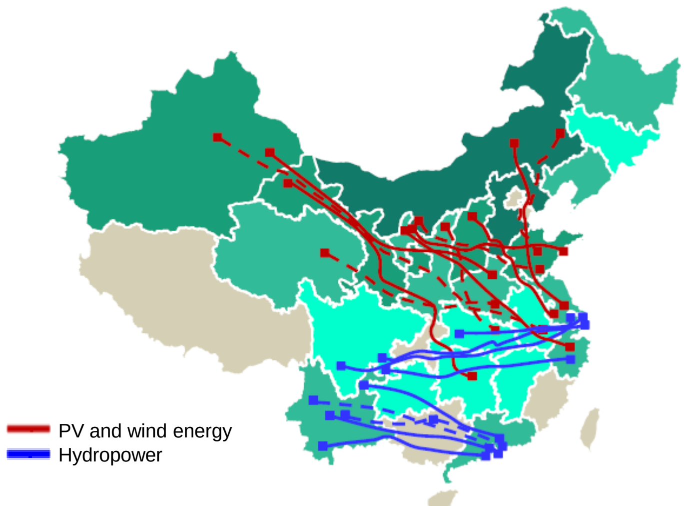


Source: IEA Energy Technology Systems Analysis Programme, 2014.

[10] **For electricity aficionados only**. For underwater or underground systems, HVDC tends to be used at distances over 50-80 km. Above that level, high capacity AC transmission systems become less feasible for reasons related to electrical capacitance, reactive power losses and the cost/feasibility of shunt reactor substations. Since polymer- or paper-insulated conductors in underground/underwater cables are located much closer to ground than conductors in overhead lines, their electrical capacitance per km is generally much higher. This causes long AC cables to generate significant reactive power, degrading performance over longer distances to the point where eventually less and less real power can be transmitted without some kind of expensive reactive power compensation.

China leads the world in the installation of HVDC transmission lines. While China has installed 30% of the world's wind and solar capacity, wind and solar power account for just 5% of Chinese electricity generation. China has a "mandatory goal" of reducing coal's contribution to primary energy from 62% in 2016 to 58% by 2020, and plans to add more wind, solar and hydro as part of this transition. However, the distance between wind, solar and hydro facilities and China's urban centers has created challenges, including the high levels of renewable curtailment shown on the prior page. As part of the solution, China is building plenty of HVDC lines, with 20 in operation or under construction.

HVDC transmission lines for transfer of renewable energy across China, Sold lines = in operation, dotted lines = to be completed by 2020



Source: "*Renewable Energy Transmission by HVDC Across the Continent: System Challenges and Opportunities*", RPI, State Grid Corporation of China, China Electric Power Research Institute. December 2017.

The table below shows announced HVDC projects of more than 400 kV for several countries. To put China's HVDC development in context, we created a metric for each country that is equal to the kilometers of its HVDC projects per gigawatt of its total electricity generation capacity. **China's HVDC ratio is more than double that of the US.** That's worrisome enough, but as we discuss on the next page, some announced US projects might not even be completed.

Announced high voltage direct current line projects > 400 kV

In-country projects

	Distance of domestic projects (km)	Total electricity generation capacity (GW)	Total distance of projects / el gen capacity
Mexico	2,740	67	**40.6**
Brazil	4,640	156	**29.8**
China	27,953	1,519	**18.4**
Indonesia	876	57	**15.3**
UK	1,187	95	**12.5**
Germany	2,495	204	**12.2**
USA	8,075	1,074	**7.5**
India	2,021	325	**6.2**

Source: Global Transmission Research, 2017. Projects shown are in-country only and exclude cross-border HVDC interconnection projects, of which there are 2,500 km in Asia and 5,200 km in Europe.

US HVDC lines: slower progress, more bottlenecks. A good way to understand challenges in the US is to track the experience of Clean Line LLC. This Houston-based company accounts for 50%-60% of all planned US HVDC development, according to data from Global Transmission Research[11]. Clean Line projects are all subject to complex regulatory approvals in multiple states. While certain legal rulings have gone in its favor, the length and complexity of the approval process has delayed some of their projects for years, with one rejected outright. We wrote about Clean Line's Plains & Eastern project last year as an example of belated success, the first HVDC transmission line to be built in the US in more than 20 years after 11 years of planning. **Now, that project is up in the air again since the Federal government has ended its partnership agreement with Clean Line**.

Name of Clean Line Project	Voltage (kV)	Distance (km)	% of total US HVDC distance	Comments
Centennial West	600	1,449	17.9%	Environmental impact statement submitted, approval pending. States affected: New Mexico, Arizona, and California
Grain Belt Express	600	1,256	15.6%	Approvals received in Kansas, Indiana and Illinois but waiting for approval in Missouri, where it has already been rejected twice since all affected Missouri counties must approve. Clean Line now appealing to Missouri Supreme Court
Plains & Eastern	600	1,160	14.4%	Approvals received in Oklahoma and Tennessee, but not from Arkansas. Clean Line appealed to US Federal Gov't for help in using Section 1222 of the Energy Policy Act of 2005 to override Arkansas objections. However, in March 2018, the Federal Government ended its partnership agreement with Clean Line, removing the possibility of Federal assistance with eminent domain. TVA recently withdrew as purchaser given lack of need and out of concern for costs of backup thermal generation. Clean Line then sold part of its ownership.
Rock Island	600	805	10.0%	Illinois Supreme Court rejected Clean Line's application since as an out of state entity with no Illinois assets, it did not quality as a public utility, which is needed to engage in transmission line development. States affected: Iowa and Illinois.
Western Spirit	345	224	2.8%	Approvals received from FERC and Bureau of Indian Affairs, negotiating with potential power end-user customers. States affected: New Mexico

Source: Global Transmission Research (2017), JPMAM.

Clean Line isn't the only company experiencing delays. The 1 GW **Northern Pass** line connecting Hydro-Quebec to Southern New England was supported by Massachusetts regulators and its Department of Energy Resources. However, a New Hampshire siting committee rejected the proposal by 7-0, since it worried that the 192-mile system would disrupt streets and harm tourism, particularly in the northern portion of the state. Concessions by the Northern Pass group to bury 52 miles of the route and set aside 5,000 acres of preservation and recreation land have been insufficient to change the outcome so far; appeals are pending. There have also been delays on the New Mexico-based **Tres Amigas** project, which was supposed to link the three US regional grids with a 750 MW, 345 kV HVDC system costing $1.5 billion. In 2017, Tres Amigas was scaled down to 200 MW and $200 mm, and will no longer include the Texas grid.

US HVDC lines are often mentioned as an integral part of a renewable energy future, but it would take a sea change in regulation and local practices to realize it. Researchers at the National Oceanic and Atmospheric Administration explored the possibility of a national US grid of interconnected HVDC lines overcoming wind and solar intermittency, and also reducing the need for storage. They found that by 2030, HVDC lines meeting at 32 nodes could add allow for enough wind and solar power to cut power sector emissions by up to 80% from 1990 levels. But if recent experience is any indication, a national grid of US HVDC lines will remain part of the renewable energy wish list rather than a reality.

[11] The GTR database includes HVDC projects that are proposed, under development or under construction.