Interregional Transmission Planning with HVDC

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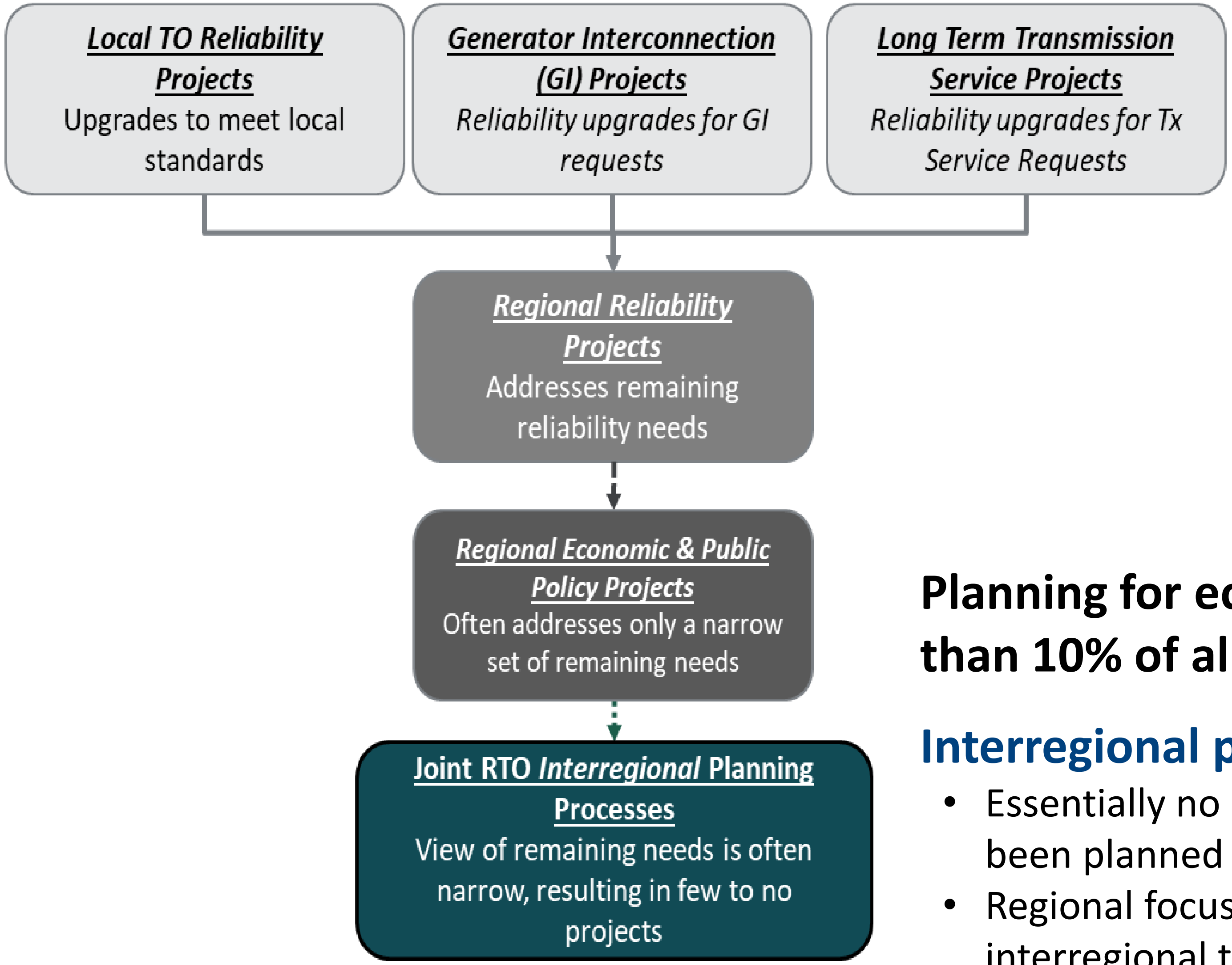
Source: Siemens

Contents

This presentation is based in part on the report, ***The Operational and Market Benefits of HVDC to System Operators***, prepared with colleagues at The Brattle Group and DNV and input from industry participants. The American Council on Renewable Energy (ACORE), GridLab, Clean Grid Alliance, Grid United, Pattern Energy, and Allete commissioned the report.

Current U.S. Grid Planning Processes are too Siloed



These solely reliability-driven processes account for > 90% of all transmission investments

- None involve any assessments of economic benefits (i.e., cost savings offered by the new transmission)
- Which also means these investments are not made with the objective to find the most valuable solutions
- Will result in higher system-wide costs and electricity rates

Planning for economic and public-policy projects: less than 10% of all transmission investments

Interregional planning processes are largely ineffective

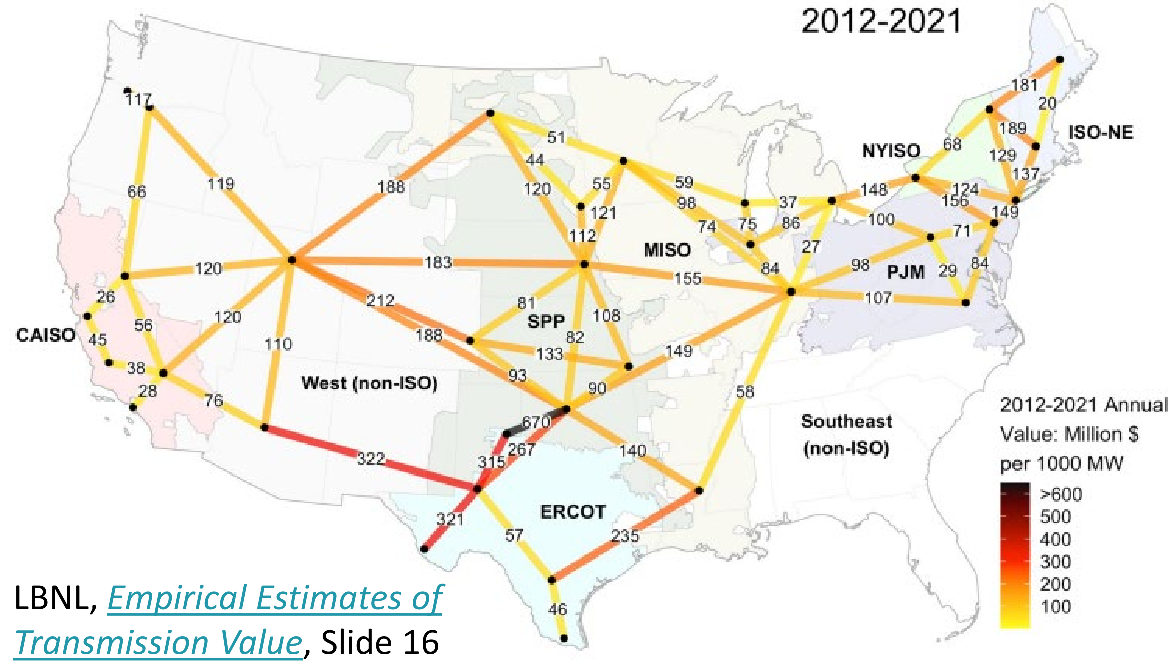
- Essentially no major interregional transmission projects have been planned by grid operators in the last decade
- Regional focus on meeting reliability needs leaves no “need” for interregional transmission, even if more cost effective

Survey: Barriers to Interregional Transmission Planning

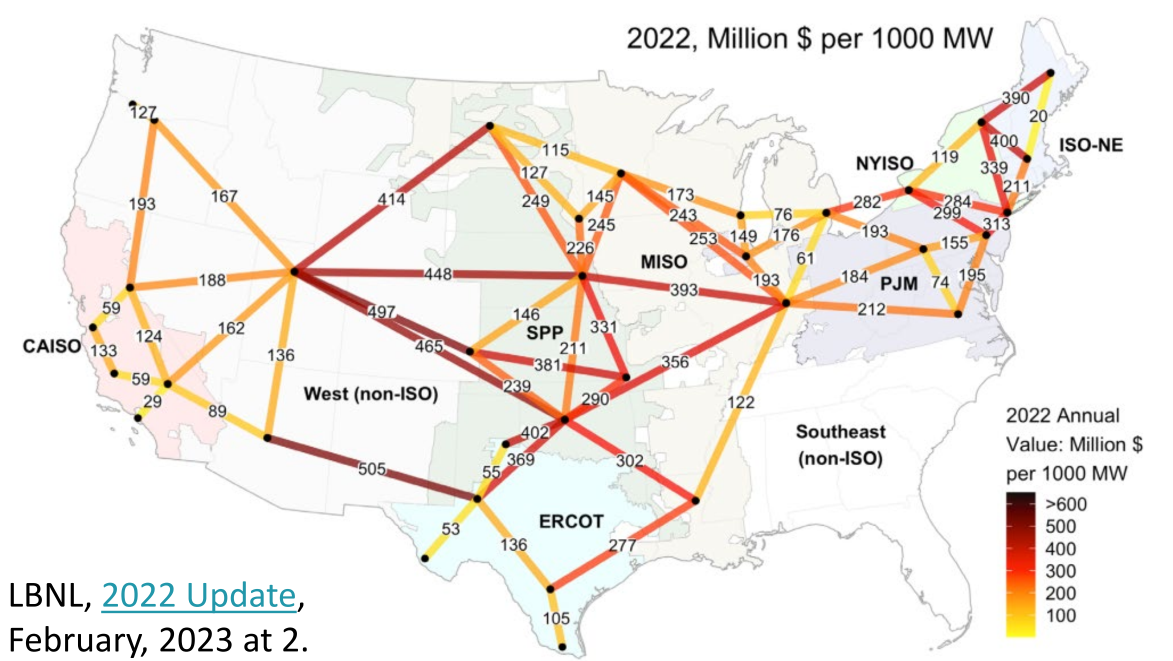
A. Leadership, Alignment and Understanding	1. Insufficient leadership from RTOs and federal & state policy makers to prioritize interregional planning 2. Limited trust amongst states, RTOs, utilities, & customers 3. Limited understanding of transmission issues, benefits & proposed solutions 4. Misaligned interests of RTOs, TOs, generators & policymakers 5. States prioritize local interests, such as development of in-state renewables
B. Planning Process and Analytics	6. **Benefit analyses are too narrow, and often not consistent between regions** 7. Lack of proactive planning for a full range of future needs and scenarios 8. **Sequencing of local, regional, and interregional planning** 9. Cost allocation (too contentious or overly formulaic)
C. Regulatory Constraints	10. Overly-prescriptive tariffs and joint operating agreements 11. State need certification, permitting, and siting

Source: Appendix A of A Roadmap to Improved Interregional Transmission Planning, November 30, 2021. Based on interviews with 18 organizations representing state and federal policy makers, state and federal regulators, transmission planners, transmission developers, industry groups, environmental groups, and large customers.

The High Value of and Large Need for Interregional Transmission



LBNL, *[Empirical Estimates of Transmission Value]*, Slide 16



LBNL, [2022 Update], February, 2023 at 2.

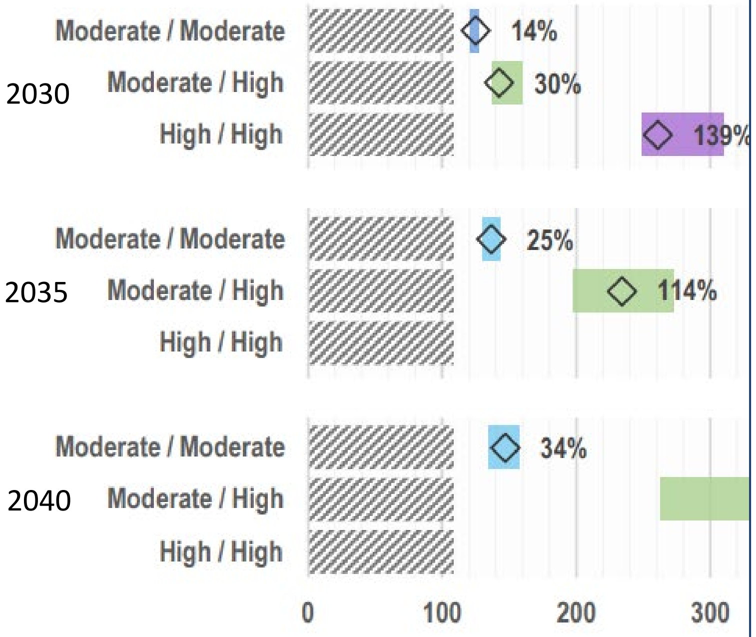
DOE's [National Transmission Needs Study] documented high historical value of interregional transmission and summarized numerous results from six national studies into 3 groups of scenarios:

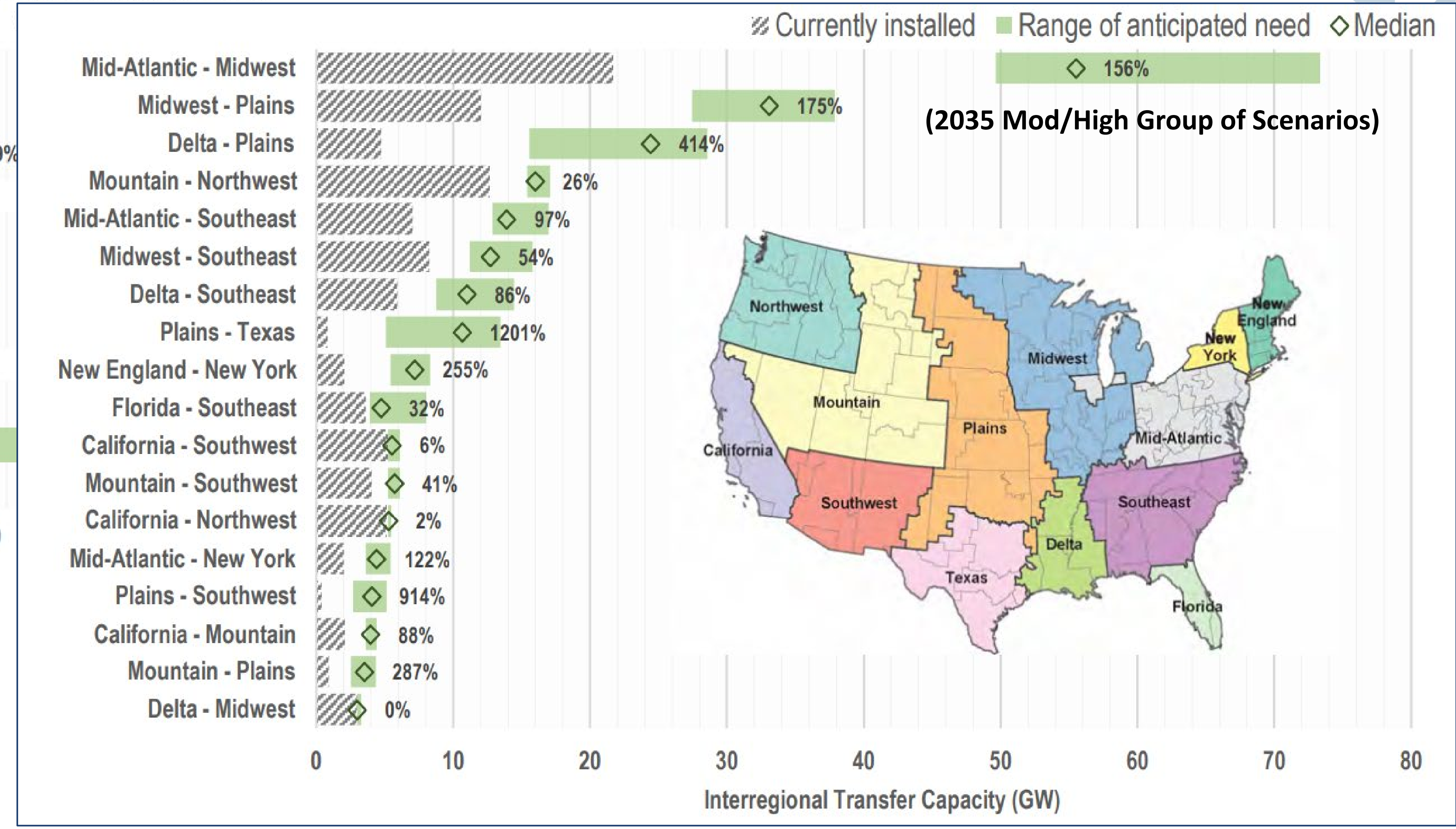
1. **Mod/Mod** = status-quo: moderate load growth and 40-70% clean-energy shares
2. **Mod/High** = moderate load growth but high (90+%) clean-energy shares
3. **High/High** = high electrification load growth and high clean-energy shares

"Need" = optimal regional/interregional transmission expansion that minimizes total system-wide costs
("Expansion" = enhancing the existing grid & existing ROW plus new transmission lines)

DOE's 2023 Transmission Needs Study: Interregional Needs

Anticipated interregional transfer capacity for contiguous United States
Median % growth compared to 2020 system shown





Source: DOE, National Transmission Needs Study, October 2023 (report) and Department of Energy's 2023 National Transmission Needs Study (slides)

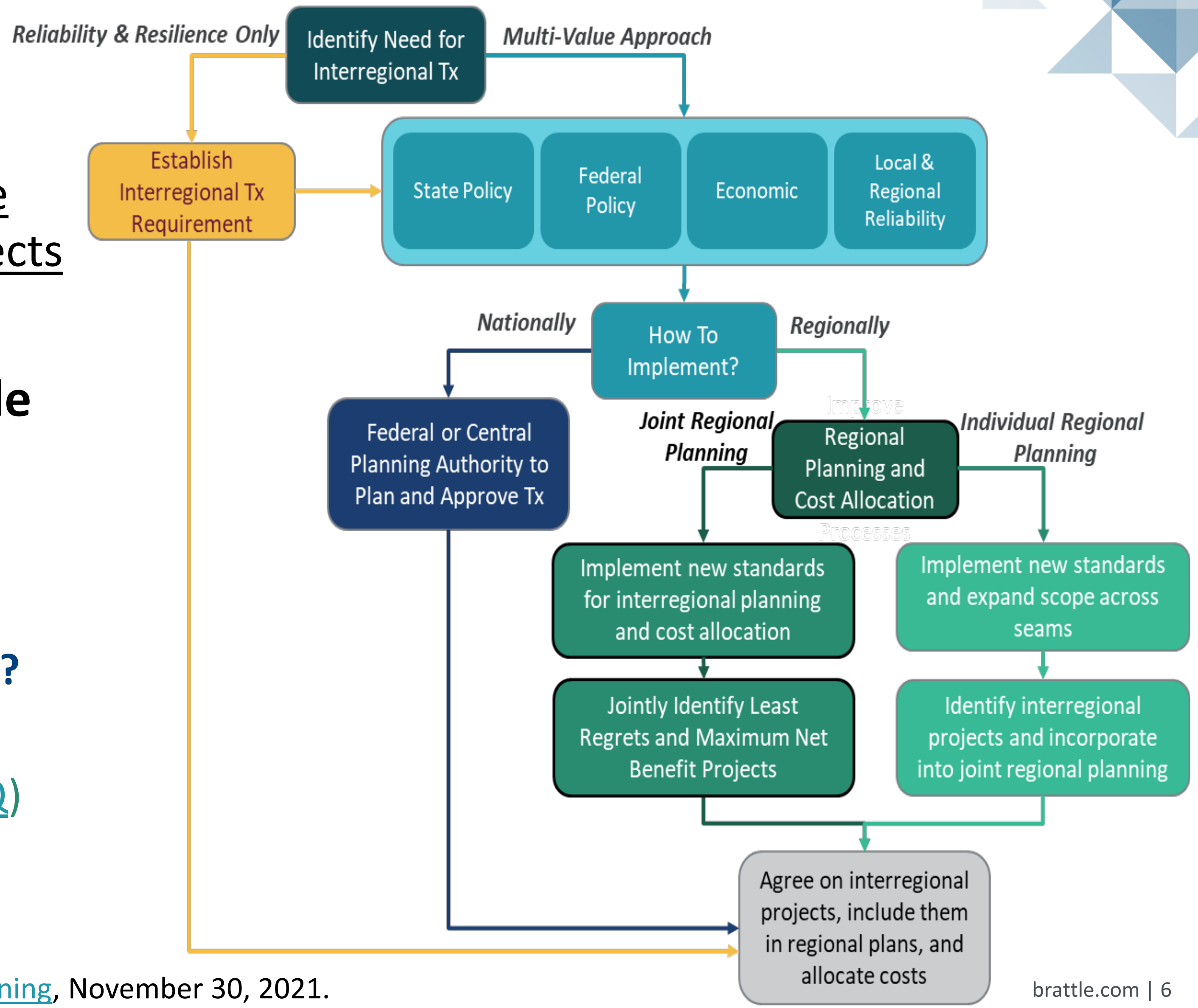
Note: Expansion options include enhancing the existing grid & existing ROW plus new transmission lines

Options for Actionable Interregional Transmission Planning

While the national studies show clear benefits of adding interregional transmission, these studies do not create an actionable "need" for approving projects

Four paths can be pursued simultaneously, identifying actionable transmission needs through:

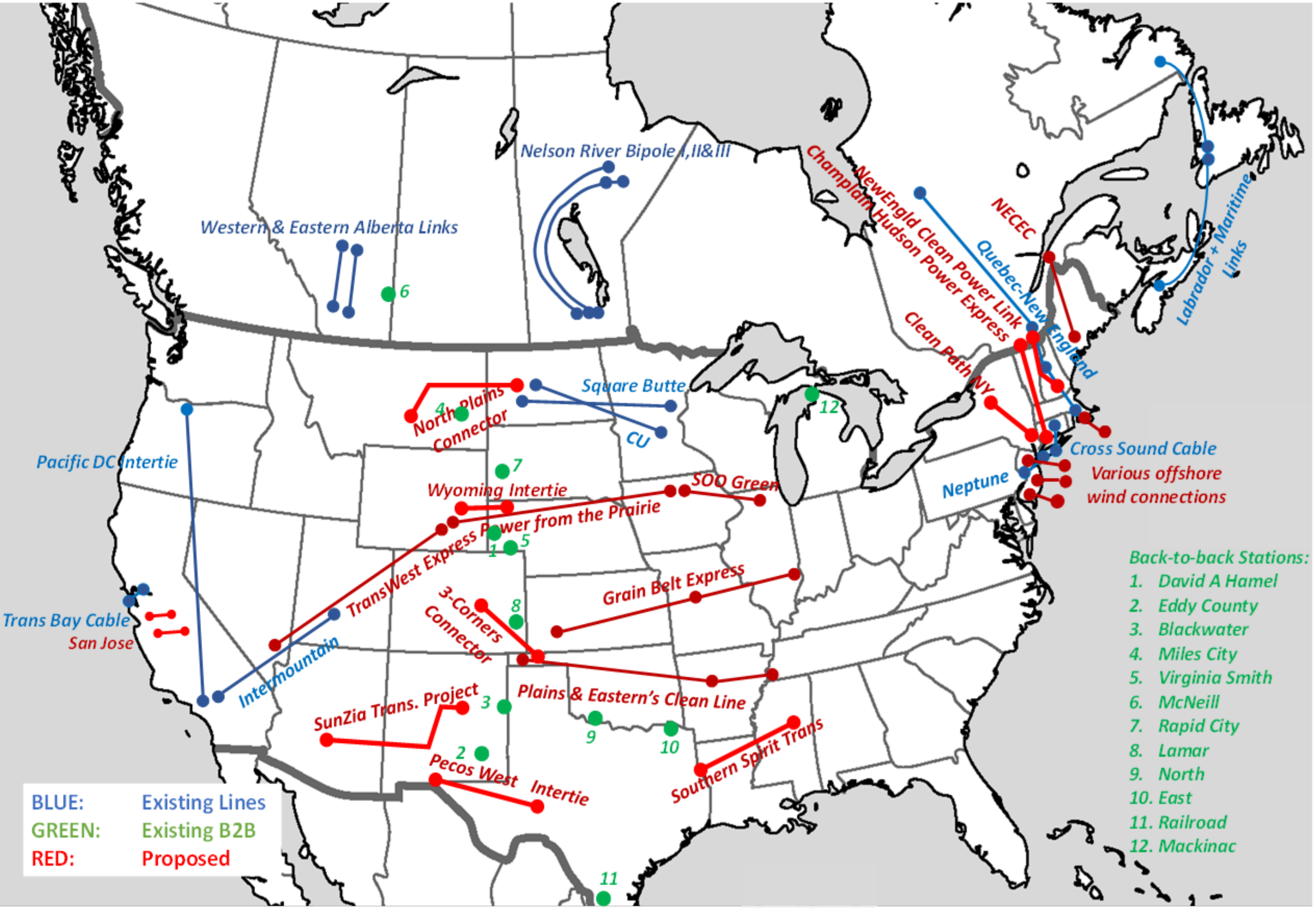
1. **New Interregional Tx requirements?** (e.g., similar to European 15% target)
2. **New Federal/Multi-regional planning?** (e.g., similar to ENTSO-e TYNDP)
3. **Improve joint RTO planning** (e.g., JTIQ)
4. **Expand planning by individual RTOs**



Source: A Roadmap to Improved Interregional Transmission Planning, November 30, 2021.

Most Proposed U.S. Interregional Transmission Lines are HVDC

North American HVDC Projects (Existing and Planned/Proposed)



Source: Jim McCalley, Iowa State University

Most U.S. interregional transmission projects are HVDC lines proposed by merchant and OSW developers (i.e, not planned by system operators)

Main HVDC advantages:

- High capacity (1-5 GW), long-distance
- Efficient right of way (including underground and submarine)
- Controllable power flows (for both economic dispatch and during contingencies)
- Synchronous and asynchronous applications
- Grid-forming capability / weak AC grids
- Grid services (to support AC network)

HVDC Background

HVDC transmission technology has evolved dramatically over the last 5-10 years

- HVDC offers higher-capacity, longer-distance, lower-loss transmission on a smaller footprint than AC
- The development of voltage-sourced converter (VSC) technology has also offered dramatic improvements in HVDC capabilities
- These VSC-based capabilities are increasingly needed to enhance the existing AC grid

Internationally, approximately 50 GW of VSC-HVDC transmission projects are in operation today and approx. 130 GW planned or under development through the end of the decade

- North America accounts for only 3% of all VSC systems in operation worldwide and (almost exclusively due to merchant developers) for approx. 30% of planned and proposed VSC systems

U.S. system operators less familiar with HVDC can benefit from the experience gained overseas (particularly in Europe) … but significant planning, supply chain, operational, and regulatory challenges need to be addressed

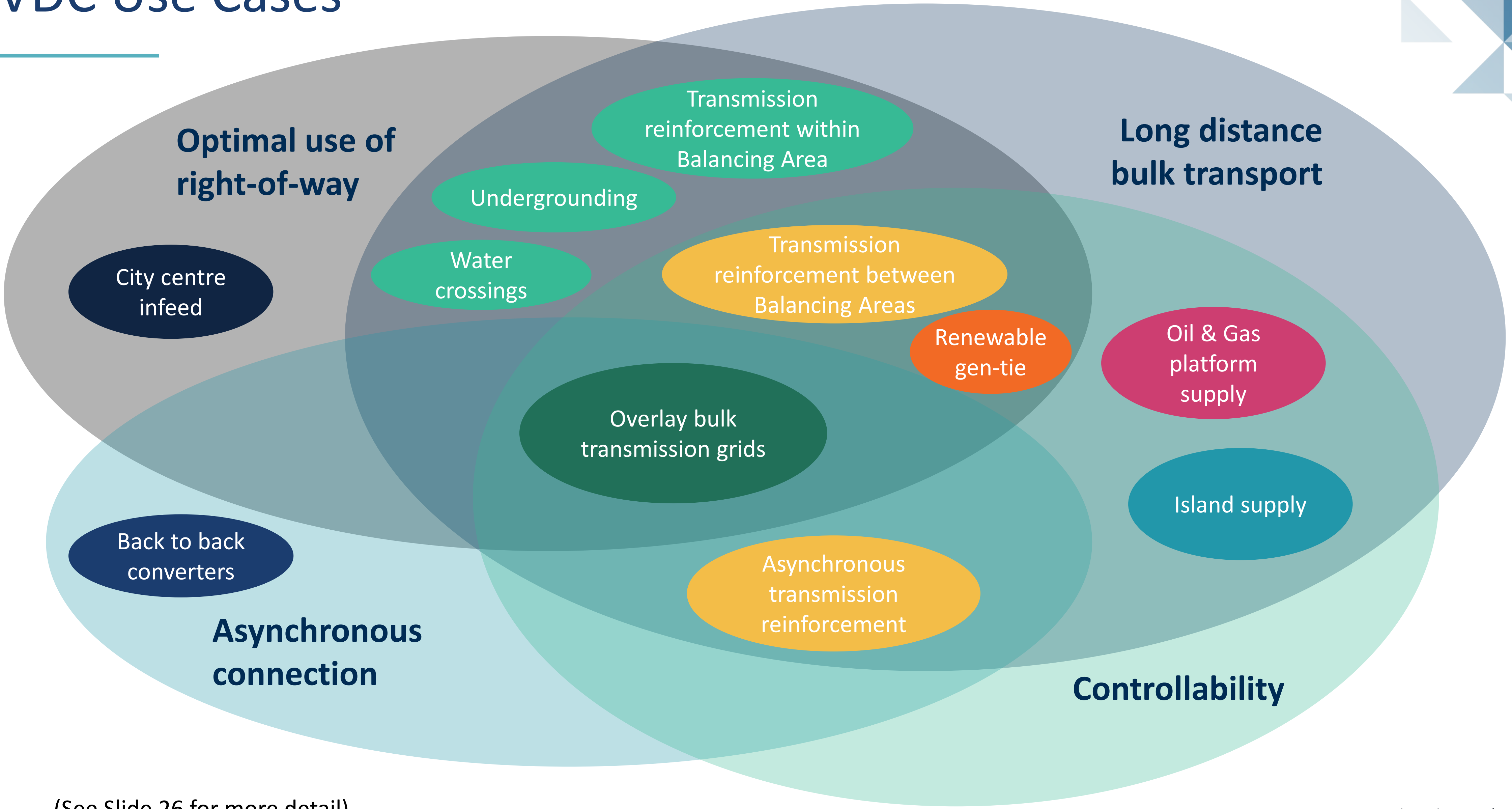
- Our report with DNV provides a primer on HVDC technology, summarizes available capabilities and experience, addresses misconceptions, and offers recommendations to collaboratively address identified challenges

Grid Planning with HVDC vs. Conventional AC Technologies

HVDC can be more expensive but offers unique advantages and a broader set of capabilities than AC lines. How to chose between HVDC and AC grid technologies within the transmission planning processes?

Making an informed decision requires multi-value transmission planning that recognizes the increasingly broad set of HVDC use cases and capabilities!

HVDC Use Cases



(See Slide 26 for more detail)

HVDC Capabilities (with VSC vs. LCC converters)

	Transmission functions	Grid operations support	Autonomous line dispatch	Power quality support	Contingency operations	Reliability & Market optimization
Both LCC & VSC	Real power control Reactive power control (static)	Synthetic inertia* Frequency response Regulation, ramping, spinning reserves	External Power (Tracking) Control AC Line Emulation	Power oscillation damping	Run-back / run-up schemes Emergency energy imports	AC grid power flow optimization Resource adequacy, capacity imports Intertie optimization
VSC only	AC voltage and frequency control* Weak and islanded grid connections*	Voltage support* / Reactive power control (dynamic)		AC phase balancing AC harmonics filtering	Black-start and system restoration*	Frequent and rapid power flow reversal Weak grid connections*

* Requires VSC converters capable of operating in grid-forming mode (but precise capabilities and requirements are evolving and specifications-dependent). See slide 26 for more detail.

Real-world Experience with Specific HVDC Capabilities

Significant experience (well beyond these examples) already exists with advanced AC grid support capabilities of HVDC

NEMO link Belgium - UK	Frequency support and emergency energy
NordLink Norway - Germany	Auto-reclosure for overhead line fault clearing and automatic bi- to monopole change
Maritime Link Canada	HVDC runback schemes for prevention of overloading of AC lines
Fenno-Skan Sweden - Finland	Mitigate AC stability constraints and improve system transfer capability
FIL France – Italy	"AC line emulation" and AC grid loss and congestion reduction
INELFE France - Spain	Power Oscillation Damping
Skagerrak 4 Norway - Denmark	Black-start and system-restoration services
ULTRAnet Germany	Converting existing AC overhead line circuits to HVDC

Source: The Operational and Market Benefits of HVDC Transmission, Section 5 (presenting 21 case studies).

HVDC Planning: Transmission Studies

Multi-value planning is critical to be able to take advantage of HVDC capabilities!

Engineering assessments are similar to AC transmission planning: HVDC systems need to be analyzed through a number of studies, sequentially adding more detail, scope, system performance, model fidelity, and temporal granularity as analyses move from planning to design and integration

Market analysis

- Security constrained economic dispatch
- Market studies
- Production cost models

Steady-state analysis

- Voltage stability / circuit breaker ratings
- Load flow / short circuit studies
- 60 Hz models

RMS analysis

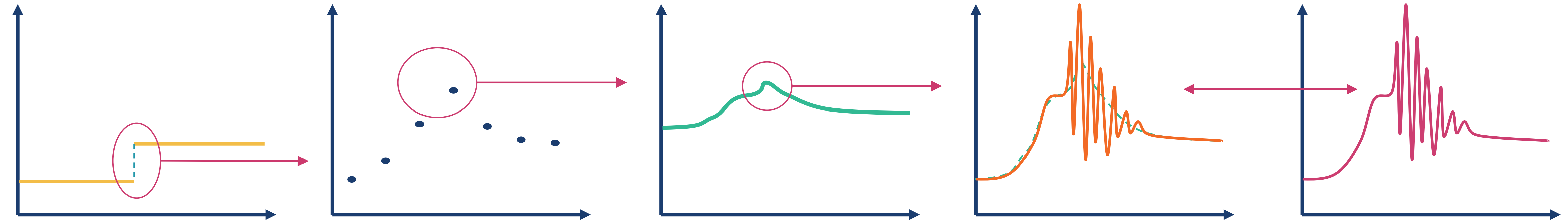
- Transient stability
- Electromechanical models
- 60 Hz models

EMT analysis

- Electro-magnetic behaviour
- Control & protection behaviour
- Instantaneous voltages and currents
- Dynamic studies
- ~0 Hz – kHz models

RTS analysis

- Real-time behaviour
- Control & protection replica performance
- Model validation
- Hardware-in-the-loop studies
- ~0 Hz – kHz models



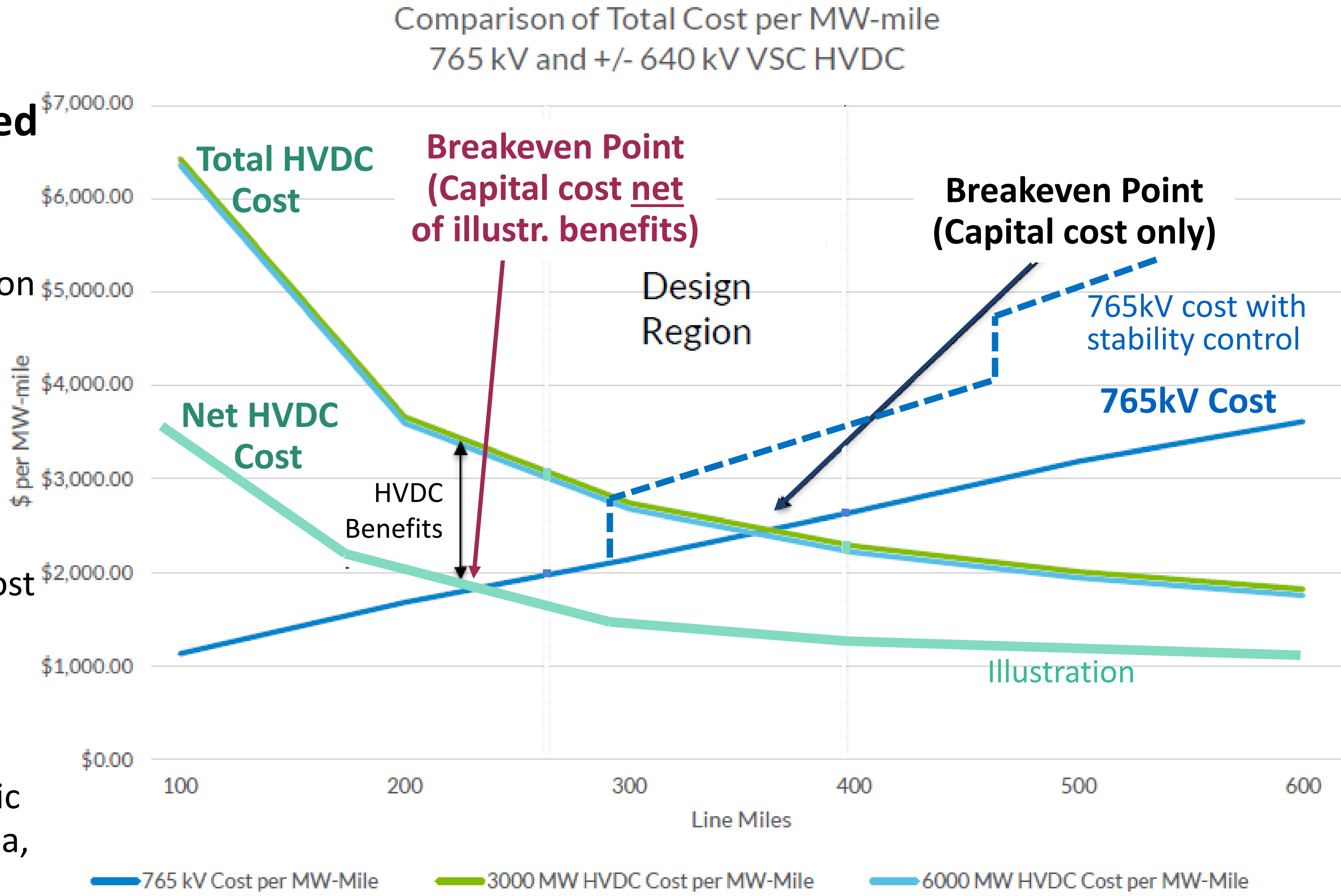
Years - hours | Minutes - seconds | Seconds | Seconds - microseconds | Seconds - microseconds

Averaged generic high-level models — Validated vendor specific models — Control & protection hardware replicas

MISO's Comparison of HVDC and 765kV Solutions: Adding multi-value planning is critical

HVDC solutions can offer additional benefits (and avoided AC facilities cost), that lower their net cost:

1. Flow control and market optimization (to reduce AC grid congestion and losses)
2. Dynamic reactive power/voltage control
3. Lower transfer losses
4. Lower ROW and undergrounding cost
5. Lower N-1 contingency
6. AC system dampening; mitigate stability constraints
7. Grid forming, grid services, synthetic inertia, blackstart/restoration inertia, etc.



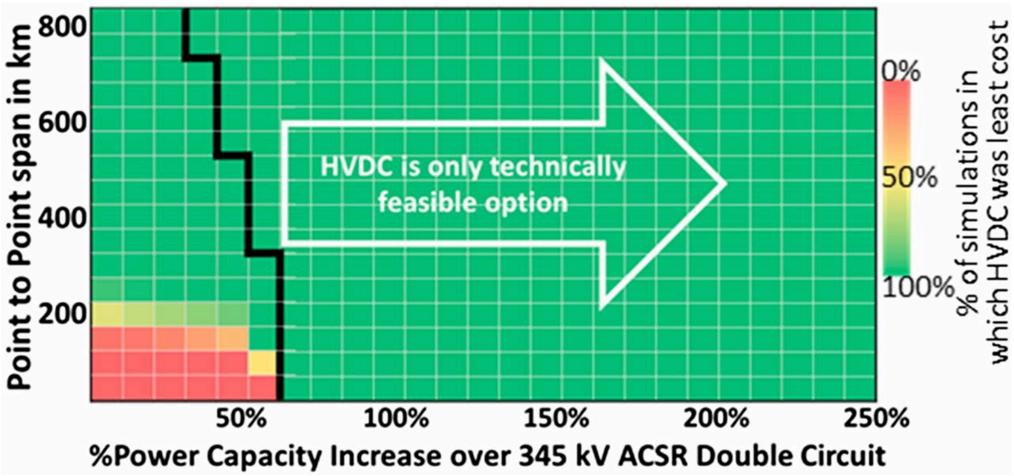
This is a modified version of the chart in slide 29 of MISO, Discussion of Legacy, 765kV, and HVDC Bulk Transmission, March 8, 2023.

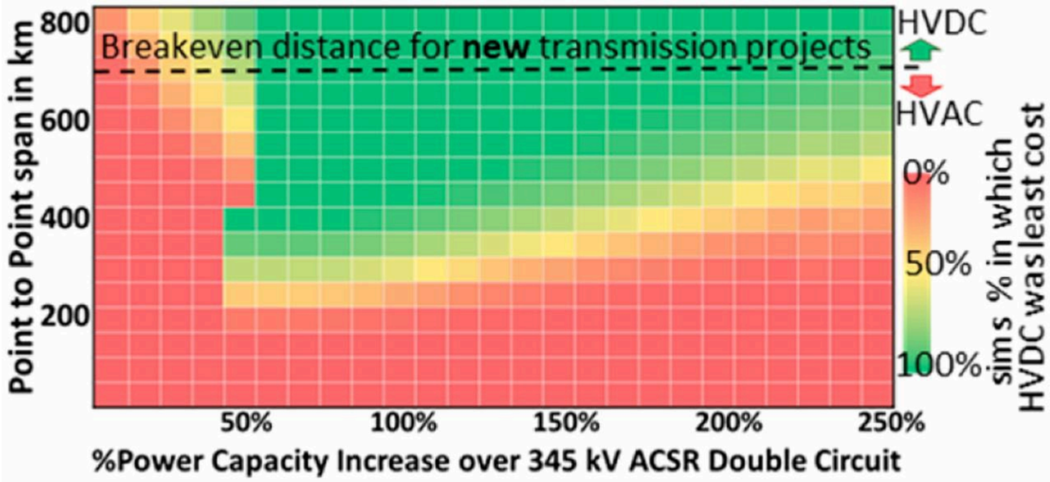
Quantifying HVDC Benefits in Transmission Planning (Examples)

HVDC-VSC Capability	Planning Benefits / Options for Quantification
1. Flow control/market optimization	• Estimated value of congestion relief and loss reduction on AC grid with nodal production cost models that can optimize HVDC
2. Dynamic reactive power and voltage control	• Avoided cost of STATCOMs, SVCs, synchronous condensers
3. Lower long-distance transfer losses	• Market value of avoided losses on transmitted energy
4. Smaller footprint/right-of-way (ROW), including for undergrounding option	• Lower cost for right-of-way (e.g., 50ft less than for 765kV AC); lower cost of undergrounding; lower risks (permitting etc)
5. Reliability benefits (fault ride-through, lower N-1 contingency for bipoles, voltage support)	• Increased transfer capacity; reduced cost of contingency reserves; avoided cost of AC equipment (e.g., additional lines, STATCOMs)
6. AC dynamic stability; power oscillation dampening; mitigate stability constraints on AC grid	• Avoided cost of power system stabilizers/supplemental power oscillation damping (POD) controllers with synchronous condensers, batteries, SVCs, STATCOMs, switched shunt equipment, etc. • Value of congestion relief on proxy constraints
7. Grid forming, grid services, synthetic inertia, blackstart/restoration, etc.	• Market value or avoided cost of providing the grid services through conventional means

Planning HVDC Conversions/Upgrades of Existing AC Lines

2019 Article: Converting existing transmission corridors to HVDC to increase transmission capacity | PNAS





If an existing double-circuit 345kV line has to be upgraded and ROW cannot be expanded:

- AC solutions may not increase capacity by more than 60%
- HVDC conversion is least cost if the transfer capability needs to be increased by more than 60% or the distance is more than 200 km (135 miles)
- Example does not even consider VSC-related benefits

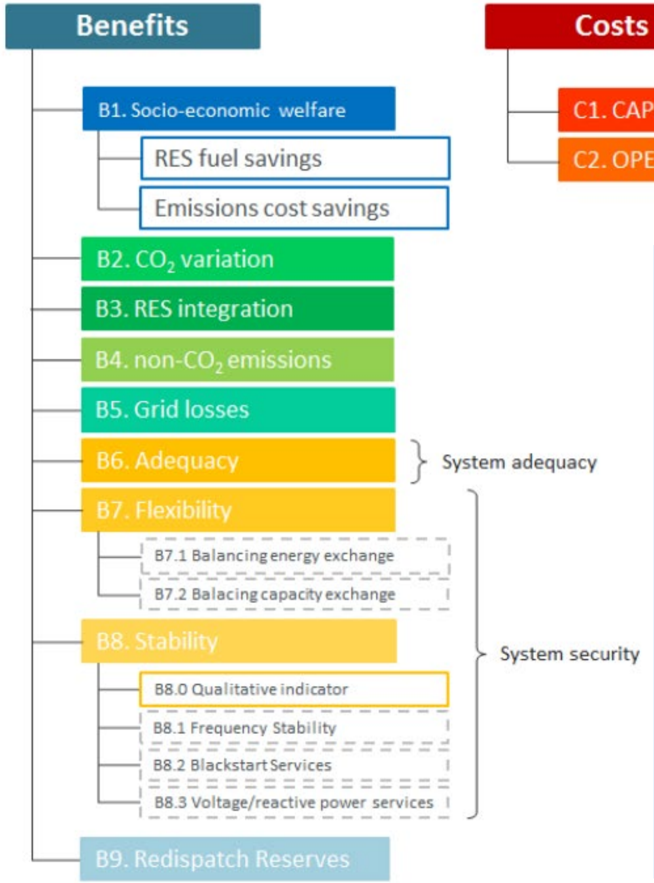
If multiple 345kV or 500kV lines are possible:

- HVDC conversion is preferable if capability needs to be increased by more than 60% and the distance is more than 300 km (185 miles) … even though the break-even distance for new transmission may be 700 km (430 miles)

Similar analyses can be done for upgrading existing HVAC or HVDC lines at different voltage levels

Example: European Transmission Planning and CBA Framework

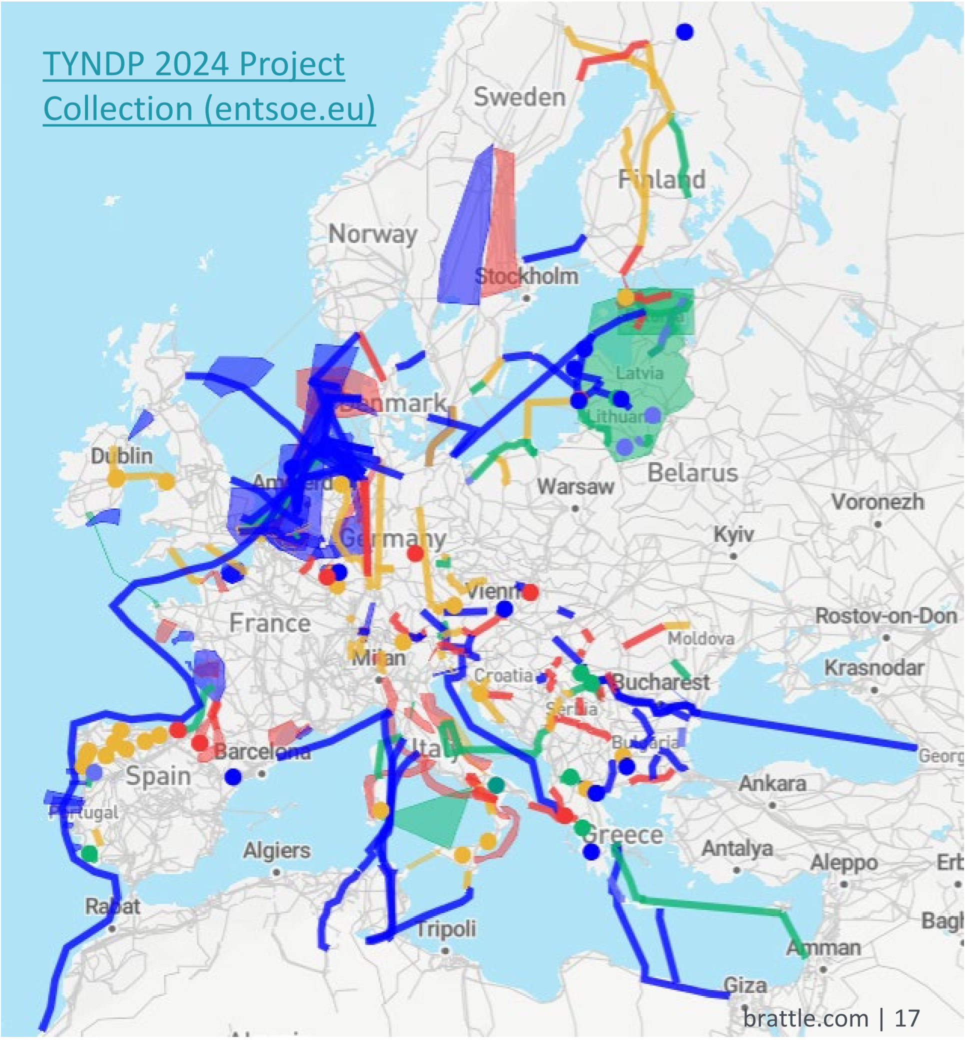
ENTSO-E: Standardized Multi-value Benefit-Cost Analysis Framework for EU-wide Transmission Planning (incl. HVDC)



Entso-E Planning and CBA framework

- Forecast-based up to 10 years
- Scenario-based for 10-30 years
- Standardized benefit-cost analysis
- Specifically addresses HVDC benefits: cost savings achievable from optimized dispatch of HVDC lines; transient, voltage, and frequency stability benefits of HVDC lines; blackstart services; voltage and reactive power support

10-Year Network Development Plan (TYNDP) to Evaluate 176 Transmission, 33 Storage Projects



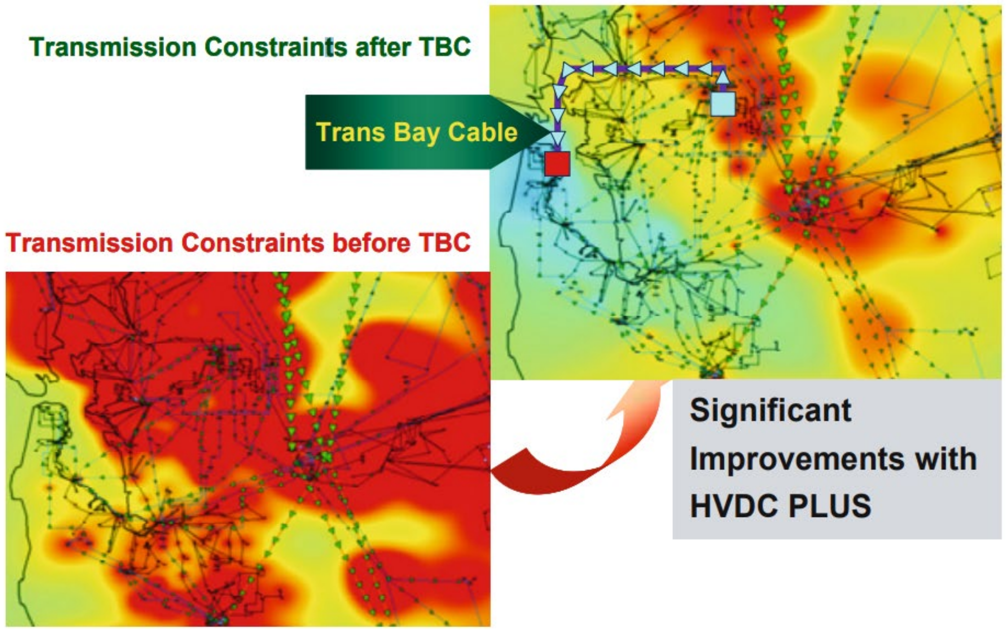
Source: ENTSO-e, *4th ENTSO-e Guideline for Cost Benefit Analysis of Grid Development Projects*, Oct 18, 2023, Figure 8; TYNDP 2024 Implementation Guidelines, Mar 4, 2024.
For a summary of the ENSTO-e framework, incl. HVDC, see pp. 77-80 here.

Example: CAISO HVDC Solutions

CAISO has been a leader in considering HVDC solutions in transmission planning:

- Transbay Cable (TBC), CAISO's first internal HVDC-VSC line, operational since 2013 (1st in North America)
- In its recent Transmission Planning Processes (TPPs), CAISO considered a dozen HVDC solutions and approved two (all VSC, some multi-terminal):

  For example: "the HVDC alternatives resulted in better performance from the power flow perspective as a result of controllability of the HVDC source. The HVDC alternative also provides benefits in reducing local capacity requirements in the San Jose subarea and overall Greater Bay Area that reduces reliance on the local gas generation."



Source: HVDC PLUS – Basics and Principle of Operation, Siemens

- Improvements in California planning studies for HVDC continue:
  - CAISO continues efforts of finding and promoting standard models and approaches for assessing HVDC VSC
  - For example, CAISO is in the process of assessing applicable models for dynamic stability analysis
  - Cal Western has been working with industry experts to develop dynamic stability models for HVDC VSC lines and to find modeling solutions that work in a PSLF environment; they are now able to do dynamic analysis of HVDC VSC lines using PSLF.

Example: HVDC Benefits Considered by CAISO

CAISO's 2022 TPP Report discusses a number of VSC-HVDC-related benefits that are considered in its Transmission Planning Process:

- "Transmission over long distances with overhead lines or underground/subsea cables; there is no practical limit on how far power could be transmitted with HVDC lines"
- "smaller rights-of-way"
- "Power flow on the line is set by the operator"
- "The AC system the VSC-HVDC converters are connected to does not need specific minimum short circuit levels"
- "Does not require reactive power support at the converter station"
- "Multi-terminal configuration is less complicated"
- "VSC-HVDC is suitable for delivering power to urban areas and systems with low short-circuit levels"
- "The converter stations are physically smaller compared to LCC HVDC stations and therefore more suitable to deliver power to urban centers"
- VSC HVDC lines can be combined with other technologies: e.g., to create a "hybrid AC and HVDC solution" to connect 14,428 MW of wind with two VSC-HVDC, two LCC-HVDC, and two 500kV AC lines

Source: ISOBoardApproved-2021-2022TransmissionPlan (caiso.com)

Example: Market Optimization to Capture HVDC Planning Benefits

To ensure that the multiple benefits of HVDC lines (as considered in planning) can actually be captured, CAISO and NYISO have both initiated and implemented several adjustments to their wholesale market design and operations:

- As part of CAISO's Market & Operational Excellence effort, **optimization of controllable transmission devices"** (e.g., HVDC lines and phase shifters) was added to the CAISO DA+RT markets in 2017:
  - Section 3.2.12: "The CAISO market system [now] optimizes the controllable transmission devices as part of its security constrained economic dispatch and security constrained unit commitment. The CAISO market system will calculate and issue the optimal position for the controllable device to the transmission owner."
- NYISO is implementing optimization of "**Internal Controllable Lines**" in its energy and capacity markets after the Clean Path NY HVDC line was selected in part for its congestion-relief benefits to the AC grid
- The Western EIM and the new Extended DA Market are able to fully **co-optimize the dispatch of interregional HVDC lines** (and phase shifters) between the 23 BAs who now participate in EIM (and several already committed to EDAM)
  - The Western EIM and EDAM use CAISO's RT+DA market engines to achieve interregional optimization
- FERC recently approved CAISO's Subscriber PTO (SPTO) framework for full DA+RT market integration of unscheduled capacity on interregional **merchant HVDC lines**

Takeaways

- **Voltage Source Converters (VSC)**, now the dominant HVDC technology, offer substantial advantages in addressing many of today's transmission needs and grid reliability challenges at lower cost
- **Multi-value planning** is necessary to consider the multiple benefits (and avoided AC grid upgrade costs) offered by VSC-based HVDC transmission solutions
- High capacity, long-distance, controllable, multi-terminal HVDC technology is particularly valuable for **interregional** transmission across multiple balancing areas
- Benefits of VSC-based HVDC lines are particularly pronounced for regions with large supply of low-cost renewable generation in areas with a **weak AC grid** that are distant from major load centers
- Gaining **hands-on experience** with VSC technology (incl. by learning from others) is critical for both (a) reliably integrating and (b) being able to take full advantage of the capabilities offered by new regional and inter-regional HVDC projects

Near-term Priorities for Capitalizing on HVDC Advantages

1. Develop and implement "**grid codes**" for interconnected/embedding HVDC lines (as ENTSO-E has done) that allow grid operators to take full advantage of modern HVDC capabilities
2. Adapt grid **planning tools** and **multi-value** planning frameworks to take full account of modern HVDC capabilities
3. Provide **training** for planning, engineering, and grid operations staff so they are able to take advantage of modern HVDC capabilities (rather than being focused solely on preventing problems that might be encountered)
4. Address current **supply chain** challenges by building manufacturing capability through clear long-term commitments
5. Develop **standardization** of HVDC functional and interface requirements, and vendor compatibility standards, taking advantage of experience gained in similar European efforts
6. Develop new **regulatory and cost-recovery** paradigms that can take advantage of the controllable nature of HVDC technology (both regionally and inter-regionally, including merchant transmission) to permit greater competition and allow for better financial/risk sharing with transmission owners

For more detailed discussions, see: The Operational and Market Benefits of HVDC Transmission

Longer-term Priorities for Capitalizing on HVDC Advantages

7. Update **grid operations** to be able to take full advantage of HVDC grid-services
8. Update **market designs** so system operators can co-optimize controllable transmission with generation
9. Implement **intertie optimization** to fully utilize existing and new interregional transmission capabilities, including merchant HVDC transmission

To implement these recommendations and address the identified challenges, grid operators and planning authorities will need to collaborate with:

- Transmission owners/developers
- HVDC equipment manufacturers
- North American Electric Reliability Corporation (NERC)
- Industry groups, regulators, and states
- U.S. Department of Energy (DOE) and its National Labs

For more detailed discussions, see: The Operational and Market Benefits of HVDC Transmission and The Need for Intertie Optimization: Reducing Customer Costs, Improving Grid Resilience, and Encourage Interregional Transmission

About the Speakers

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(webbio and publications)

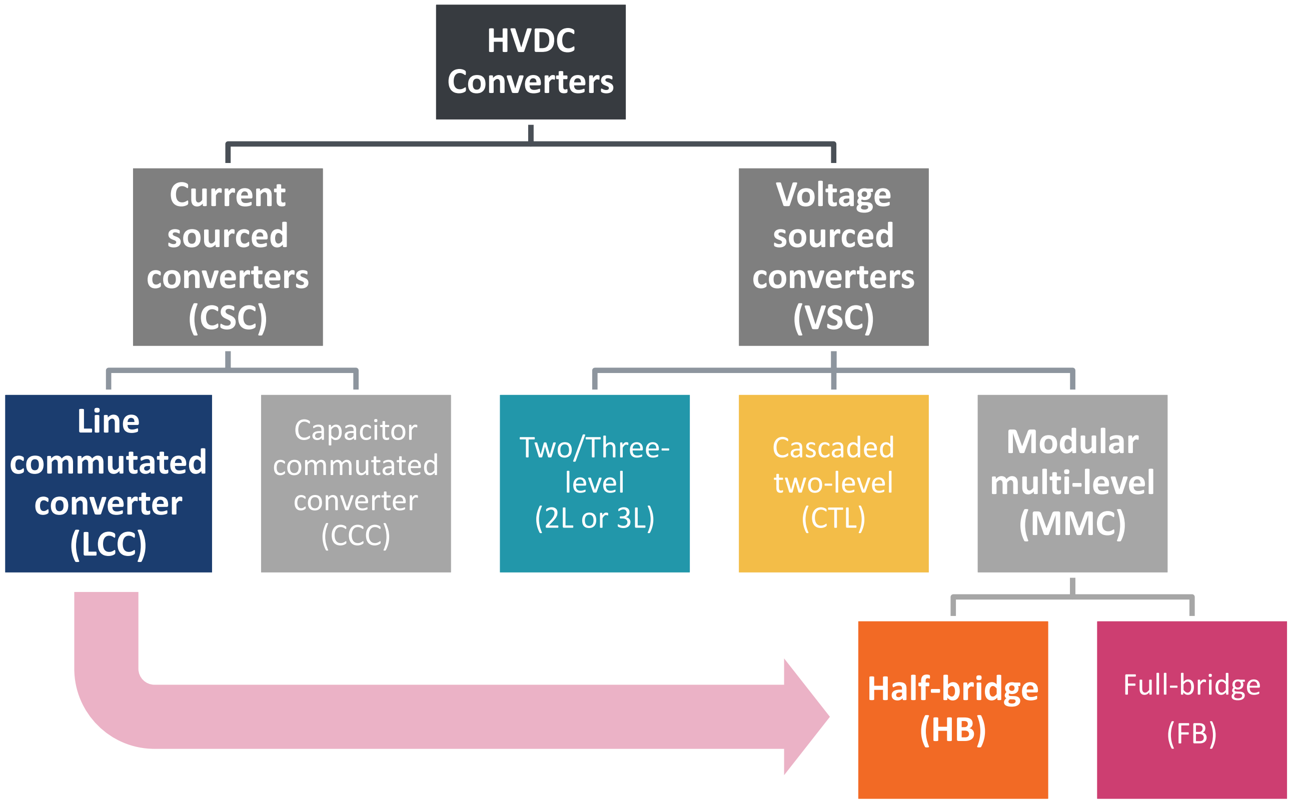
Johannes (Hannes) Pfeifenberger, a Principal at The Brattle Group, is an economist with a background in electrical engineering and over twenty-five years of experience in wholesale power market design, renewable energy, electricity storage, and transmission. He also is a Visiting Scholar at MIT's Center for Energy and Environmental Policy Research (CEEPR), a former Senior Fellow at Boston University's Institute of Sustainable Energy (BU-ISE), a IEEE Senior Member, and currently serves as an advisor to research initiatives by the U.S. Department of Energy, the National Labs, and the Energy Systems Integration Group (ESIG).

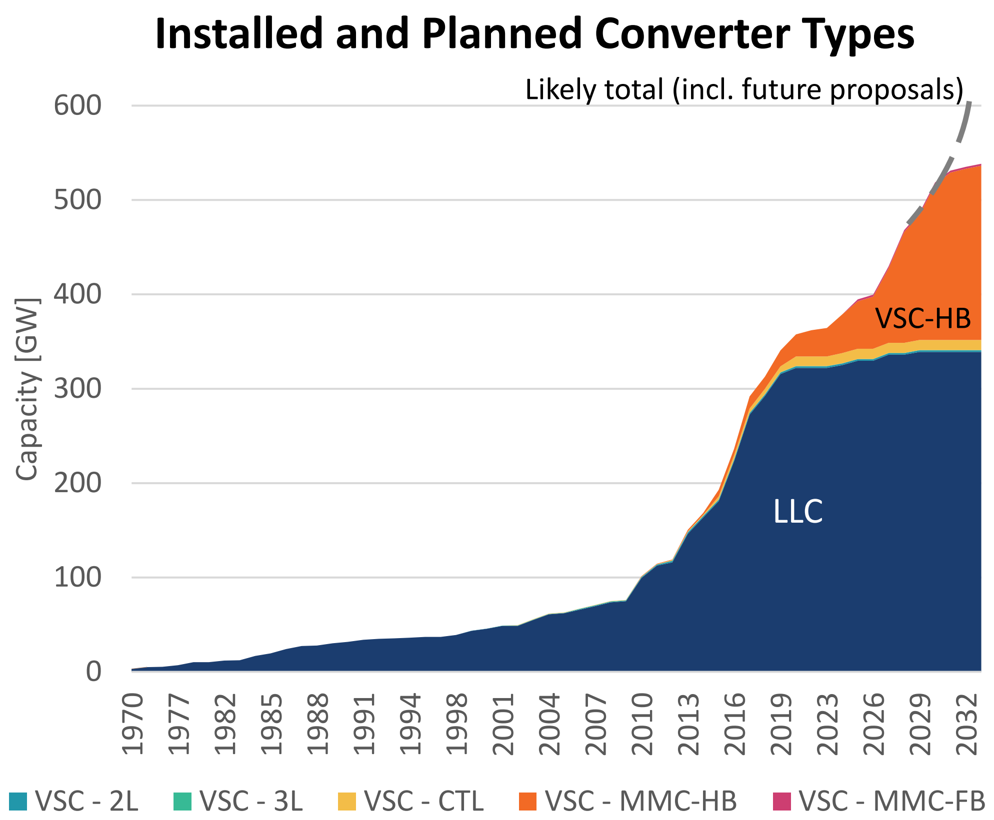
Hannes specializes in wholesale power markets and transmission. He has analyzed transmission needs, transmission benefits and costs, transmission cost allocations, and renewable generation interconnection challenges for independent system operators, transmission companies, generation developers, public power companies, industry groups, and regulatory agencies across North America. He has worked on transmission matters in SPP, MISO, PJM, New York, New England, ERCOT, CAISO, WECC, and Canada and has analyzed offshore-wind transmission challenges in New York, New England, and New Jersey.

He received an M.A. in Economics and Finance from Brandeis University's International Business School and an M.S. and B.S. ("Diplom Ingenieur") in Power Engineering and Energy Economics from the University of Technology in Vienna, Austria.

HVDC converter technologies

Many different converter technologies exist, but growth is driven by **modular multi-level voltage source converter technology**





Source: The Operational and Market Benefits of HVDC Transmission

Added Detail: Use Cases for HVDC Transmission

Source: The Operational and Market Benefits of HVDC Transmission

Use Case	Description/Features
1. Integration of remote renewables and offshore wind	More cost effective and stable for long-distance access to remote renewables Offers relatively high availability and capacity, low maintenance, and low losses for long distance transmission of renewables Superior controllability for integrating volatile renewable generation and stabilizing AC networks Allows for large export capacity from weak (but renewable rich) portions of the AC grid
2. Long-distance bulk-transmission	Overhead HVDC lines: Offers lower-cost, high-capacity transmission over longer distances, with lower losses, and less right of way than AC transmission lines Underground and submarine HVDC cables: offers lower-cost, high-capacity transmission over long distances; using underground HVDC minimizes environmental impact and reduces outage risks
3. Corridor transfer capability increase	Conversions of AC transmission to HVDC (and upgrades of aging HVDC lines) allow for substantial increases in the transfer capacity of existing transmission lines and corridors without the need for additional right of way and new greenfield transmission lines
4. Interconnections between asynchronous grids	Allows power transmission between AC grids that are not synchronized Asynchronous HVDC interconnection also allows for precise control of power transfer (for both reliability and trading) and the blocking of cascading failures without an increase of the grids' short-circuit current Two asynchronous systems can use HVDC to provide each other frequency support, balancing power, and operating reserve when needed
5a. Interconnections between BAs within a synchronous region	An HVDC link connecting neighboring balancing areas within a single synchronous AC network allows the BAs to exchange energy (for reliability and trading), provide balancing power, and share operating reserves (similar to HVAC transmission links) HVDC can additionally provide AC grid support services, such as power flow control (avoiding the need for phase shifters), dynamic voltage control (avoiding the need for STATCOMs), and system stability and dynamic support
5b. Transmission Embedded within a single BA[57]	HVDC transmission connected to different points of the AC grid within a single balancing area provides large transfer capability without imposing stability issues or loop flows on the AC grid It also provides power flow control functions within the AC network (such as for congestion management and loss reduction), dynamic voltage control (at each interconnection point), system stability improvement (including mitigation of stability-based AC transmission constraints), and the mitigation of AC-grid contingency impacts and system cascading failure risks
6. Infeed to load centers/urban areas	Allows for more cost-effective, high-capacity transmission feeds into urban areas and other large load centers where overhead lines are not an option or rights-of-way are very limited VSC-based underground DC transmission can be added to existing transmission rights-of-way to reliably deliver more power to load centers without increasing short-circuit levels Provides additional reliability services, such as dynamic voltage support within the load center
7. Providing power to remote locations (including small islanded grids and offshore platforms)	VSC HVDC transmission can support weak or even passive islanded or remote grids, stabilize the islanded AC networks, and improve grid performance in the event of power disturbances

	Type of AC grid connection →	Islanded AC grids		Strong / weak AC grids			
					Embedded		
	Grid Service ↓ / Type of use case →	Integration of remote renewables	Providing power to remote locations	Connections between asynchronous regions	Embedded within a synchronous region	Embedded within a single BA	Infeed to load centers/urban areas
Transmission functions	AC voltage and frequency control	VSC	VSC				
	Reactive power control (static)	VSC	VSC	VSC	VSC	VSC	VSC
	Real power control	**HVDC**	**HVDC**	**HVDC**	**HVDC**	**HVDC**	**HVDC**
Grid operations support	Voltage support/reactive power control (dynamic)	VSC	VSC	VSC	VSC	VSC	VSC
	Synthetic inertia*	*		VSC	*	*	*
	Frequency response*	VSC		**HVDC**	*	*	*
	Regulation, ramping, spinning reserves*	VSC		**HVDC**	**HVDC**	*	*
Autonomous line dispatch	External Power (Tracking) Control			**HVDC**	**HVDC**	**HVDC**	**HVDC**
	AC Line Emulation			**HVDC**	**HVDC**	**HVDC**	**HVDC**
Power quality support	AC grid oscillation damping			**HVDC**	**HVDC**	**HVDC**	**HVDC**
	AC phase balancing			VSC	VSC	VSC	VSC
Contingency operations	Run-back / run-up schemes			**HVDC**	**HVDC**	**HVDC**	**HVDC**
	Emergency energy imports			**HVDC**	**HVDC**	**HVDC**	**HVDC**
	Black-start and system restoration	VSC	VSC	VSC	VSC	VSC	VSC
Reliability & Market Optimization	AC grid power flow optimization			**HVDC**	**HVDC**	**HVDC**	**HVDC**
	Resource adequacy, capacity imports*			**HVDC**	**HVDC**		
	Intertie optimization*			**HVDC**	**HVDC**		

HVDC = both LCC & VSC can provide the service

VSC = only VSC converters can provide the service

* requires coordination with neighboring system or connected resource (e.g. storage)

Examples of Available HVDC-Related Training

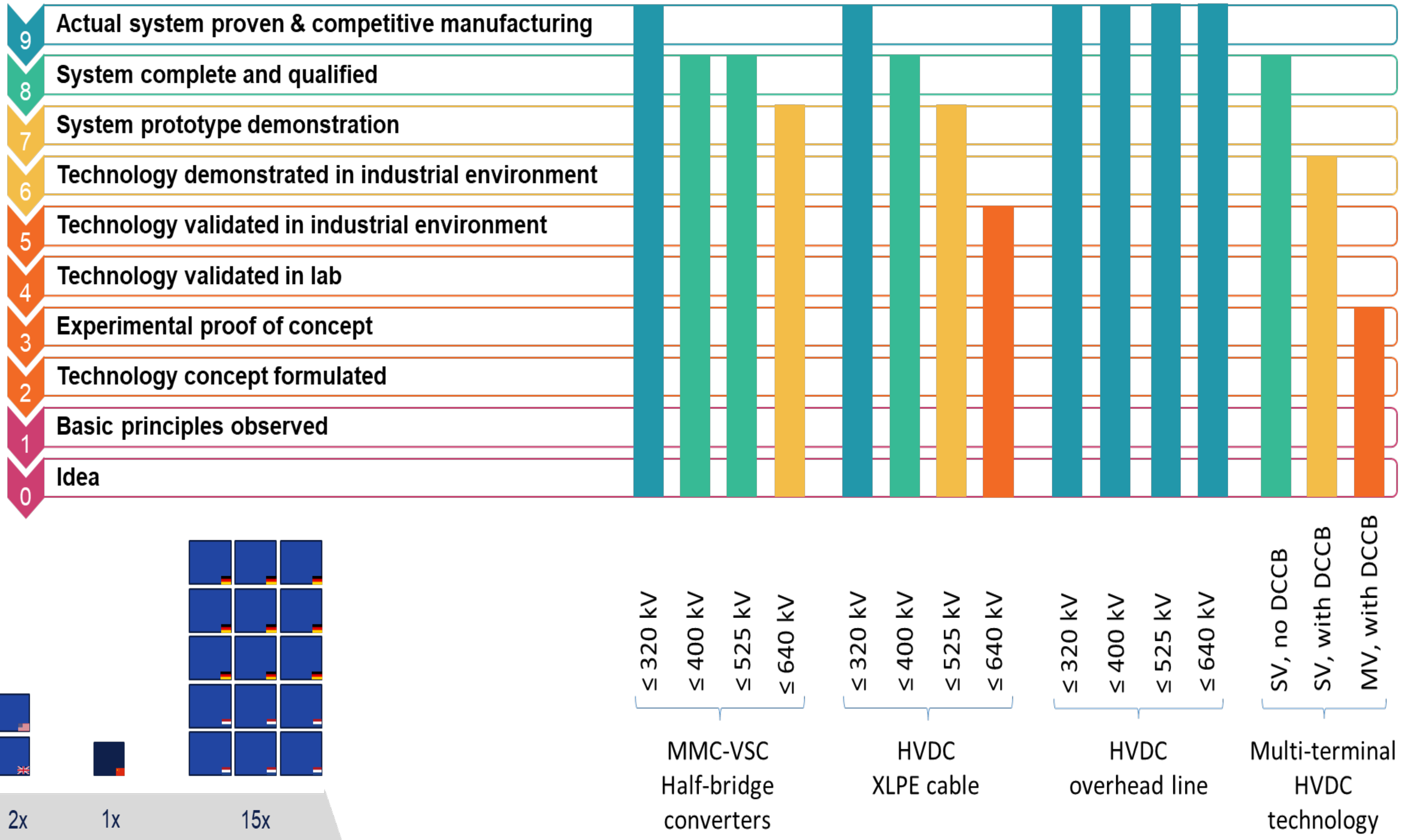
Topic	Audience	Specificity	Trainer	Examples
HVDC technology & systems	System planners, technologists, project engineers, researchers	Generic, could be focused on different technology groups, or systems	Consultants, universities, industry associations, vendors, etc.	• HVDC Converter Technologies training course (dnv.com) • Training – The National HVDC Centre • Services - TransGrid Solutions (myftpupload.com)
HVDC modelling & analysis	System planners, project engineers, researchers	Generic	Consultants, universities, industry associations, vendors,…	• Training & Support - RTDS Technologies • HVDC Control & Project Management | PSCAD • HVDC-VSC System Training - RTE international (rte-international.com)
HVDC project management	Project teams	Generic	Consultants, industry associations, vendors,…	
HVDC operation (operator training)	Grid Operators	Vendor specific	Vendors, consultants,…	• Training | Hitachi Energy • High Voltage Direct Current (HVDC) Systems e-learning – GE Grid Solutions
HVDC maintenance	Maintenance teams	Vendor specific	Vendors, consultants,…	
Market operations	Market Operators	TSO specific	TSO, market operator, consultants	• Controllable Lines Proposal (nyiso.com)

Source: The Operational and Market Benefits of HVDC Transmission

HVDC Project Size and Commercial Readiness of HVDC Elements

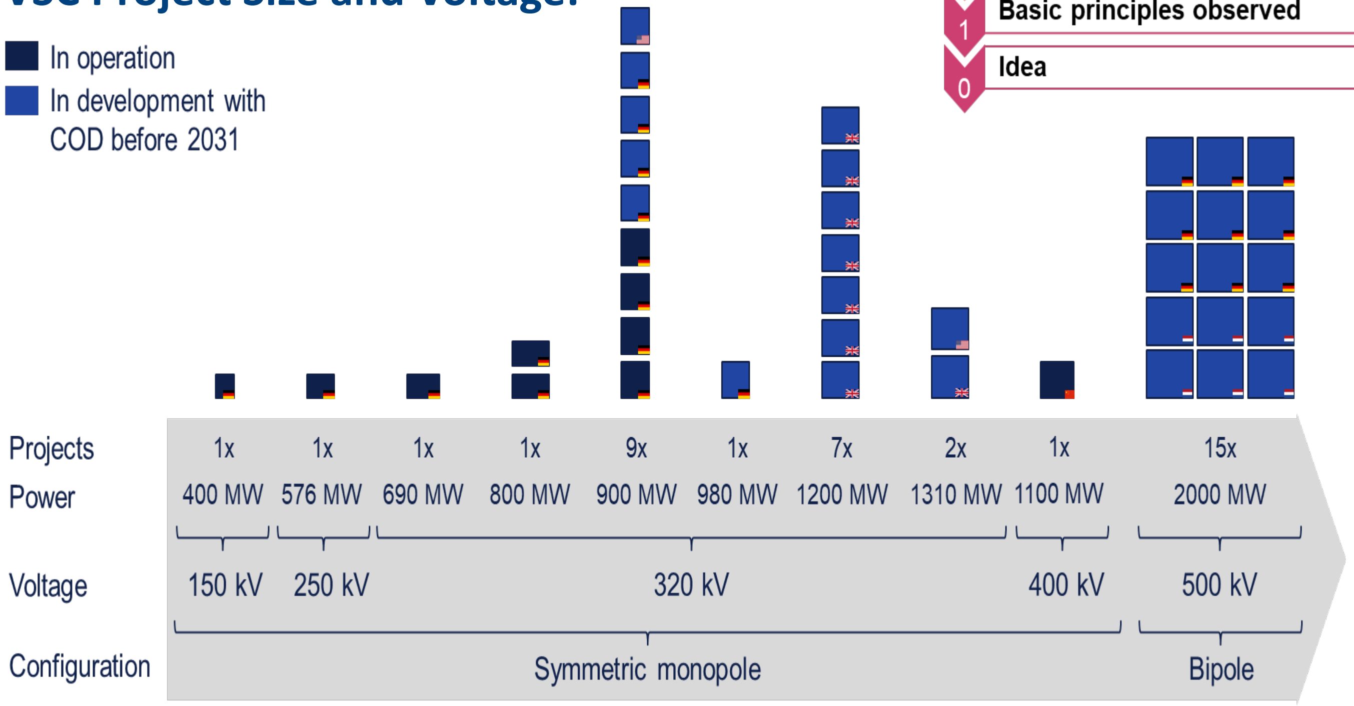
Note: Excluding Chinese market

Commercial Readiness:



SV = single vendor
MV = multi-vendor

VSC Project Size and Voltage:



Source: The Operational and Market Benefits of HVDC Transmission

Challenges to the utilization of HVDC capabilities

Outdated, incomplete and uncoordinated technical standardization

- Existing standards do not fully take into account characteristics of modern HVDC transmission technology.
  - MMC-VSC converter technology
  - Underground and submarine HVDC cable technology
- Some ongoing standardization initiatives are overtly conservative and reduce ability to realize VSC-HVDC benefits
- Existing standards do not cover all HVDC applications
  - IEEE P2800 does not cover offshore converter AC performance requirements
  - No operational guideline for DC grid behavior
- HVDC standardization is not coordinated across regions and between functional disciplines
  - Health, safety, and environment
  - System performance and design
  - Technology & equipment (to ensure modularity and compatibility)
  - Test, measurement, & analysis
  - Communication and Cyber security

Source: The Operational and Market Benefits of HVDC Transmission

Challenges to the utilization of HVDC capabilities (cont'd)

Supply chain challenges

- Small number of HVDC suppliers
- Limited production capacity of the vendor in terms of engineering staff, number of production lines, limited transport and installation equipment, availability of testing facilities
- Technical maturity of the vendors' HVDC technology
- Project management experience of the vendor
- Country of origin of the vendor and the resulting export restrictions
- Sub-supplier/partnership strategy of vendors

Planning, regulatory, and market-design challenges

- Lack of proactive, multi-value planning processes that are able to capture long-term HVDC-related values
- Lack of grid codes to ensure that system operators are able to take advantage of the technology's grid-supporting HVDC capabilities
- Limited operator experience
- Lack of market-clearing software able to co-optimize generation and controllable HVDC transmission facilities

Source: The Operational and Market Benefits of HVDC Transmission

Examples of Brattle Reports on Regional and Interregional Transmission Planning and Benefit-Cost Analyses

Well-Planned Electric Transmission Saves Customer Costs:
Improved Transmission Planning is Key to the Transition to a Carbon-Constrained Future

PREPARED FOR
WIRES

Link: Well-Planned Transmission

PREPARED BY
Judy W. Chang
Johannes P. Pfeifenberger

May 2016

THE Brattle GROUP

Toward More Effective Transmission Planning:
Addressing the Costs and Risks of an Insufficiently Flexible Electricity Grid

PREPARED FOR
WIRES

Link: Effective Transmission Planning

PREPARED BY
Johannes P. Pfeifenberger
Judy W. Chang
Akarsh Sheilendranath

April 2015

The Brattle Group

Link: Transmission Benefits

The Benefits of Electric Transmission: Identifying and Analyzing the Value of Investments

July 2013

Judy W. Chang
Johannes P. Pfeifenberger
J. Michael Hagerty

Link: Diversity Value

BU
Boston University Institute for Sustainable Energy

The Value of Diversifying Uncertain Renewable Generation through the Transmission System

September • 2020

A Roadmap to Improved Interregional Transmission Planning

Link: Interregional Roadmap

PREPARED BY
Johannes P. Pfeifenberger
Kasparas Spokas
J. Michael Hagerty
John Tsoukalis

November 30, 2021

Transmission Planning for the 21st Century: Proven Practices that Increase Value and Reduce Costs

Link: Brattle Grid Strategies

PREPARED BY

The Brattle Group:
Johannes Pfeifenberger
Kasparas Spokas
J. Michael Hagerty
John Tsoukalis

Grid Strategies:
Rob Gramlich
Michael Goggin
Jay Caspary
Jesse Schneider

OCTOBER 2021

Brattle
GRID STRATEGIES LLC

Summarizes proven approaches to quantifying various benefits

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Brattle Group Practices and Industries

ENERGY & UTILITIES

Competition & Market Manipulation
Distributed Energy Resources
Electric Transmission
Electricity Market Modeling & Resource Planning
Electrification & Growth Opportunities
Energy Litigation
Energy Storage
Environmental Policy, Planning and Compliance
Finance and Ratemaking
Gas/Electric Coordination
Market Design
Natural Gas & Petroleum
Nuclear
Renewable & Alternative Energy

LITIGATION

Accounting
Analysis of Market Manipulation
Antitrust/Competition
Bankruptcy & Restructuring
Big Data & Document Analytics
Commercial Damages
Environmental Litigation & Regulation
Intellectual Property
International Arbitration
International Trade
Labor & Employment
Mergers & Acquisitions Litigation
Product Liability
Securities & Finance
Tax Controversy & Transfer Pricing
Valuation
White Collar Investigations & Litigation

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Infrastructure
Natural Gas & Petroleum
Pharmaceuticals & Medical Devices
Telecommunications, Internet, and Media
Transportation
Water

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