High Voltage DC Transmission

1.0 Introduction

HVDC has been applied in electric power systems for many years now. Figure 1a illustrates worldwide many of the HVDC applications as of 2000 [1].

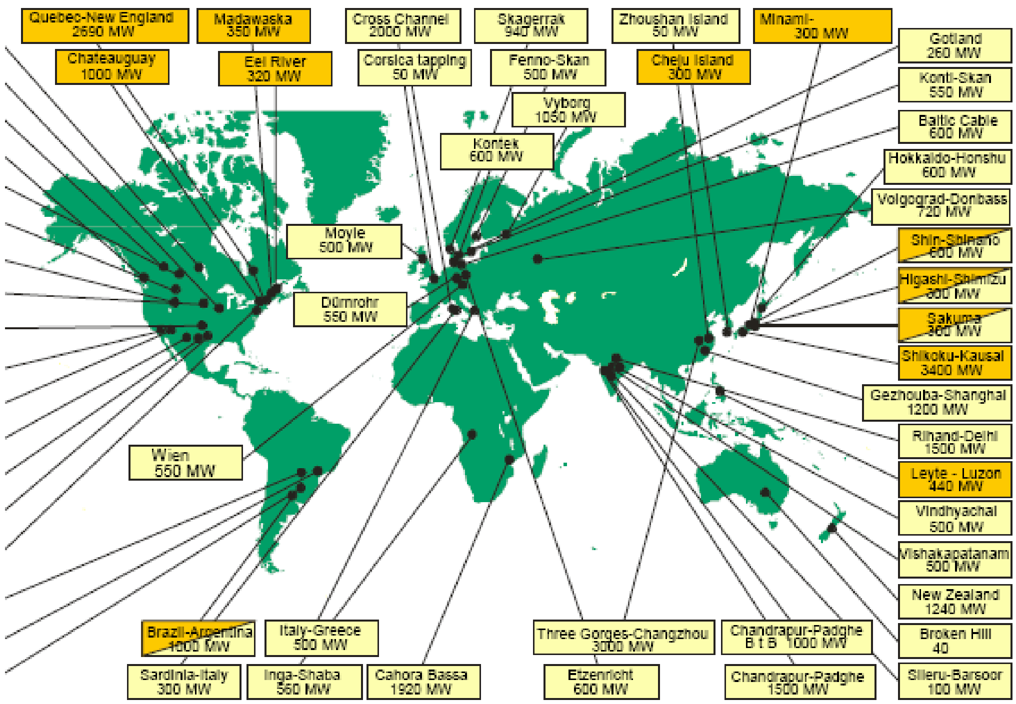


Fig. 1a

A more recent summary, 2017, is given in Fig. 1b [2] where one distinguishes between lines & B2B facilities.

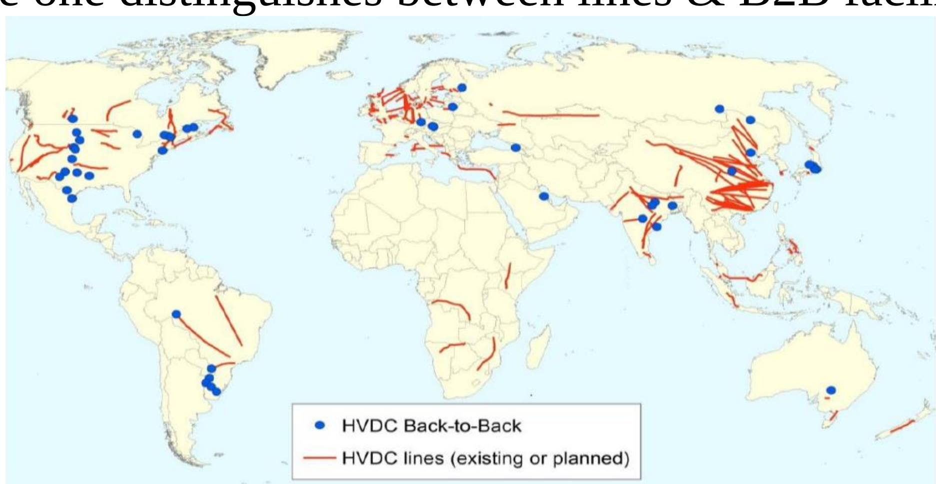


Fig. 1b: HVDC summary worldwide

Wikipedia [3] provides an extensive table of all HVDC projects worldwide which can be visualized, as illustrated in Fig. 2a [4]. It has both recent (2021) and planned projects, and it is organized by continent. However, the accuracy of this information is unknown. I updated Fig. 2a as Fig. 2b, 3/21/2024.

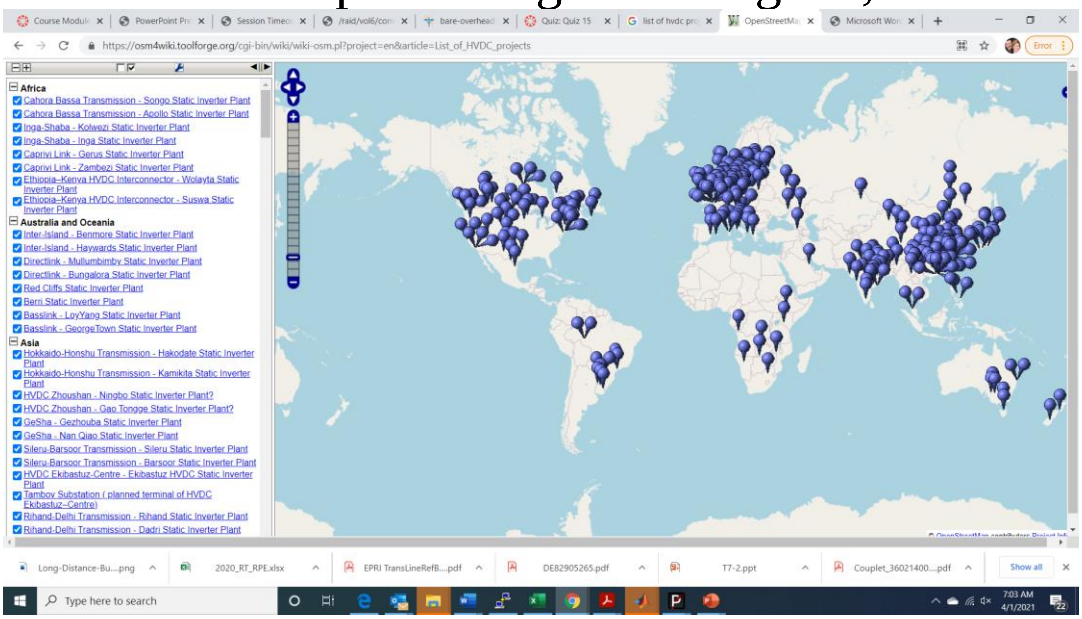


Fig. 2a

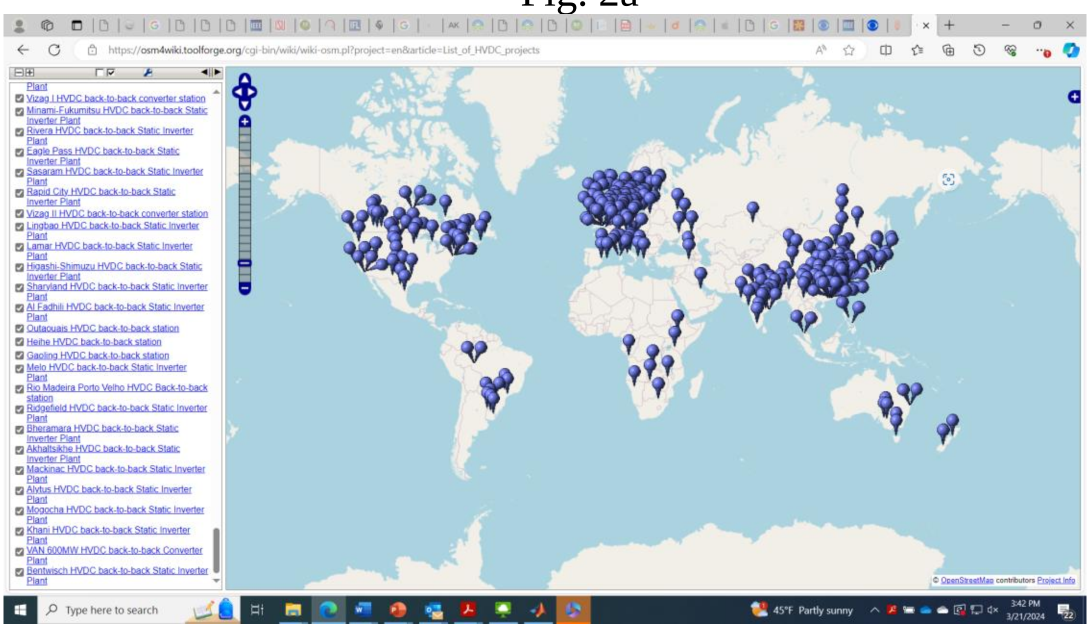


Fig. 2b

Another resource was the webpages of the IEEE HVDC and FACTS Subcommittee. They had posted on the internet HVDC projects worldwide that are existing or under construction as of 2013, and information from this posting was obtained and summarized in Table 1a. Some observations:

- The table is sorted from least capacity to most.
- The capacity (power rating) and line length of the various projects - both generally increase with installation date. Note the largest projects (at the end of the table) are 3000-7200MW and mainly in China.
- The converter type, mercury, thyristor, or transistor, with the mercury being very early and the transistor being more recent, and the thyristor occurring from about 1970 until now.
- The voltage level, which is highly varied for small capacity projects, with ±500kV being the most common for large capacity projects, but ±600kV and ±800kV being used for some of the largest projects.
- The PDCI installation on the 3rd and 4th pages of the table (and other North American installations).
- The Rio Madeira, in Brazil, on the last page of Table 1a, is a ±600kV, 3150MW HVDC project that is 2375km long (1475 miles) - the longest HVDC project in the world – see Fig. 3.
- This resource is no longer available; I am unsure why.

Fig. 3

Table 1a: HVDC Projects Existing or Under Construction as of 2013

HVDC PROJECTS LI+A1:H45STING
Prepared for the
HVDC and Flexible AC Transmission Subcommittee
of the
IEEE Transmission and Distribution Committee

SYSTEM / PROJECT	HVDC SUPPLIER	YEAR COMMISSIONED	POWER RATING (MW)	DC VOLTAGE (kV)	LINE/ CABLE (km)	MERCURY/ THYRISTOR/ TRANSISTOR	LOCATION
TJAEREBORG	ABB	2000	7	9	4.3	TRA	DENMARK
GOTLAND I (retired from service)	ASEA	1954 (1986)	20	±100	96	MERC	SWEDEN
MOSOW-KASHIRA (retired from service)	RUSSIAN	1951 (____)	30	±100	100	MERC	RUSSIA
GOTLAND EXTENSION (retired from service)	ASEA	1970 (1986)	30	±150	96	THY	SWEDEN
EAGLE PASS	ABB	2000	36	15.9	B-B	TRA	U.S.A.
BROKEN HILL	ASEA	1986	40	2x17 (±8.33)	B-B	THY	AUSTRALIA
GOTLAND HVDC LIGHT	ABB	1999	50	±60	70	TRA	SWEDEN
SACOI TAP ON CORSICA (LUCCIANA)	CGEE/ALSTHOM	1985	50	200	415	THY	ITALY-CORSICA-SARDINIA
ZHOU SHAN PROJECT		1982	50	100	42	THY	CHINA
URUGUAIANA	TOSHIBA	1994	50	15	B-B	THY	BRAZIL-ARGENTINA
VISBY-NAS	ABB	1999	50	80	70	THY	SWEDEN
ACARAY	SIEMENS	1981	55	±25	B-B	THY	PARAGUAY-BRAZIL
RIVERA	GEC ALSTHOM	2000	70	20	B-B	THY	URUGUAY-BRAZIL
VALHALL	ABB	UNDER CONSTRUCTION 2011	78	150	292	TRA	NORWAY
DAVID A. HAMIL	GENERAL ELECTRIC	1977	100	±50	B-B	THY	U.S.A
BARSOOR LOWER SILERU	BHEL	1989/91	100	±200	196	THY	INDIA
GOTLAND II	ASEA	1983	130	150	100	THY	SWEDEN
HOKKAIDO-HONSHU	ASEA	1979	150	125	167	THY	JAPAN
McNEILL	GEC ALSTHOM	1989	150	42	B-B	THY	CANADA
SHARYLAND	ABB	2007	150	±21	B-B	THY	USA - MEXICO
ENGLISH CHANNEL (retired from service)	ASEA	1961 (1984)	160	±100	64	MERC	ENGLAND-FRANCE
SACOI 1	ENGLISH ELECTRIC	1965	200	200	385	THY	ITALY
SARDINIA (retired from service)	ENGLISH ELECTRIC	1967 (1992)	200	200	413	THY	ITALY
EDDY COUNTY	GENERAL ELECTRIC	1983	200	82	B-B	THY	U.S.A.
OKLAUNION	GENERAL ELECTRIC	1984	200	82	B-B	THY	U.S.A
BLACKWATER	BBC	1985	200	57	B-B	THY	U.S.A.
HIGHGATE	ASEA	1985	200	±56	B-B	THY	U.S.A.
MILES CITY HVDC SYSTEM (MCCS)	GENERAL ELECTRIC	1985	200	82	B-B	THY	U.S.A
VIRGINIA SMITH	SIEMENS	1987	200	50	B-B	THY	U.S.A
MURRAYLINK	ABB	2002	200	±150	176	TRA	AUSTRALIA
HIGHGATE CONVERTER STATION REFURBISHMENT	ABB	SCHEDULED 2012	200	57	B-B	THY	USA - CANADA
LAMAR	SIEMENS	2005	210	±64	B-B	THY	U.S.A.
KONTI-SKAN 1	ASEA	1965	250	±250	180	MERC	DENMARK-SWEDEN
KONTI-SKAN 1	AREVA	2005	250	±250	180	THY	DENMARK-SWEDEN
LEVIS DE-ICER	AREVA	2008	250	±17.4	27 to 242	THY	CANADA
GOTLAND III	ASEA	1987	260	±150	103	THY	SWEDEN
SKAGERRAK I	ASEA	1976	275	±250	240	THY	NORWAY-DENMARK
SKAGERRAK II	ASEA	1977	275	±250	240	THY	NORWAY-DENMARK
KONTI-SKAN 2	ASEA	1988	300	285	150	THY	DENMARK-SWEDEN

SAKUMA (reti+A56:H100red from service)	ASEA	1965 (1993)	300	2x125	B-B	MERC	JAPAN
SACOI (CODRONGIANOS AND SUVERETO)	ANSADO/GENERAL ELECTRIC	1993	300	±200	385	THY	ITALY-CORSICA-SARDINIA
SHIN-SHINANO 1	HITACHI/TOSHIBA/NISSHIN	1977	300	125	B-B	THY	JAPAN
SHIN-SHINANO 2	HITACHI/TOSHIBA/NISSHIN	1992	300	125	B-B	THY	JAPAN
HOKKAIDO-HONSHU	HITACHI/TOSHIBA	1980	300	250	167	THY	JAPAN
SAKUMA	HITACHI/TOSHIBA/MITSUBISHI/NISSHIN	1993	300	±125	B-B	THY	JAPAN
HAENAM-CHEJU	GEC ALSTHOM	1997	300	±180	101	THY	KOREA
MINAMI-FUKUMITZU	HITACHI/TOSHIBA	1999	300	125	B-B	THY	JAPAN
HIGASHI-SHIMIZU	HITACHI/TOSHIBA	2001	300	125	B-B	THY	JAPAN
THAILAND-MALAYSIA	SIEMENS	2001	300	±300	110	THY	THAILAND-MALAYSIA
CAPRIVI	ABB	2010	300	350	950	TRA	NAMIBIA
VANCOUVER I	ASEA	1968/69	312	±260	74	MERC	CANADA
EEL RIVER	GENERAL ELECTRIC	1972	320	±80	B-B	THY	CANADA
CROSS SOUND	ABB	2002	330	±150	40	TRA	U.S.A
MADAWASKA	GENERAL ELECTRIC	1985	350	130.5	B-B	THY	CANADA
ESTLINK	ABB	2006	350	±150	105	TRA	ESTONIA-FINLAND
VYBORG	MINISTRY FOR ELECTROTECHNICAL INDUSTRY OF USSR	1981	355	1X170(±85)	B-B	THY	RUSSIA-FINLAND
LINGBAO		2005	360	168	B-B	THY	CHINA
VANCOUVER II	GENERAL ELECTRIC	1977/79	370	±280	74	THY	CANADA
NORDE.ON 1	ABB	2009	400	150	203	TRA	GERMANY
TRANS BAY CABLE	SIEMENS AND PIRELLI	2010	400	200	88	TRA	U.S.A.
BORWIN1	ABB	SCHEDULED 2012	400	±150	200	TRA	GERMANY
JINDO-JEJU	ALSTOM	2011	400	±250	105	THY	KOREA
COMETA	PRYSMIAN/NEXANS/SIEMENS	UNDER CONSTRUCTION 2011	400	250	247	THY	SPAIN
LEYTE-LUZON	ABB/MARUBENI	1998	440	350	455	THY	PHILIPPINES
SKAGERRAK III	ABB	1993	500	±350	240	THY	NORWAY-DENMARK
SQUARE BUTTE	GENERAL ELECTRIC	1977	500	±250	749	THY	U.S.A.
VINDHYACHAL	ASEA	1989	500	2x69.7	B-B	THY	INDIA
FENNO-SKAN	ABB/ALCATEL	1989/98	500	400	303	THY	FINLAND-SWEDEN
VIZAG 1	GEC ALSTHOM	1999	500	205	B-B	THY	INDIA
VIZAG 2	ABB	2005	500	±88	B-B	THY	INDIA
GRITA	PIRELLI/ABB	2001	500	400	316	THY	GREECE-ITALY
SASARAM	GEC ALSTHOM	2002	500	205	B-B	THY	INDIA
BASSLINK	SIEMENS	2006	500	400	350	THY	AUSTRALIA
EAST-WEST INTERCONNECTOR	ABB	UNDER CONSTRUCTION 2012	500	±200	261	TRA	IRELAND-UNITED KINGDOM
MELO INTERCONNECTOR	ALSTOM	SCHEDULED 2012	500	525	B-B	THY	URUGUAY-BRAZIL
DUERNROHR 1 (retired from service)	BBC/SIEMENS	1983 (1997)	550	145	B-B	THY	AUSTRIA
SYLMAR EAST (VALVE RECONSTRUCTION)	SIEMENS	1995	550	500	1200	THY	U.S.A.
INGA-SHABA	ASEA/GE	1982/83	560	±500	1700	THY	ZAIRE
NEW ZEALAND HYBRID INTER ISLAND LINK	ASEA	1965	600	±250	609	MERC	NEW ZEALAND
HOKKAIDO-HONSHU	HITACHI/TOSHIBA	1993	600	±250	167	THY	JAPAN
GESHA (GEZHOUBA-SHANGHAI)	BBC/SIEMENS	1989	600	500	1000	THY	CHINA
ETZENRICHT (retired from service)	SIEMENS	1993 (1997)	600	160	B-B	THY	GERMANY-CZECH REPUBLIC
VIENNA SOUTH-EAST (retired from service)	SIEMENS	1993 (1997)	600	145	B-B	THY	AUSTRIA-HUNGARY
BALTIC CABLE	ABB	1994	600	450	261	THY	SWEDEN-GERMANY

WEL+A1+A112+A101:H129+A101:H131+A101:H13+A101:H129	SIEMENS	1995	600	170	B-B	THY	U.S.A
KONTEK	ABB/NKT CABLES	1995	600	400	171	THY	DENMARK-GERMANY
WELCH-MONTICELLO	SIEMENS	1998	600	162	B-B	THY	U.S.A.
SWEPOL LINK	ABB	2000	600	±450	254	THY	SWEDEN-POLAND
STOREBAELT	SIEMENS	2010	600	400	56	THY	DENMARK
KINGSNORTH (retired from service)	ENGLISH ELECTRIC	1972 (1987)	640	±266	82	THY	UNITED KINGDOM
Inter-Island NZ 2		1992	640	350	610	THY	NewZ (Benmore - Haywards)
NEPTUNE	SIEMENS	2007	660	500	105	THY	U.S.A.
HUDSON TRANSMISSION	SIEMENS / PRYSMIAN	SCHEDULED 2013	660	±345	12	THY	USA
ESTLINK 2	SIEMENS	SCHEDULED 2014	670	±450	171	THY	ESTONIA-FINLAND
DES CANTONS-COMFERFORD	GENERAL ELECTRIC	1986	690	±450	172	THY	CANADA-U.S.A.
NORNED	ABB	2008	700	±450	580	THY	NORWAY-NETHERLANDS
SKAGERRAK 4	ABB	UNDER CONSTRUCTION 2014	700	500	244	TRA	NORWAY - DENMARK
INTER ISLAND CONNECTOR	SIEMENS	SCHEDULED 2013	700	±350		THY	NEW ZEALAND
VYBORG	MINISTRY FOR ELECTROTECHNICAL INDUSTRY OF USSR	1982	710	2x170	B-B	THY	RUSSIA-FINLAND
VOLGOGRAD-DONBASS	MINISTRY FOR ELECTROTECHNICAL INDUSTRY OF USSR	1962/65	720	±400	473	MERC/THY	RUSSIA
RIHAND-DELHI	ABB/BHEL	1991	750	500	814	THY	INDIA
LINGBAO II EXTENSION PROJECT	ABB/ALSTOM	2010	750	168	B-B	THY	CHINA
FENNO-SKAN II	ABB/NEXANS	2011	800	500	303	THY	FINLAND-SWEDEN
NELSON RIVER 2	AEG/BBC/SIEMENS	1978	900	±250	940	THY	CANADA
CU	ASEA	1979	1000	±400	701	THY	U.S.A
CHANDRAPUR-RAMAGUNDUM	GEC ALSTHOM	1997/98	1000	2x205	B-B	THY	INDIA
SAPEI	ABB	UNDER CONSTRUCTION 2011	1000	±500	435	THY	ITALY MAINLAND-SARDINIA
BRITNED	SIEMENS	2011	1000	±400	260	THY	UK - NETHERLANDS
VYBORG	MINISTRY FOR ELECTROTECHNICAL INDUSTRY OF USSR	1984	1065	3x170	B-B	THY	RUSSIA-FINLAND
GARABI 1	ABB	2000	1100	±70	B-B	THY	ARGENTINA-BRAZIL
GESHA (GEZHOUBA-SHANGHAI)	BBC/SIEMENS	1990	1200	±500	1000	THY	CHINA
NEW ZEALAND HYBRID INTER ISLAND LINK	ABB	1992	1240	+270/-350	612	THY	NEW ZEALAND
KII CHANNEL	HITACHI/TOSHIBA/MITSUBISHI	2000	1400	±250	102	THY	JAPAN
PACIFIC INTERTIE	ASEA/GE	1970	1440	±400	1362	MERC	U.S.A
RIHAND-DELHI	ABB/BHEL	1992	1500	±500	814	THY	INDIA
CHANDRAPUR BACK-TO-BACK	ABB	1998	1500	±500	736	THY	INDIA
QINGHAI-TIBET	CET/SGCC	SHEDULED 2012	1500	±400	1038	THY	CHINA-TIBET
ITAIPU 1	ASEA	1984	1575	±300	785	THY	BRAZIL

PACIFIC INTERTIE	ASEA/GE	1982	1600	±400	1362	MERC	U.S.A
TIAN-GUANG	SIEMENS	2001	1800	±500	960	THY	CHINA
NELSON RIVER 1	ENGLISH ELECTRIC/GEC ALSTHOM	1973	1854	±463	890	MERC	CANADA
NELSON RIVER 1	GEC ALSTHOM	1992/93	1854	±463	890	MERC/THY	CANADA
NELSON RIVER 1	SIEMENS	2001/02	1854	±463	890	THY	CANADA
CAHORA-BASSA	AEG/BBC/SIEMENS	1975/1998	1920	±533	1456	THY	SOUTH AFRICA/MOZAMBIQUE
CAHORA-BASSA	ABB	2008	1920	±533	1420	THY	SOUTH AA112:H141FRICA/MOZAMBIQUE
INTERMOUNTAIN POWER PROJECT (I.P.P.)	ASEA	1986	1920	±500	785	THY	U.S.A.
PAC INTERTIE UPGRADE	ASEA	1985	2000	±500	1362	THY	U.S.A
NELSON RIVER 2	AEG/BBC/SIEMENS	1985	2000	±500	940	THY	CANADA
CROSS CHANNEL BP 1+2	CGEE ALSTHOM/GEC	1985/86	2000	±270	70	THY	FRANCE-U.K.
GARABI 2	ABB	2002	2000	±70	B-B	THY	ARGENTINA-BRAZIL
EAST-SOUTH INTERCONNECTOR II	SIEMENS	2003	2000	±500	1450	THY	INDIA
FRANCE - SPAIN INTERCONNECTION LINK	SIEMENS	UNDER CONSTRUCTION 2013	2000	±320	65	THY	FRANCE - SPAIN
QUEBEC-NEW ENGLAND (THREE TERMINAL)	ABB	1990-92	2250	±450	1500	THY	CANADA-U.S.A.
ITAIPU 1	ASEA	1985	2383	±300	785	THY	BRAZIL
I.P.P. UPGRADE	ABB	UNDER CONSTRUCTION 2010	2400	±500 kV	785	THY	USA
EAST-SOUTH INTERCONNECTOR II UPGRADE	SIEMENS	2007	2500	±500	1450	THY	INDIA
THE APOLLO CONVERTER STATION	ABB	REFURBISHED 2008	2500	±533	1420	THY	SOUTH AFRICA
BALLIA - BHIWADI	SIEMENS	2010	2500	500	800	THY	INDIA
MUNDRA - HARYANA	SIEMENS	UNDER CONSTRUCTION 2012	2500	±500	960	THY	INDIA

THREE GORGES-CHANGZHOU	ABB/SIEMENS	2003	3000	±500	860	THY	CHINA
THREE GORGES-GUANGDONG	ABB	2004	3000	±500	940	THY	CHINA
GUI-GUANG I	SIEMENS	2004	3000	±500	980	THY	CHINA
GUI-GUANG II	SIEMENS	2007	3000	±500	1200	THY	CHINA
THREE GORGES-SHANGHAI	ABB	2006	3000	±500	900	THY	CHINA
HULUNBEIR (INNER MONGOLIA) - SHENYANG		2010	3000	± 500	920	THY	CHINA
SUMATRA-JAVA		UNDER CONSTRUCTION 2013	3000	±500	700	THY	INDONESIA
THREE GORGES - SHANGHAI 3	ALSTOM	2010	3000	±500	1000	THY	CHINA
HULUNBEIR-LIAONING HVDC LINK	ABB	2010	3000	±500	920	THY	CHINA
PACIFIC INTERTIE EXPANSION	ABB	1989	3100	±500	1362	THY	U.S.A
PACIFIC INTERTIE SYLMAR REFURBISHMENT	ABB	UNDER CONSTRUCTION 2010	3100	±500	1362	THY	U.S.A.
CELILO (VALVE REPLACEMENT)	SIEMENS	2004	3100	±400	1200	THY	U.S.A.
ITAIPU 1	ASEA	1986	3150	±600	785	THY	BRAZIL
ITAIPU 2	ASEA	1987	3150	±600	805	THY	BRAZIL
NINGDONG - SHANGDONG	Alstom	2011	4000	±660	1335	THY	CHINA
YUNNAN-GUANGDONG	SIEMENS	2010	5000	±800	1418	THY	CHINA
NUOZHADU-GUANGDONG	SIEMENS	SCHEDULED 2013	5000	800	1500	THY	CHINA
BISWANATH-AGRA	ABB	UNDER CONSTRUCTION 2014-2015	6000	±800	1728	THY	INDIA
XIANJIABA-SHANGHAI	ABB	2010	6400	±800	1980	THY	CHINA
XILUODU-HANZHOU	SIEMENS	SCHEDULED 2013	6400	800	1300	THY	CHINA
JINPING - SUNAN (SGCC)	ABB	SCHEDULED 2013	7200	±800	2090	THY	CHINA
RAPID CITY TIE	ABB	2003	2 x 100	±13	B-B	THY	U.S.A.
RIO MADEIRA	ABB (BIPOLE 1) &ALSTOM (BIPOLE 2)	UNDER CONSTRUCTION 2012 (BIPOLE 1) 2013 (BIPOLE 2)	2 x 3150	±600	2375	THY	BRAZIL
MOYLE INTERCONNECTOR	SIEMENS	2001	2x250	2x250	64	THY	NORTHERN IRELAND-SCOTLAND
BLACK SEA TRANSMISSION NETWORK	SIEMENS	SCHEDULED 2013	2x350	96	B-B	THY	GEORGIA - TURKEY
TROLL A	ABB	2004	2x40	±60	70	TRA	NORWAY
POSTE CHATEAUGUAY	BBC/SIEMENS	1984	2x500	145	B-B	THY	CANADA-U.S.A.
CHATEAUGUAY UPGRADE	ABB	2009	2x500	145	B-B	THY	CANADA
OUTAOUAIS	ABB	2009	2x625	315	B-B	THY	CANADA
DIRECTLINK	ABB	2000	3 x 60	±80	59	TRA	AUSTRALIA
AL FADHILI	AREVA	2009	3 x 600	3 x 222	B-B	THY	SAUDI ARABIA
VYBORG	MINISTRY FOR ELECTROTECHNICAL INDUSTRY OF USSR	1999	4x405	±85	B-B	THY	RUSSIA-FINLAND
RIO MADEIRA	ABB	PLANNED 2012	800 (2x400 BTB)	100	B-B	THY	BRAZIL

Table 1b also came from the IEEE HVDC/Facts Subcommittee. It lists planned HVDC projects worldwide as of 2013. Observe that

- For smaller capacities, many of them are transistor-based, but for larger capacities, all of them are thyristor-based.
- New ±500kV bipole projects have capacities between 2000 and 3000MW, by ABB, Alstom, and Siemens. ABB and Alstom have been developing new ±600kV bipole projects of 3150MW (see Table 1a). ABB and Siemens have been developing new ±800kV bipole projects of 6400MW.

Table 1b: Planned HVDC Projects as of 2013

HVDC PROJECTS LISTING
Prepared for the
HVDC and Flexible AC Transmission Subcommittee
of the
IEEE Transmission and Distribution Committee

SYSTEM / PROJECT	HVDC SUPPLIER	YEAR COMMISSIONED	POWER RATING (MW)	DC VOLTAGE (kV)	LINE/ CABLE (km)	MERCURY/ THYRISTOR/ TRANSISTOR	LOCATION
TROLL A 3&4		PLANNED 2015	100	±60	280	TRA	NORWAY
HUGO INTERTIE		PLANNED 2010	375		B-B	THY	U.S.A
BORWIN 1		PLANNED 2012	400	±150	400	TRA	GERMANY
HAWAII INTER-ISLAND CABLE PROJECT		PLANNED	400		48		USA
BARSOOR LOWER SILERU	BHEL	FUTURE	400			THY	INDIA
LEYTE-MINDANAO		PLANNED 2015	500	250	478	THY	PHILIPPINES
EAST-WEST ENERGY BRIDGE		PLANNED 2005	500	600	1800	THY	GERMANY-POLAND-RUSSIA
MEPANDA UNCUA		PLANNED 2006	500			THY	MOZAMBIQUE
MARITIME LINK		PLANNED 2017	500	±200 TO ±250			CANADA
ICELAND-SCOTLAND LINK		PLANNED 2005	550	400	950	THY	ICELAND-SCOTLAND
INGA-KOLWEZI	ABB	PLANNED UPGRADE 2013	560	±500	1 700	THY	DEMOCRATIC REPLIC OF CONGO
EUROCABLE		PLANNED 2002	600	500	600	THY	NORWAY-GERMANY
ISACCEA		FUTURE	600		B-B	THY	ROMANIA
BENMORE-HAYWARDS POLE 1 REPLACEMENT		PLANNED 2012 (AWAITING REGULATORY APPROVAL)	700	350	40	THY	NEW ZEALAND
NORDBALT		PLANNED 2015	700	±300	450	TRA	SWEDEN - LITHUANIA
CHINA-RUSSIA (HEIHE)		PLANNED 2008	750		B-B	THY	CHINA-RUSSIA
TRES AMIGAS SUPERSTATION	ALSTOM	PLANNED 2014	750	±345	B-B	TRA	USA
DOLWIN 1		PLANNED 2013	800	±320	330	TRA	GERMANY
DOLWIN 2		PLANNED 2015	900	±320	270	TRA	GERMANY
EAST-WEST ENERGY BRIDGE		PLANNED 2010	1000			THY	GERMANY-POLAND-RUSSIA
INDIA-SRI LANKA ELECTRICITY GRID INTERCONNECTION		PLANNED 2013	1000	400			INDIA-SRI LANKA
NORTH-CENTRAL		PLANNED 2012	1000		B-B	THY	CHINA
POLAND-LITHUANIA		FIRST 500MW PLANNED BY 2015 INCREASE TO 1000MW- BY 2020	1000		154	THY	POLAND-LITHUANIA
INDIA - BANGLADESH TRANSMISSION LINK		PLANNED 2012	1000		B-B		INDIA - BANGLADESH
ITALY - MONTENEGRO INTERCONNECTION LINK			1000	±500			ITALY - MONTENEGRO
ITALY - LYBIA INTERCONNECTION LINK			1000	±500	1030		ITALY - LYBIA
ICELAND-SCOTLAND LINK		FUTURE	1100	±400	950	THY	ICELAND-SCOTLAND
SHANDONG-EAST		PLANNED 2011	1200		B-B	THY	CHINA
SYDVASTLANKEN		PLANNED 2013-2015	1200	400		TRA	SWEDEN, NORWAY
SOUTHWEST LINK	ABB - CONVERTERS; ALSTOM - CABLES	PLANNED 2014	1420	300	200	TRA	SWEDEN
NORTHEAST-NORTH (GOALING)		PLANNED 2008	1500		B-B	THY	CHINA
ALBERTA EAST HVDC TRANSMISSION PROJECT		PLANNED 2013	2000	±500	500	THY	CANADA
ALBERTA WEST HVDC TRANSMISSION PROJECT		PLANNED 2014	2000	±500	400	THY	CANADA
NELSON RIVER BIPOLE III		PLANNED 2017	2000	500		THY	CANADA

TALCHER-BANGALORE	SIEMENS	FUTURE	2000	±500	1400	THY	INDIA
CEPA (RASPIER-RAJASTHAN)		FUTURE	2000	500		THY	INDIA
WESTERN HVDC LINK		REQUIRED BY 2015	2000		400		UK
BAKUN		PLANNED 2013 (MONOPOLE), 2015 (BIPOLE)	2400	±500	1715	THY	MALAYSIA
AYSEN-SIC		PLANNED 2012	2500	±500 or ±600	2000	THY	CHILE
IB VALLEY-JAIPUR		PLANNED 2002	3000			THY	INDIA
TRANS-AMUR		TESTING 2012	3000			THY	CHINA-RUSSIA
NINGXIA-TIANJING		PLANNED 2010	3000			THY	CHINA
NW-SICHUAN (BAOJI-DEYANG)		PLANNED 2011	3000			THY	CHINA
NORTH SHAANXI-SHANDONG		PLANNED 2011	3000			THY	CHINA
GEZHOUBA-SHANGHAI EXPANSION		PLANNED 2011	3000			THY	CHINA
GOUPITAN-GUANGDONG		PLANNED 2016	3000			THY	CHINA
CHINOOK		FUTURE	3000	±500	1600	THY	USA
NORTHERN LIGHTS		ON HOLD	3000	±500	1550	THY	CANADA-USA
EGYPT - SAUDI ARABIA INTERCONNECTION LINK			3000	±500	1500		EGYPT - SAUDI ARABIA
LOWER CHURCHILL PROJECT		FUTURE	3074	±450	1100	THY	CANADA
IRKUTSK (RUSSIA) - BEIJING		PLANNED 2015	6400	800		THY	RUSSIA-CHINA
JINSHA RIVER II - EAST CHINA		PLANNED 2016	6400	800		THY	CHINA
HUMENG-TIANJING		PLANNED 2016	6400	800		THY	CHINA
HUMENG-LIAONING		PLANNED 2018	6400	800		THY	CHINA
JINSHA RIVER II - FUJIAN		PLANNED 2018	6400	800		THY	CHINA
HAMI-C.CHINA		PLANNED 2018	6400	800		THY	CHINA
JINSHA RIVER II - EAST CHINA		PLANNED 2019	6400	800		THY	CHINA
PLAINS AND EASTERN CLEAN LINE		PLANNED 2013-2020	7000	±500	1288	THY	USA
WESCOR SOUTH W (3 TERMINAL)		PLANNED 2012					AFRICA
WESCOR SOUTH E (3 TERMINAL)		PLANNED 2013					AFRICA
WESCOR NORTH (4 TERMINAL)		PLANNED 2018					AFRICA
NEW ZEALAND HYBRID INTER ISLAND LINK		PLANNED				THY	NEW ZEALAND
ELECLINK							UK - FRANCE
FRANCE - ITALY INTERCONNECTION LINK							FRANCE - ITALY
EASTERN HVDC LINK		REQUIRED BY 2018					UK

Therefore, the highest capacity HVDC of the future appears likely at 600kV and 800kV, although today, there are not many operating at this voltage level (the Brasilian Itaipu project operates at ±600kV and there are several Chinese projects operating at ±800kV).

Figure 4a shows the growth of HVDC 1954 to 2010 in terms of aggregated MW transfer capability [5].

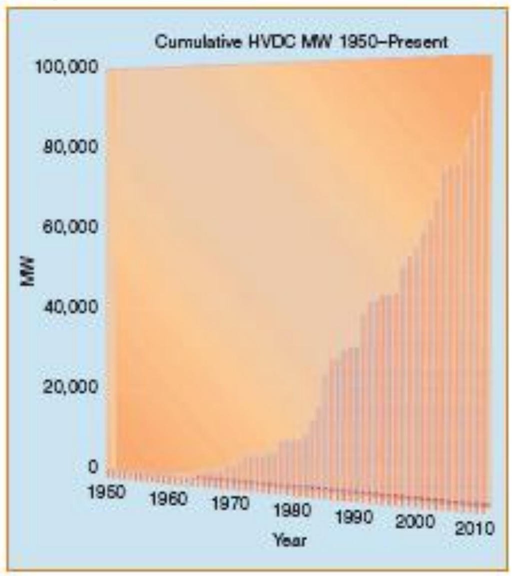


Fig. 4a

One 2013 report [6] forecasted HVDC cumulative capacity to reach 544 GW by 2020 (above chart indicates less than 100GW at 2010). Addition of each year's annual HVDC MW growth from Fig. 4b [7] indicates the total growth from 2010 to 2021 has been 357 MW, so that the total is now about 457 MW (the 544 forecast was a little high, but not too much).

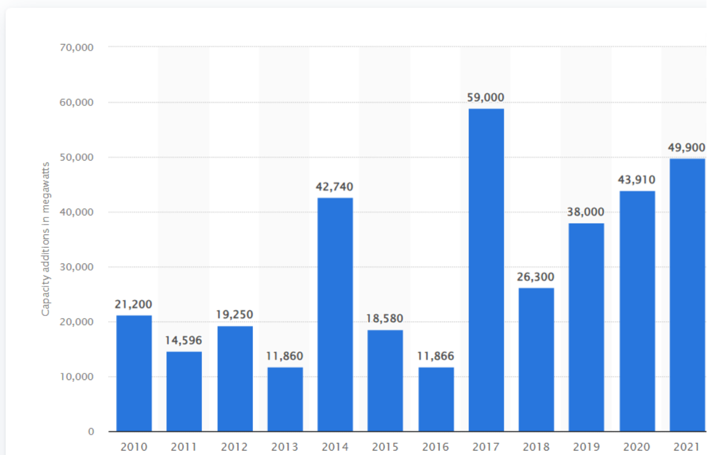


Fig. 4b

China alone, as of 2020, has a total of 349GW of HVDC, as described Section 1.1.

1.1 HVDC in China

Recently, China has deployed more HVDC than any other single nation in the world. By October 2019, there were 14 UHVDC transmission lines [8]. The 14 UVDC lines form an "eight-vertical six-horizontal" structure across China.

A total of more than 30,000 km of UHV lines have been built across China [9, 10], most of which is HVDC, with the largest link being the Changji-to-Guquan 1100kV HVDC link from the west to the east [11]. Figure 5a shows the existing and planned UHV lines in China by 2025.

Fig. 5a: Existing, planned (dashed) UHV lines by 2025 [12]

Table 2 shows the length and capacity of existing ultra high voltage transmission built in China until 2019.

Table 3: Ultra High voltage transmission in China [13]

		Transmission line length built (km)		Power transmission capacity (GW)	
		2019	2018	2019	2018
AC	1000kV	11,709	10,396	162	147
	750kV	22,198	20,543	178	168
DC	±1100kV DC	608	608	18	6
	±800kV DC	21,954	21,954	178	178
	±660kV DC	2091	2091	19	19
	±550kV DC	15,428	15,428	134	134
Total		73,988	71,020	689	652
UHV (≥800kV)		34,271	32,958	358	331

Since 2020, China has proposed to build 14 new UHV lines: seven UHVDC and seven UHVAC [14,15], as listed in Table 4. The total size of these UHV projects are estimated to be $26.8 billion in 2020. Among these planned UHV lines, there has been significant progress for three UHVDC lines: the 1700km Yazhong-Nanchang UHVDC line, the 1100km Shaanbei-Wuhan UHVDC line, and the 1500km Qinghai-Henan UHVDC line [16]. Each line has 8GW capacity.

Table 4: Near term investments in China - UHV transmission projects as of 2020 [14,12]

Technology	Transmission Line Name	Voltage (kV)	Timeline	Investment ($bn)
UHVDC	Qinghai - Henan	±800	2020 partial COD	3.79
UHVDC	Shanbei - Hubei	±800	2020 partial COD	2.59
UHVDC	Longdong - Shandong	±800	2020 seek approval	NA
UHVDC	Hami - Chongqing	±800	NA	NA
UHVDC	Yazhong - Nanchang	±800	2021 COD	4.44
UHVDC	Baihetan - Jiangsu	±800	2020 seek approval	2.28
UHVDC	Baihetan - Zhejiang	±800	2020 seek approval	2.79
HVDC	Yunnan - Guizhou	±500	2020 COD	NA
HVDC	Fujian - Guangdong DC B2B	NA	2020 seek approval	NA
UHVAC	Zhangbei - Xiongan	1000	2020 COD	1.47
UHVAC	Nanyang - Jingmen - Changsha	1000	2020 seek approval	2.94
UHVAC	Zhumadian - Nanyang	1000	2020 COD	1.26
UHVAC	Zhumadian - Wuhan	1000	2020 seek approval	1.26
UHVAC	Jingmen - Wuhan	1000	2020 seek approval	0.63

UHVAC	Nanchang - Wuhan	1000	2020 seek approval	1.68
UHVAC	Nanchang - Changsha	1000	2020 seek approval	1.68

1.1 HVDC in North America

Fig. 5b indicates HVDC projects in North America; existing is blue, planned is red; back to back is green. Observe most proposed projects (red) are east-west.

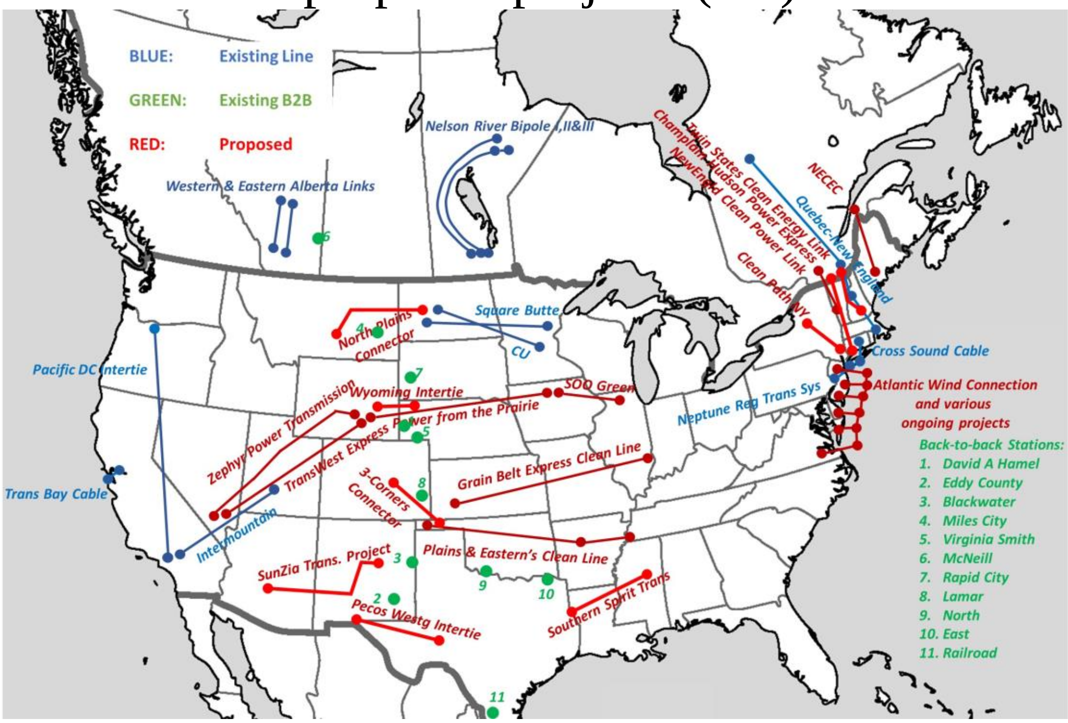


Fig. 5b: North American Projects

The North American projects shown in Fig. 5b are summarized in Table 1c. It is indicative of changes over the last few decades that the first set of HVDC projects were to transfer either hydro or coal-developed electricity, or to supply a particular load center, but the last few HVDC projects have been to transport wind and/or solar electricity.

Table 1c: North American HVDC Projects

Project Name (overhead or underground)	Year of Commission	Power Rating (MW)	Voltage Rating (kV)	Line Length (mile)	Original Application	Status
Pacific Intertie (overhead)	1970 (upgrades in 2020 planned)	3800 (Celilo), 3220 (Sylmar)	±500	845	Transport hydro generation	Existing
Square Butte (overhead)	1977	500	±250	449	Transport coal generation	Existing
CU (overhead)	1979 (upgrades in 2004, 2019)	1172	±400	427	Transport coal generation	Existing
Intermountain (overhead)	1986 (upgrades in 2010)	2400	±500	488	Transport coal generation	Existing
Quebec-New England (overhead)	1990 (upgrades in 2016)	2000	±450	920	Transport hydro generation	Existing
Cross Sound Cable (undersea)	2003	330	±150	24	Supply Long Island	Existing
Neptune Reg Trans System [17] (undersea/grnd)	2007	660	±500	65	Supply Long Island	Existing
Trans Bay Cable (underwater)	2010	400	±200	53	Supply San Francisco	Existing
TransWest Express [18] (overhead)	2024 (expected)	3000	±600	730	Renewable Resource Integration	Planned
SOO Green [19] (undergrnd)	2024 (expected)	2100	±525	350	Transport wind generation	Proposed
NewEngld Clean Power Link [20] (underwater)	Unknown	1000	±300	150	Transport wind & hydro generation	Proposed
Power from the Prairie [21] (overhead)	Unknown	4000	Unknown	700	Transport wind/solar across seam	Proposed
Grain Belt Express Clean Line [22] (overhead)	Unknown	4000	±600	800	Transport wind generation	Proposed
Zephyr Power Transmission [23] (overhead)	Unknown	3000	±500	500-850	Transport wind generation	Proposed
Plains & Eastern's Clean Line [24] (overhead)	Unknown	4000	±600	700	Transport wind generation	Proposed
Atlantic Wind Connection [25] (undersea)	Unknown	7000	±800	560	Transport offshore wind generation	Proposed
ChamplainHudson Power Express [26] (under-water/grnd)	Unknown	1000	Unknown	330	Transport hydro and wind	Proposed

2.0 HVDC Applications

HVDC has for many years represented a viable alternative for several different types of situations in power system planning. These situations include:

- Long distance bulk power transmission: These can come in two forms:
    - *A generation outlet*, where an HVDC line is built to move energy from a specific generation facility to a load center;
    - *An interconnection*, where two areas of a single network are connected via HVDC.
- Asynchronous ties: HVDC can be used to provide links of any capacity between two asynchronous networks while avoiding problems associated with low capacity AC links or the costs of high-capacity AC links.

Figure 5c [5] shows a dated (2007) summary of HVDC systems in the US, where each system is identified based on whether it is a generation outlet, an interconnection, or an asynchronous tie.

Fig. 5c

A third application area not shown in Fig. 5 is *cable transmission*. Use of either AC or DC underground transmission (as opposed to overhead transmission) becomes of interest whenever right-of-way is limited or unavailable to overhead, or when the application is submarine (river or bay crossings, and offshore wind). DC cables are less expensive than AC cables (but have higher termination cost), and they do not suffer from the high capacitive charging associated with AC cables and therefore do not have a physical restriction limiting distance or power level.

There are three underwater HVDC cables installed in North America today (see Table 1c): Cross Sound Cable; Neptune Trans System; and the Trans Bay Cable. The first two supply Long Island, New York, while the third supplies San Francisco, California. They are not shown in Fig. 5c but are in Fig. 5b).

Some slides from MISO:

Key Comparisons: 345 kV, 765 kV, and HVDC

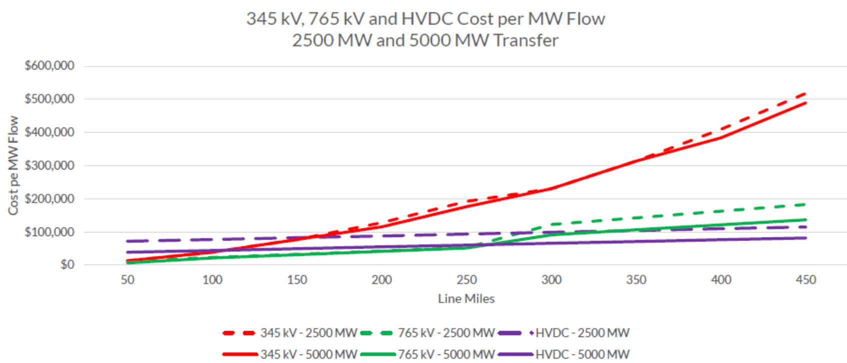
	345 kV	765 kV	HVDC
Incremental Need	Pro		
Cost per MW-Mile[1]		Pro	
Land Use per MW-Mile		Pro	Pro
Flow Control[2]			Pro
Long Distance Transmission Capabiliy[3]	Good	Better	Best
Contingency Impact	Pro		
Transmission Losses		Pro	Pro

Notes:
1) Pro for HVDC on very long lines
2) Flow control not needed everywhere
3) Long distance transmission capability is best on HVDC and proportional to voltage on AC

Comparison of **Typical** 345 kV, 765 KV and HVDC Preferred Applications - There are Exceptions

Transfer Level \ Transfer Distance	Short	Intermediate	Long
High	765 kV	HVDC 765 kV	HVDC
Intermediate	345 kV 765 kV	765 kV	HVDC 765 kV
Low	345 kV	345 kV 765 kV	765 kV

Comparison of **Typical** 345 kV, 765 kV and +/- 640 kV HVDC Costs to Transfer 2500 MW and 5000 MW



SO WHAT?

- For transfers of 2500 MW and 5000 MW, 345 kV is not more cost effective than 765 kV, even for short distances.
- For transfers of 2500 MW and 5000 MW, HVDC becomes more economical at line lengths of 280 miles and 260 miles respectively

3.0 Configurations

HVDC transmission can be configured in a number of ways. Some of these ways are discussed here, using figures from [27].

3.1 Monopole

The monopole configuration uses an earth return, as shown in Fig. 7 [27].

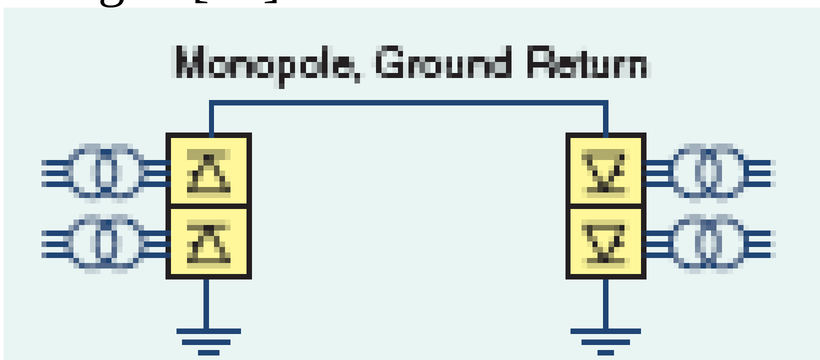


Fig. 7

The earth return is facilitated by an electrode at either end, similar to what is shown in Fig. 8 below [28].

Fig. 8

Earth returns cannot be used where earth resistivity is high, in heavily congested areas, or in freshwater crossings (the resistivity, RA/l, of sea water is on the order of 0.2Ω-m, 10Ω-m for good land sites, and 100Ω-m for freshwater). A (zero-voltage) neutral conductor is used in such cases for monopole operation, resulting in the monopole with metallic return, shown in Fig. 9 [27].

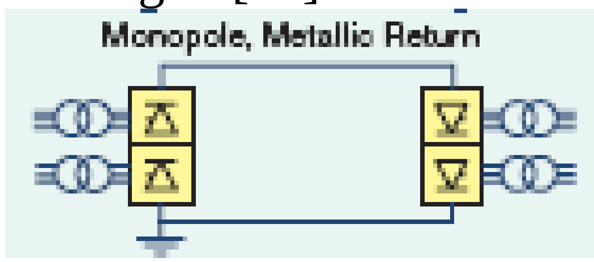


Fig. 9

3.2 Back-to-back

Back to back (B2B) HVDC is used to interconnect asynchronous networks. Their power handling capacity is limited by the capacities of the AC network on either side at the point of interconnection. Figures 10 and 11 [28] illustrate B2B designs.

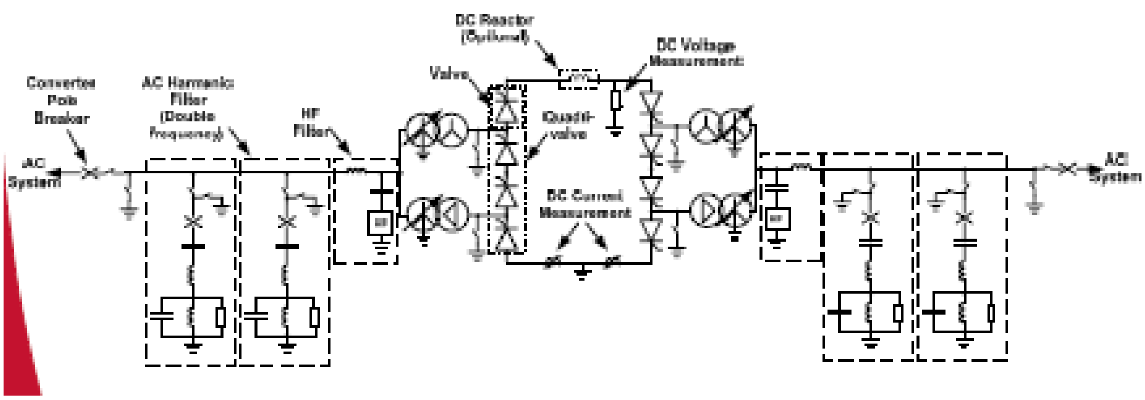


Fig. 10

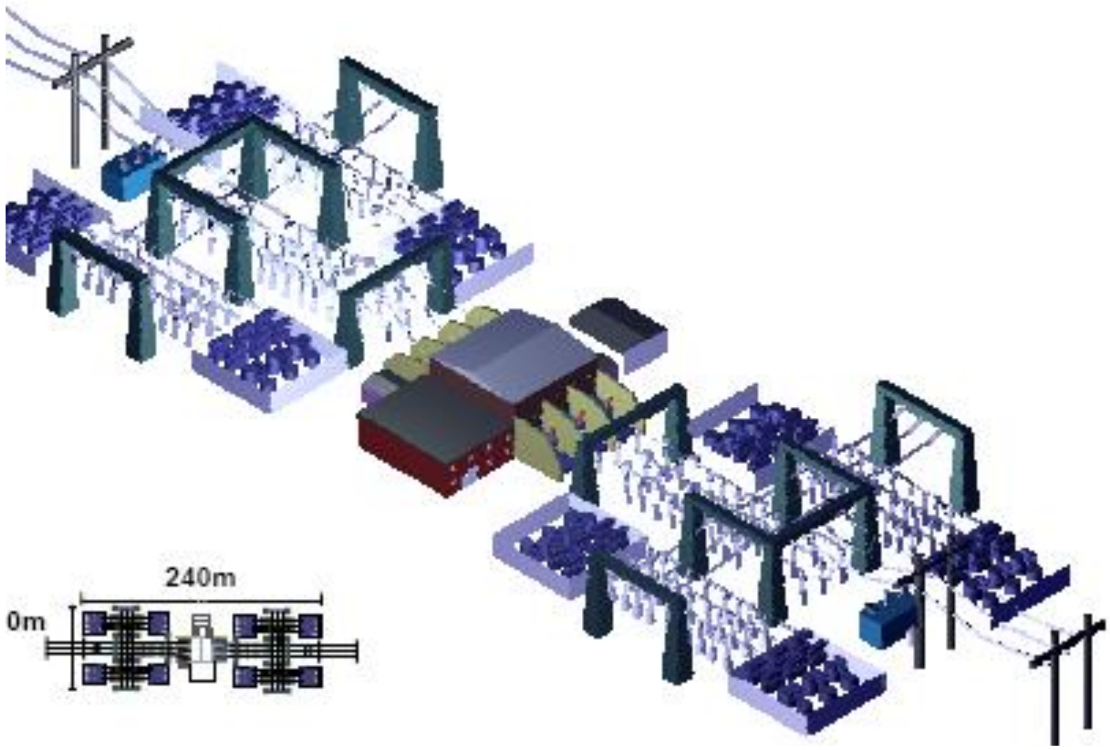


Fig. 11

B2B HVDC provides the desirable attribute that it enables transfer between two areas but will insulate each area from cascading problems occurring in the other area. Such a situation arose during the August 14, 2003 cascading blackout in the Northeast US when Quebec was unaffected by the blackout and in fact, its HVDC links (lines in this case, not B2B) to the Northeast US continued transferring throughout the day, with no blackout influence at all [29]. This is indicated in Fig. 12 [30] where we observe that Boston, which receives power from the HVDC connection to Quebec, is brightly lit, as opposed to Long Island, which is almost dark.

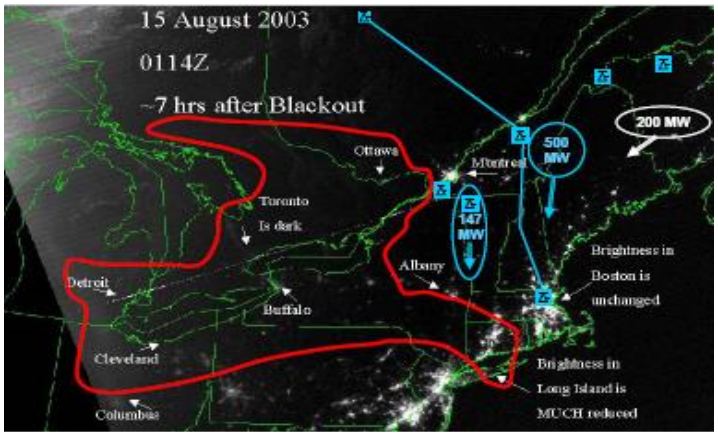


Fig. 12

3.3 Bipole

A bipole configuration is illustrated in Fig. 13.

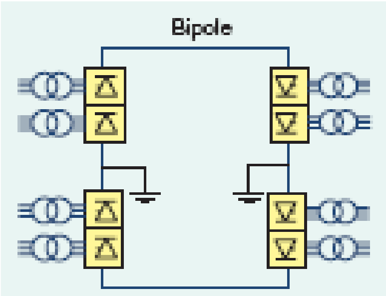


Fig. 13

Here, one terminal will operate at positive voltage and the other at negative voltage. This is the reason why HVDC voltages are typically referred to as ±.

An advantage over monopole of bipole configuration (in addition to its higher capacity under normal operations), is that it can continue operating despite the loss of one pole, as indicated in Fig. 14 [28].

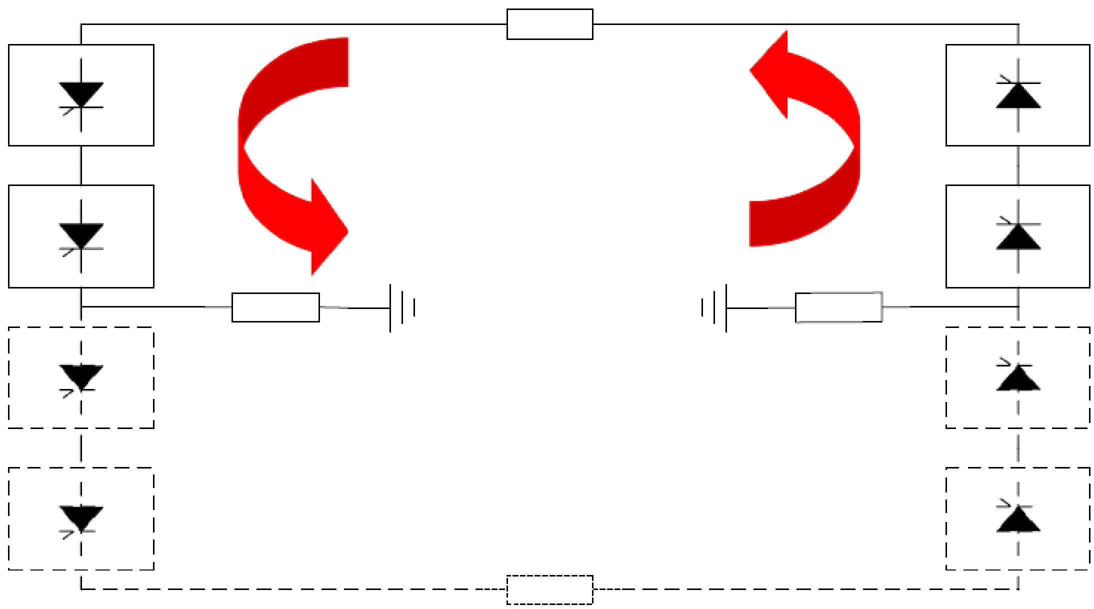


Fig. 14

Figure 14 illustrates the de-rated monopole mode using an earth return. Bipole configurations may also be run in the monopole mode with a metallic return if appropriate switching is provided, as shown in Fig. 15 [27], where we observe that “normal” bipole configuration on the left can be changed so that the second pole is used as the metallic return by switching to achieve the figure on the right.

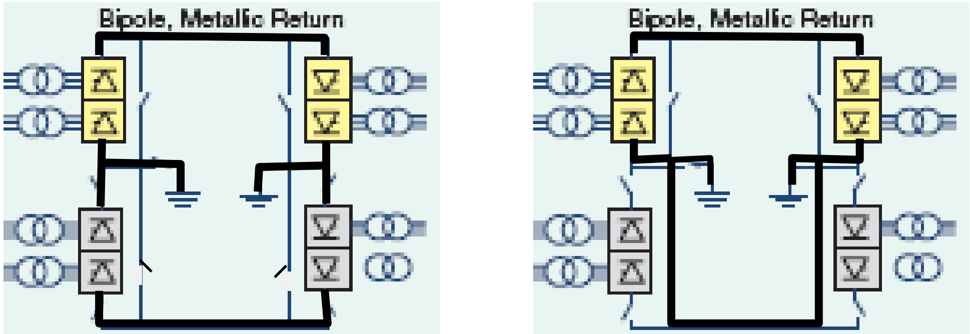


Fig. 15

The bipole configuration is the most common configuration for new HVDC installations today.

3.4 Tripole

Reference [31] proposes a *tripole* arrangement with three conductors and one metallic return which provides for high utilization of the thermally-limited conductors. This arrangement, consists of a bipole and a monopole system fed from the same bus and supplying a common receiving-end bus, as shown in Fig. 16.

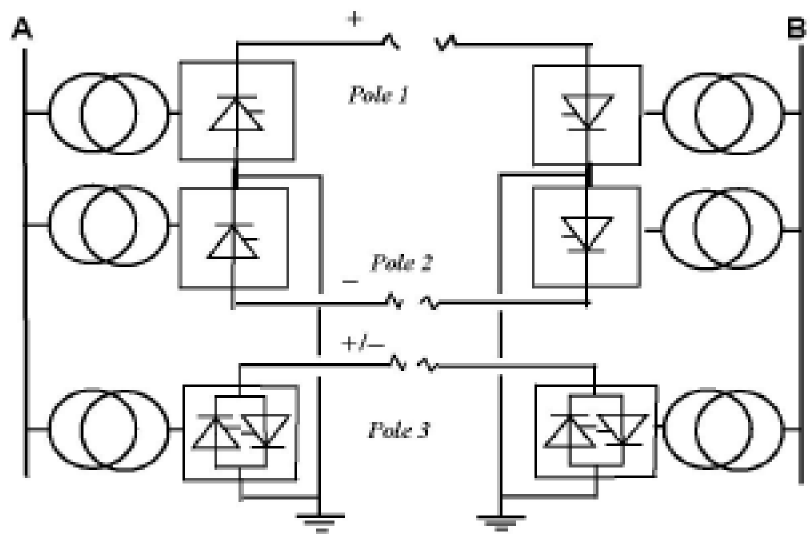


Fig. 16: Tripole arrangement

Case#1: Such a system can be advantageous as described in what follows [32]. Assume the continuous per-pole rating of an 800 kV HVDC terminal is 3600 MW, and the overload per-pole rating is 4500 MW for 22 minutes. If the system can be redispatched within the 22-minute interval, a tripole overlay on top of an AC system capable of handling an additional 1500 MW transfer would allow a post-contingency flow, following loss of one pole, of 2*4500+1500=10,500 MW of transfer. This means the pre-contingency flow per pole would need to be 10,500/3=3500 MW/pole. This is 3500/3600=97% utilization of the tripole arrangement's continuous rating.

We may assess this situation as follows.

➔Let n be the number of lines; in the case of this tripole scenario,

- n=3;
- we have that each line has normal rating of C=3600MW;
- but in an emergency,
  - each line can carry $C+\Delta C=3600+900=4500$MW.
  - and the underlying AC system can carry an additional $\Delta C_0=1500$MW.

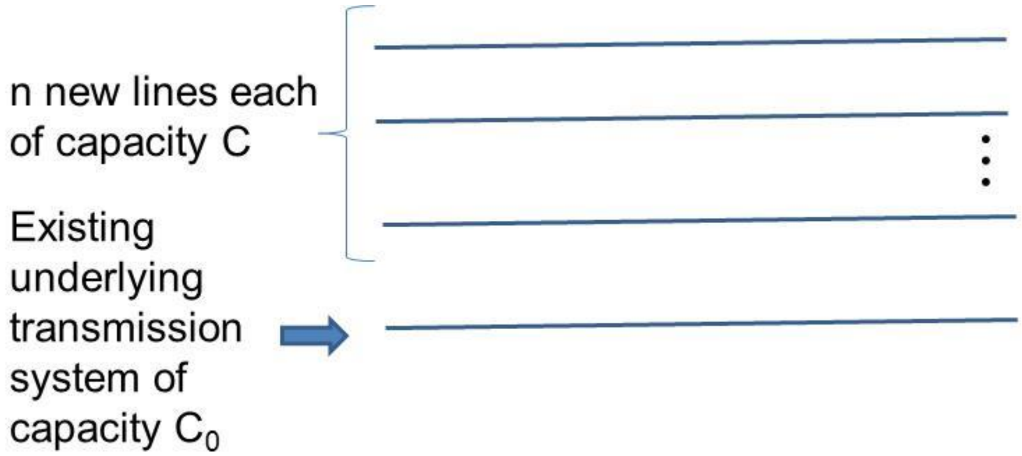
For N-1 security, the flow before the contingency must not exceed the post-contingency flow capability after loss of one line. In other words, with C=3600, $\Delta C=900$, $\Delta C_0=1500$, we will have to derate the conductors by 100p%:

$$nCp \le (n-1)(C+\Delta C)+\Delta C_0 \rightarrow n(3600p) \le (n-1)(4500)+1500$$

Using n=3, we have

Here (unlike in tripole example), we assume (a) underlying system is for normal, not emergency; (b) pre-contingency capacity on new lines and existing underlying is same as post-contingency capacity. This is conservative, because normally we can use emergency rating for post-contingency capacity.

<u>Case#2</u>: The tripole arrangement illustrates a case of what is called the "Rule of 3." We illustrate this rule with a set-up where we assume underlying capacity is C_0, and both the n new lines and the underlying capacity must be curtailed to 100p% to maintain N-1 security. The situation is illustrated below.



Assume that overall design must be able to withstand loss of one of the new lines when maximally loaded. To satisfy this, we restrict each line (new & existing) to 100p% of the line's capacity (0<p<1). This means:

Flow before loss of one line $\leq$ Capacity after loss of one line

$$pnC+pC_0 \leq (n-1)C+C_0$$

$$\Rightarrow \quad C/C_0 \leq (1-p)/(np-n+1)$$

From design point of view, let's explore the situation for different values of p and n.

There are 2 guiding concepts when using the above, as indicated from LHS of first expression $p(nC+C_0)$:

- **Investment economics** has potential to be attractive if total new capacity, nC, is significant relative to existing capacity, C_0. We want nC/C_0 to be high.
- **Operational economics** will be attractive if we can use a significant percentage of the total capacity➔We want p to be high.

Below table provides max C/C_0 for values of p, n.

p	n	Maximum C/C_0	Maximum nC/C_0
0.7	1	0.429	0.429
0.7	2	0.75	1.5
0.7	3	3.0	9
0.75	1	0.33	0.33
0.75	2	0.5	1
0.75	3	1.0	3
0.80	1	0.25	0.25
0.80	2	0.33	0.66
0.80	3	0.50	1.5
0.90	1	0.111	0.111
0.90	2	0.125	0.25
0.90	3	0.143	0.429

And then we have to derate by 70%...

Is the project worth doing if we only get an additional 43% more (not-derated) capacity?

On the other hand, with 3 lines, we can get an additional 900% more capacity!

And this shows we can relieve derating to 80% and still get 150% more capacity.

Some conclusions we may draw from the above:

- n=1 or 2 does not give good C/C_0 ratio, unless p is small.
- n=3 provides ability to build lines 100% of existing capacity while utilizing 75% of total capacity. n>3 works too, and gives higher p.

Case#3, No existing capacity or overload capability. The question may arise: what happens if there is zero underlying capacity, i.e., $C_0=0$ (implying $\Delta C_0=0$)? This is the case when two regions are connected where they were not at all connected previously. In this case, we can write that

Flow before loss of one line ≤ Capacity after loss of one line

$$pnC \le (n-1)C$$
$$\Rightarrow pn \le n-1$$
$$\Rightarrow n-pn \ge 1$$
$$\Rightarrow n(1-p) \ge 1$$
$$n \ge 1/(1-p)$$

If p is the percent of each line's capacity that is allowed to be used in the pre-contingency state, then 1-p is the required operating reserve on each line. So n ≥ 1 / pbar where pbar=1-p. One way to look at this is using

$$n \times pbar \ge 1$$
$$\Rightarrow C \times n \times pbar \ge C$$

which says that <u>the total pre-contingency reserve (on the left) must equal to or exceed the capacity of one line (on the right)</u>.

If p=0.7, pbar=0.3➔n ≥ 3.33, i.e., we must have at least 4 lines.

If p=0.666, pbar=0.333➔n ≥ 3, i.e., we must have at least 3 lines.

Three more examples:

<u>Case #4</u>: Existing capacity and overload capacity on new lines (but not on existing lines).

Here is situation with an emergency overload capacity of $C+\Delta C$ on HVDC line, capacity C_0 on underlying system, but no additional overload capacity on underlying system.

$pnC+pC_0 \le (n-1)(C+\Delta C)+C_0$

$pnC \le (n-1)(C+\Delta C)+C_0-pC_0$

$pnC \le (n-1)(C+\Delta C)+C_0(1-p)$

$pnC \le n(C+\Delta C)-(C+\Delta C)+C_0(1-p)$

$pnC \le nC+n\Delta C-C-\Delta C+C_0(1-p)$

$pnC-nC+C \le n\Delta C-\Delta C+C_0(1-p)$

$C(pn-n+1) \le n\Delta C-\Delta C+C_0(1-p)$

$C \le [n\Delta C-\Delta C+C_0(1-p)] / [pn-n+1]$ [assume $pn-n+1>0 \Rightarrow p>(n-1)/n$]

$C \le [\Delta C(n-1)+C_0(1-p)] / [pn-n+1]$

So for n=3, ΔC=900MW, p=0.9722, C_0=1500MW

$C \le [900(3-1)+1500(1-0.9722)] / [0.9722*3-3+1]=[1800+41.7] / .9166=2009.3$MW

Case #5:

Here is situation with an emergency overload capacity of $C + \Delta C$ on HVDC line and an additional overload capacity on underlying system of $C_0+\Delta C_0$.

$pnC+pC_0 \leq (n-1)(C+\Delta C)+(C_0+\Delta C_0)$

$pnC+pC_0 \leq n(C+\Delta C)-C-\Delta C+C_0+\Delta C_0$

$pnC+pC_0 \leq nC+n\Delta C-C-\Delta C+C_0+\Delta C_0$

$pnC-nC+C \leq n\Delta C-\Delta C-pC_0+C_0+\Delta C_0$

$C(pn-n+1) \leq n\Delta C-\Delta C-pC_0+C_0+\Delta C_0$

$C \leq [n\Delta C-\Delta C-pC_0+C_0+\Delta C_0] / [pn-n+1]$

Let $n=3$, $\Delta C=900$, $p=0.9722$, $C_0=1500$, $\Delta C_0=1500$ then

$C \leq [3*900-900-0.9722*1500+1500+1500] / [.9722*3-3+1]=[1800-1458.3+3000]/ 0.9166=3645.8$

Case #6:

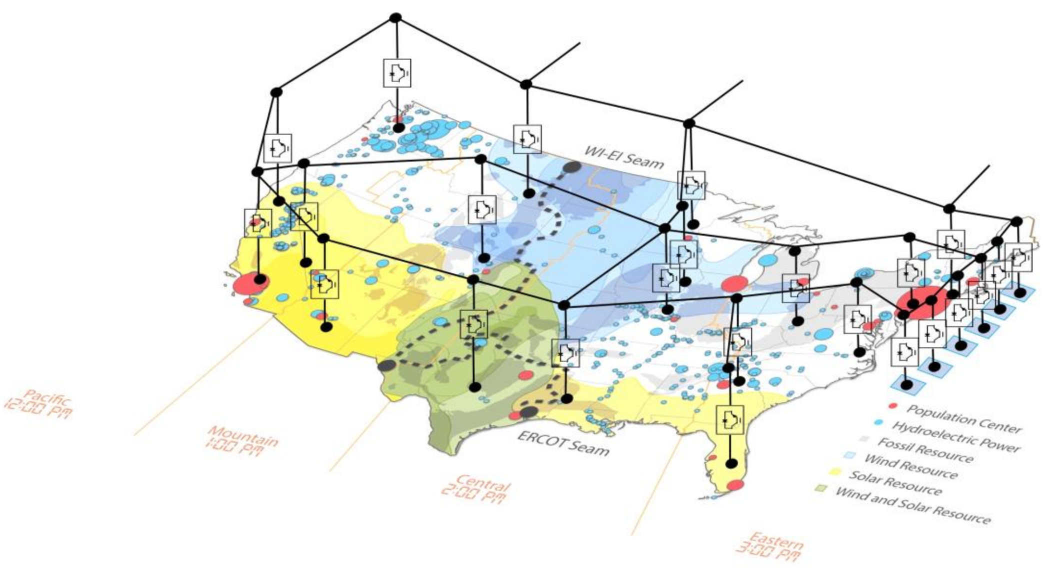
Now let's assume in the above that $C_0=0$ ($\Delta C_0=1500$). This becomes almost the same as Case#1 described at the beginning of this section; the only difference is that in Case#1, C_0 was not derated and so, whatever it was, it appeared on both sides and had no influence. Setting $C_0=0$ accomplishes the same thing.

$C \leq [3*900-900+1500] / [.9722*3-3+1]=[1800+1500]/ 0.9166=3600$ MW

And this was the continuous ("normal") capacity of each DC line in that original tripole example.

We may summarize the above examples in the following table.

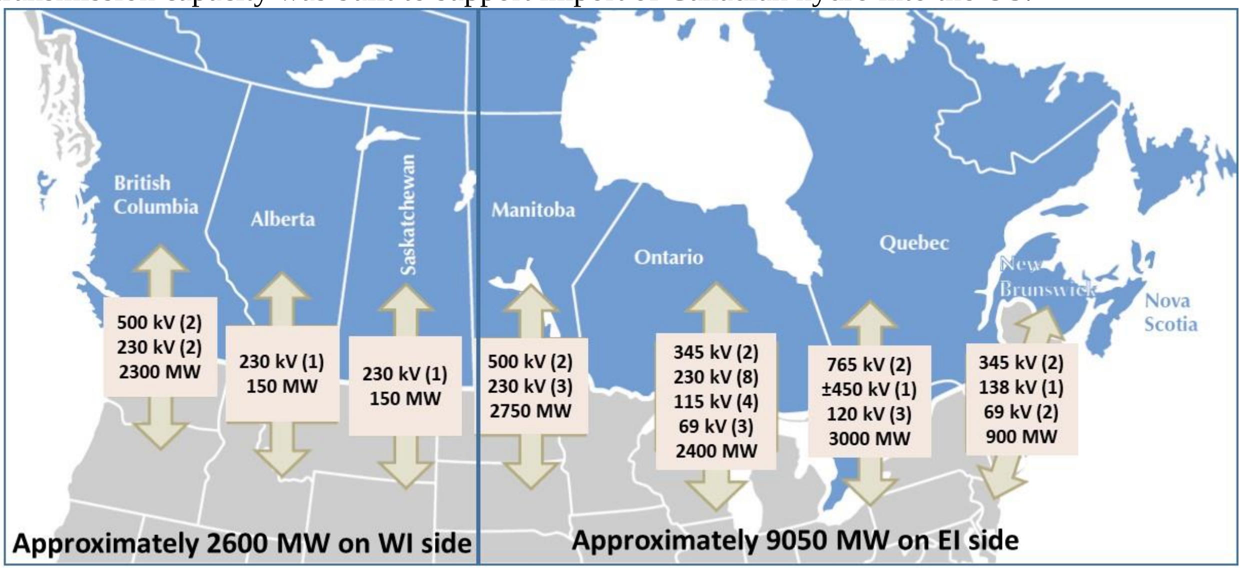
Case#	C	ΔC	C_0	ΔC_0	p	Comments
1	3600	900	No spec	1500	97.22	Tripole is specified (n=3). C_0 is unspecified and not derated (it adds to both sides).
2	C	0	C_0	0	p	No emergency overload on either new lines or existing underlying.
3	C	0	0	0	p	Zero underlying capacity.
4	C	C_0	C_0	0	p	Underlying capacity is there, C_0, but no additional emergency underlying capacity.
5	C	C_0=1500	C_0=1500	ΔC_0=1500	p=97.22	Underlying capacity is there; both underlying and new capacity have emergency capacity.
6	C	0	0		p=97.22	Same as #1, except here, C_0 is specified to be zero (equivalent to unspecified when no derating is applied to C_0).



The above figure raises a question related to whether anyone has considered transmission from the US into

Canada. Indeed, such transmission exists today, as indicated by the below figure.

As of 2017, total transmission capacity between the US and Canada is approximately 11.6GW, with about 2.6GW in the WI and about 9GW in the EI (adapted from [33]; for links where capacity information was available, north-to-south capacities were used; otherwise, capacities were estimated based on the voltage level of the lines). Most of this transmission capacity was built to support import of Canadian hydro into the US.



US-Canada interregional transmission corridors [adapted from 33]

4.0 Economics for long-distance transmission

A good review of HVDC technologies and costs was done by CIGRE in 2001 [34]. Tables 2 and 3, below, are two useful tables for economic assessment of HVDC that are in this report.

Table 2 [34] shows the relative cost of different HVDC designs, where each successive design as one moves down the table is more reliable than the previous designs, as indicated by the two contingency types listed under "Remaining Transmission Capacity":

- Loss of one pole
- Tower breakage

The numbers in parentheses in the "Remaining transmission capacity" columns of Table 2 indicate the capacity if a converter is lost and the two poles are switched to operate in parallel as a single pole, and the line conductors and converters have short-term emergency thermal capacity for twice the current. This is illustrated in Fig. 17 for the single bipole configuration, where P_0 is the normal per-pole MW capacity.

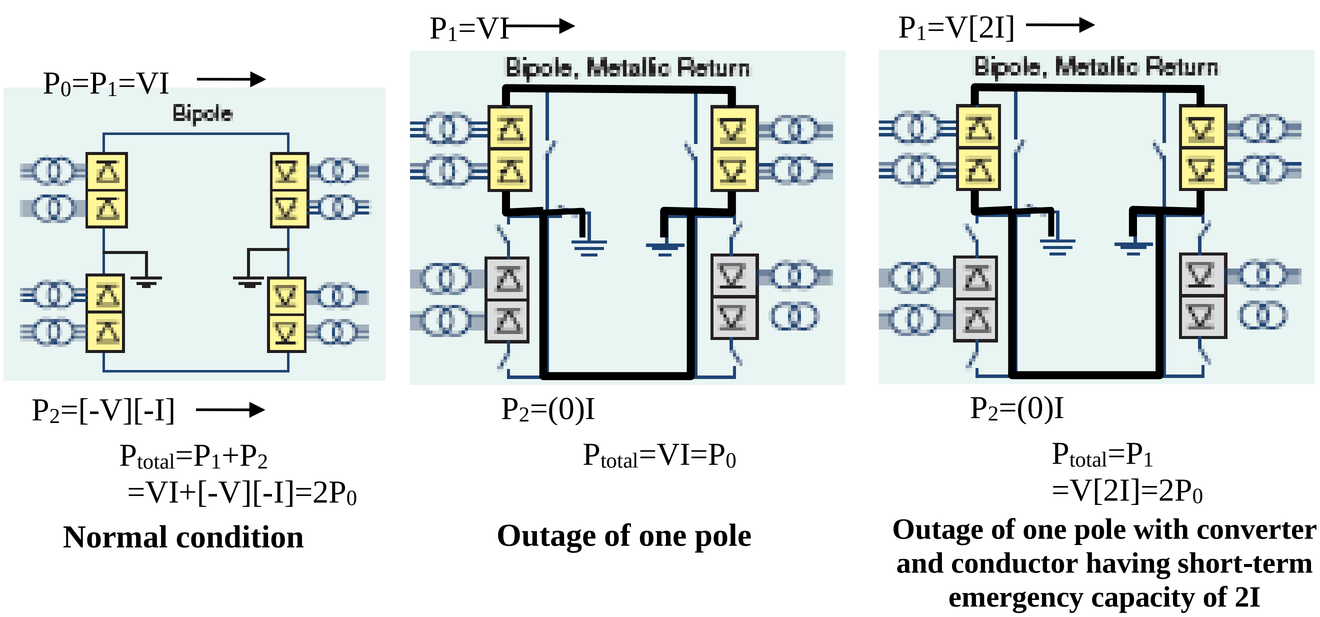
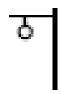
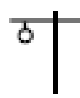
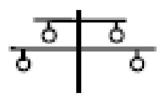
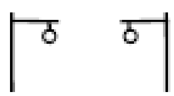
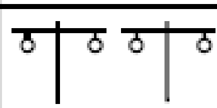


Figure 17: Illustration of Single Bipole with 100% Transmission Capacity Following Loss of One Pole

One also observes that the relative cost as a percentage of a single bipolar line increases with more reliable designs.

Table 2

Variant	Tower Configuration	Remaining Transmission Capacity			Relative cost %
		Loss of one pole		Tower breakage	
		Ground return permitted	Ground return not permitted		
Single monopolar line		0	0	0	85
single bipolar line		50 (100)	0	0	100
double bipolar line		100	100	0	114
Two monopolar lines		50 (100)	0	50 (100)	126
two lines (bipolar or homopolar)		100	100	100	136

It is interesting to observe in Table 2 that the double bipolar configuration loses no transmission capacity with loss of one pole. As described in [35], this is accomplished by "doubling-up" on the remaining pole having polarity the same as the outaged pole. That is, if the positive pole of line 1 is lost, then we use the positive pole of line 2 for both line 1 and line 2. This requires that each pole be capable of handling an emergency overload of twice the rated current. The situation is illustrated in Fig. 18.

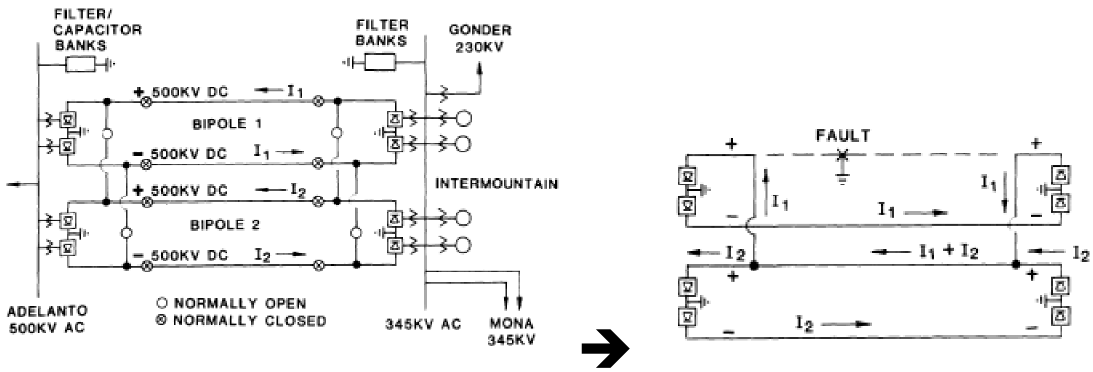


Figure 18: IPP DC Line –
normal operation (left), loss of one pole (right)

Table 3 [34] provides the relative percentage of various cost items for a typical HVDC project. Here, the "total" level gives typical turnkey costs of the vendor's HVDC supply and installation. These costs cover both terminals (of a two-terminal scheme), and are based on some simplifying assumptions, as follows:

- The DC bipole is made up of one valve group per pole;
- No special measures are required for reactive power compensation and/or voltage control to incorporate a DC scheme into a weak AC system.
- These costs do not include costs by the purchasing entity itself, taxes, interest during construction or other money borrowing costs. In certain applications, the purchaser's costs can be substantial.

The conclusion is that there is not much difference between percentage allocations among cost items for terminal costs across the different configurations and power handling levels.

Table 3[1]

Cost values given in year 2000 US$/kW (both ends inclusive) for one valve group per pole.

	Back-Back		Monopole 500kV	Bipole ±500kV	Bipole ±500kV	Bipole ±600kV
	200MW %	500MW %	500MW %	1000MW %	2000MW %	3000MW %
Valve Groups	19	19	21	21	22	22
Convertor Transformers	22.5	22.5	21	22	22	22
DC Switchyard & Filtering	3	3	6	6	6	6
AC Switchyard & Filtering	11	11	10	9.5	9	9
Control/Prot./Comm.	8.5	8.5	8	8	8	8
Civil/Mech. Works	13	13	14	14	13.5	13.5
Aux. Power	2	2	2.5	2.5	2.5	2.5
Project Eng. & Admin.	21	21	17.5	17	17	17
	100	100	100	100	100	100
Total per kW	$130	$90	$180	$170	$145	$150

Note that the total cost per kW given on the last row is low, as it reflects the situation in 2001. For example, the most expensive station cost given is $170/kw or $170000/MW. For a 2000MW line, this would be $340M, which is lower than what is typically quoted in more recent years; for example, reference [36] gives $461M for a 500kV converter station and $507M for a 600kV converter station.

Aside: Reference [36] - this reference is a good treatment of transmission costs and the influences

[1] If ±500kV is selected in place of ±600kV for a 3000MW bipole, a station cost approximately 5 to 10% lower applies.

causing transmission cost to vary. It gives "base costs" per the below

LINE DESCRIPTION	NEW LINE COST 2014 ($/MILE)
230 kV Single Circuit	$959,700
230 kV Double Circuit	$1,536,400
345 kV Single Circuit	$1,343,800
345 kV Double Circuit	$2,150,300
500 kV Single Circuit	$1,919,450
500 kV Double Circuit	$3,071,750
500 kV HVDC Bi-pole	$1,536,400
600 kV HVDC Bi-pole	$1,613,200
Assumptions: Aluminum Conductor Steel Reinforced (ACSR), Tubular (230 kV)/ Lattice (345 kV – 600 kV), > 10 miles	

It then provides "multipliers" or other adjustment methods to account for other influences such as conductor choice (ACSR, ACSS, HTLS), tower design, transmission length, terrain, and ROW cost. For example, below are multipliers for terrain.

TERRAIN	PG&E[3]	SCE[4]	SDG&E[5]	WREZ	WECC
Desert	1.00	1.10	1.00	-	**1.05**
Scrub / Flat	1.00	1.00	1.00	1.00	**1.00**
Farmland	1.00	1.00	1.00	1.10	**1.00**
Forested	1.50	3.00	-	1.30	**2.25**
Rolling Hill (2-8% slope)	1.30	1.50	-	-	**1.40**
Mountain (>8% slope)	1.50	2.00	1.30	-	**1.75**
Wetland	-	-	1.20	1.20	**1.20**
Suburban	1.20	1.33	1.20	-	**1.27**
Urban	1.50	1.67	-	1.15	**1.59**

Reference [34] also reports a survey where line designers were asked to calculate, for a typical situation familiar to them, the ratio of costs per km of each DC line, using the corresponding AC line cost as 1.0 per unit per km length (terminal costs were excluded). Suitable design parameters, including conductor sizes, with which they were familiar for each case, could be used, assuming a simple bipolar tower without a metallic neutral return. The results are given in Table 4. The intent was to compare the cost of towers, conductors and construction only, without taking into account other parts of the system.

Table 4

Case	AC equivalent line	Cost pu	HVDC bipolar line ratings	Range of Costs pu
1.	230kV, double circuit	1.00	±250kV, 500MW	0.68 to 0.95
2.	400kV, double circuit	1.00	±350kV, 1000MW	0.57 to 0.75
3.	500kV, double circuit	1.00	±500kV, 2000MW	0.54 to 0.7
4.	765kV double circuit	1.00	±500kV, 3000MW	0.33 to 0.7

It is clear that from Table 4 that HVDC lines are less expensive than corresponding AC lines.

However, converter costs necessary for HVDC causes it to be more expensive overall up to a certain distance. For example, Figure 20a [1] shows the breakover distance to be about 650 km (403 miles).

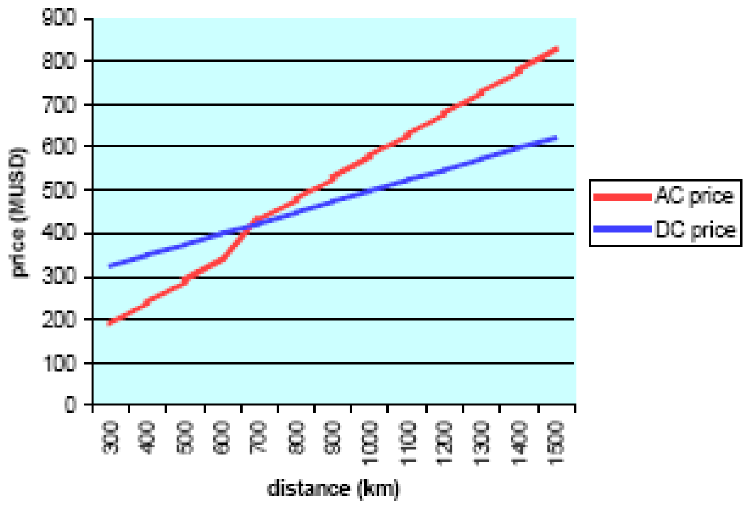


Fig. 20a

➔The line cost for a ±500kV DC line is 80-100% of the line cost for a 500kV AC line, but dc line advantage is that you get twice the capacity of the AC line.

Reference [37] concludes a similar economic analysis as provided above by saying, “A simple rule of thumb may be applied in that the cost of a d.c. transmission line may be 80% to 100% of the cost of an a.c. line whose rated line voltage is the same as the rated pole-to-ground voltage of the d.c. line. The cost advantage of d.c. transmission for traversing long distances is that it may be rated at twice the power flow capacity of an a.c. line of the same voltage.”

Table 5 [27] compares capital costs and losses for different ac and dc transmission alternatives for a hypothetical 750-mile, 3,000-MW transmission system. HVAC is higher in terms of both capital and operating (due to losses) costs. The higher capital costs of the AC alternatives are partly due to the fact that long transmission distance requires intermediate substations or switching stations and shunt reactors, and in some cases, a high level of series compensation. These ac station costs are included in the cost estimates for the ac alternatives.

Table 5

table 1. Comparative costs of HVDC and EHV AC transmission alternatives.

Alternative	DC Alternatives + 500 Kv Bipole	 2 x + 500 kV 2 bipoles	 + 600 kV Bipole	 +800 kV Bipole	AC Alternatives 500 kV 2 Single Ckt	 500 kV Double Ckt	 765 kV 2 Singl Ckt	Hybrid AC/DC Alternative + 500 kV Bipole	 500 kV Single Ckt	 Total AC + DC
Capital Cost										
Rated Power (MW)	3000	4000	3000	3000	3000	3000	3000	3000	1500	4500
Station costs including reactive compensation (M$)	$420	$680	$465	$510	$542	$542	$630	$420	$302	$722
Transmission line cost (M$/mile)	$1.60	$1.60	$1.80	$1.95	$2.00	$3.20	$2.80	$1.60	$2.00	
Distance in miles	750	1,500	750	750	1,500	750	1,500	750	750	1,500
Transmission Line Cost (M$)	$1,200	$2,400	$1,350	$1,463	$3,000	$2,400	$4,200	$1,200	$1,500	$2,700
Total Cost (M$)	**$1,620**	**$3,080**	**$1,815**	**$1,973**	**$3,542**	**$2,942**	**$4,830**	**$1,620**	**$1,802**	**$3,422**
Annual Payment, 30 years @ 10%	$172	$327	$193	$209	$376	$312	$512	$172	$191	$363
Cost per kW-Yr	$57.28	$81.68	$64.18	$69.75	$125.24	$104.03	$170.77	$57.28	$127.40	$80.66
Cost per MWh @ 85% Utilization Factor	$7.69	$10.97	$8.62	$9.37	$16.82	$13.97	$22.93	$7.69	$17.11	$10.83
Losses @ full load	193	134	148	103	208	208	139	106	48	154
Losses at full load in %	6.44%	3.35%	4.93%	3.43%	6.93%	6.93%	4.62%	5.29%	4.79%	5.12%
Capitalized cost of losses @ $1500 kW (M$)	$246	$171	$188	$131	$265	$265	$177	$135	$61	$196
Parameters:										
Interest rate %	10%									
Capitalized cost of losses $/kW	$1,500									

Note:
AC current assumes 94% pf
Full load converter station losses = 9.75% per station
Total substation losses (transformers, reactors) assumed = 0.5% of rated power

It is worthwhile considering the possibilities in regards to adding high-capacity transmission capability between two points. These statements were lifted from [38], written by three Siemens engineers.

1. “The simplest way is to build new additional AC lines between some of the subsystems to strengthen the interconnection. However, this method would be only a provisional solution as congestion and

bottlenecks can occur after local outages or due to changing requirements for power transmission routes to other locations."

2. "Building a new, superposed higher AC voltage level as "backbone," enables an essential increase of power flows among the subsystems. This solution is, however, not possible in high density populated areas due to right-of-way limitations and environmental restrictions. In some developing countries where the networks are still isolated or underdeveloped this is, however, the preferable solution."

   Figure 21a [39] (from Siemens) compares right-of-way requirements for an HVDC solution to that of an AC solution for 2000MW of capacity.

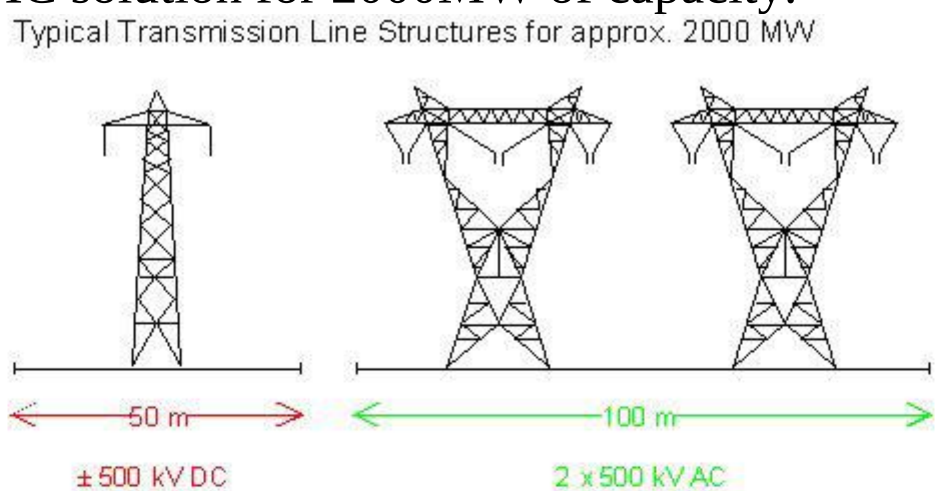


Fig. 21a

This point is also visually apparent in Fig. 20b where we observe (on the left) a ±500kV HVDC line with power transfer capacity of 3100 MW in contrast to (on the right) a 345kV AC transmission line having power transfer capacity of 300MW. Both have approximately the same ROW requirement (~50m), so that the capacity per unit ROW of the DC line is an order of magnitude greater than that of the AC line, i.e., for the same ROW, this DC lines gives ~10 times the power transfer capacity of the adjacent 345 kV line. Use of 765 kV in this situation, instead of 345 kV, reduces this ratio from 10 to about 2 [40]; nonetheless, these examples show why DC can be so effective in minimizing ROW requirements in response to public concerns. Furthermore, right-of-way requirements can be less than 10 feet if the project can afford to be undergrounded (although at more than double the project cost), something that is possible with DC.

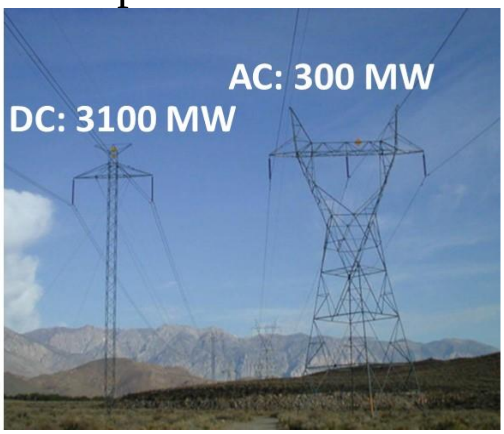


Fig. 20b: Comparison of Capacity-to-ROW requirement ratio

3. "The use of HVDC back-to-back schemes instead of, or in addition to a weak AC interconnection between the subsystems. Advantage of this solution compared to the additional AC lines is that no additional technical problems can be expected as the HVDC doesn't depend on the technical parameters of the subsystems. Fast control of the HVDC further enables control of load flow and, if

needed, active damping of power oscillations. The same problems can also be solved at least partly by the implementation of series and/or parallel FACTS equipment in the interconnections."

4. "Use of HVDC long distance transmission, integrated into the system to transmit power between power generation and load centers directly point to point. Possible additional bottlenecks inside the AC systems, resulting from the increased transmitted power, can so be avoided. The HVDC transmission further offers the ability to damp power oscillations and to improve the system stability. The need for right of way at HVDC is much smaller than for equivalent AC transmission and can therefore be realized much easier. The right of way for a +/- 500 KV DC line is e. g. less than half for a 400 kV double line."

5.0 Comparison of HVDC vs. EHVAC

Reference [41] is an excellent reference which you should read; it compares EHVAC with HVDC, and is written by engineers from AEP (experts in 765 kV AC) and ABB (experts in HVDC).

It provides "performance characteristics" for an "EHV interstate transmission overlay," lifted out in what follows:

- “Accessibility: The system must be open and accessible to integrate new generation resources and loads. There are two aspects to accessibility –
    - the initial ability to integrate and deliver power, and
    - the longer term flexibility for tapping into facilities to integrate additional loads and sources as they develop over time.

  On ramps and off ramps for the electrical expressway are essential. Generation and delivery points may emerge at various locations over time as have the extraordinary wind resources in the middle of the country. That area cannot consume all the available capacity whereas great demand exists elsewhere. Transmission must not pose barriers to integrate this generation, to transport it, or to tap it along the route. Accessibility implies flexibility for needs that develop over the long term. Accessibility and flexibility for tapping (at various voltages and capacities) are generally advantages of AC transmission over HVDC. AC transmission lines can be tapped more easily than HVDC to serve loads or pick up resources over moderate distances using intermediate substations. An AC tap into the HVDC system would be difficult and potentially very costly.”
- “Reliability: The interstate system must be highly reliable, stable and robust over its long term service

life. Critical system components must have low outage rates, minimal maintenance requirements, and long expected life."

- "Loadability: The system must be built with ample capacity to meet today's needs while building a firm foundation for the long term future. Capacity must be sufficient to overcome operating uncertainties and reasonable contingencies without congestion while taking into account transport path characteristics. Congestion bears economic and environmental consequences. When power from optimal sources is constrained, it likely leads to incremental cost and emissions from substitute generation."
- Efficiency: The system must deliver energy efficiently, with minimal internal electrical loss both along the transport path and in the system overall. It must minimize property and public impact while maximizing utilization of right of way. Its design and construction must use materials and labor wisely. Ongoing operation and maintenance must be practical and economical. Its implementation must achieve all of the above in the most reasonable time frame, to avoid undesirable operational or market constraints.

- Economics: The economic and environmental benefits of the system must justify its cost and environmental impact.
- A Supportive Public Policy: Although not a performance characteristic of the system, governmental and regulatory policies, standards and actions must support and guide the prudent planning and development of such a system. Siting authority, as well as cost recovery and cost allocation policies must be clarified and enacted. A business environment conducive to investment also is needed to encourage those who would invest in building and owning the needed assets.

A comparison was made in terms of the following:
"A transfer capacity of 6000 MW is required over the distances from 200 to 800 miles (322 to 1287 km). AC line lengths are assumed to be 200 miles (322 km) between substations. This is not a limit but is a reasonable distance to use in order to allow for placement of reactive compensation equipment and system interconnection points. Actual line distances in practice will vary according to specific transmission plans. It is assumed that each 500 kV and 765 kV line terminal is equipped with switched shunt reactors for voltage control. Shunt capacitors are assumed for all AC lines. Surge Impedance Loading (SIL) levels of 345 kV, 500 kV and 765 kV

AC lines are assumed to be 400, 900, and 2400 MW, respectively. The SIL can vary based upon specific line design, but is generally in this range."

"For this comparison loading of 345 kV and 500 kV lines will be permitted to approach twice their SIL, requiring series compensation [9]. This is not common practice in the eastern US, with its generally shorter lines, but is used more widely in the western US, where lines tend to be longer and generation is more remote. To achieve the 6000 MW transfer capacity, two 765 kV lines are assumed, operating at 1.25 times SIL, which does not require series capacitors for the 200-mile length."

"Two HVDC alternatives are assumed, +500 kV DC and +800 kV DC, each in a bipolar configuration, without intermediate stations for the 200 mile to 800 mile (1287 km) length. Table 1 summarizes some key assumptions used for each of the following analyses."

Table 6 summarizes the technologies that are being compared.

Table 6

Table 1 EHV AC and HVDC Systems for 6000 MW Delivery – Technology Comparisons

Voltage (kV)	No. of Lines	Cir-cuits per Tower	Circuit SIL (MW)	Circuit Capacity* (MW)	Series Compen-sation	Shunt Reactors	Shunt Capacitors	Conductor Type	Conductor No. in Bundle	Conductor Area kcmil (mm^2)
345 AC	4	2	400	800	Yes	No	Yes	ACSR	2	1590 (806)
500 AC	4	1	900	1800	Yes	Yes	Yes	ACSR	3	1590 (806)
765 AC	2	1	2400	3100	No	Yes	Yes	ACSR/TW	6	957 (485)
+500 DC	2	1	N/A	3000	N/A			ACSR	3	2515 (1274)
+800 DC	1	1	N/A	6000	N/A			ACSR	4	2515 (1274)

Figure 21 provides results of the comparison in terms of capacity vs. distance.

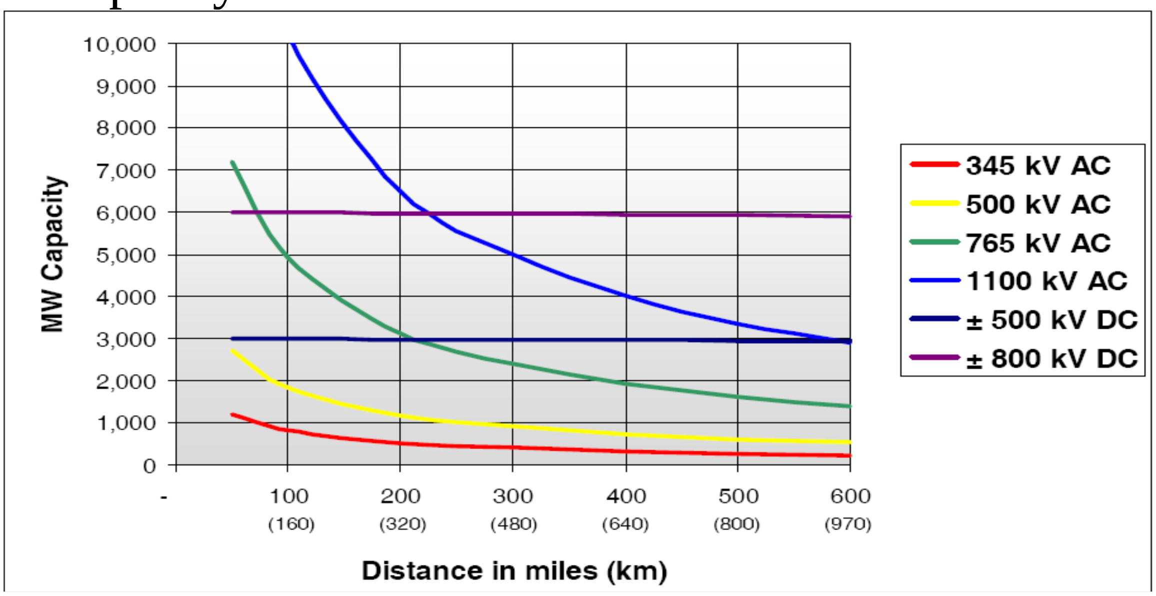


Fig. 21

In terms of reliability, the paper states, "For AC systems, typical outage experience for 765 kV, 500 kV and 345 kV was documented at 1.0, 1.4 and 1.6 forced outages per 100 miles per year [42], respectively."

"HVDC outage data (collected from existing applications through +600 kV) indicate outage rates of under 0.5 permanent outages per 100 line miles per year."

For energy efficiency, Fig. 22 compares losses, where we observe that losses are always less in the HVDC solution.

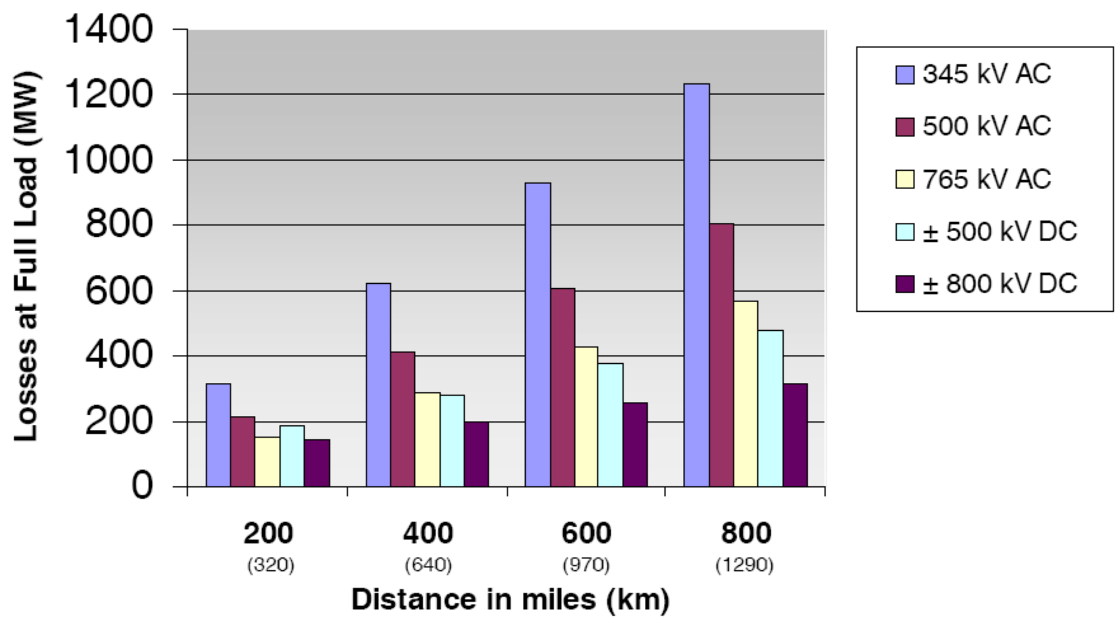


Fig. 22

Cost is compared in Fig. 23, which shows that 765 kV is least cost for 200 mile long lines, but for 400 miles and 800 miles, HVDC is more cost-effective.

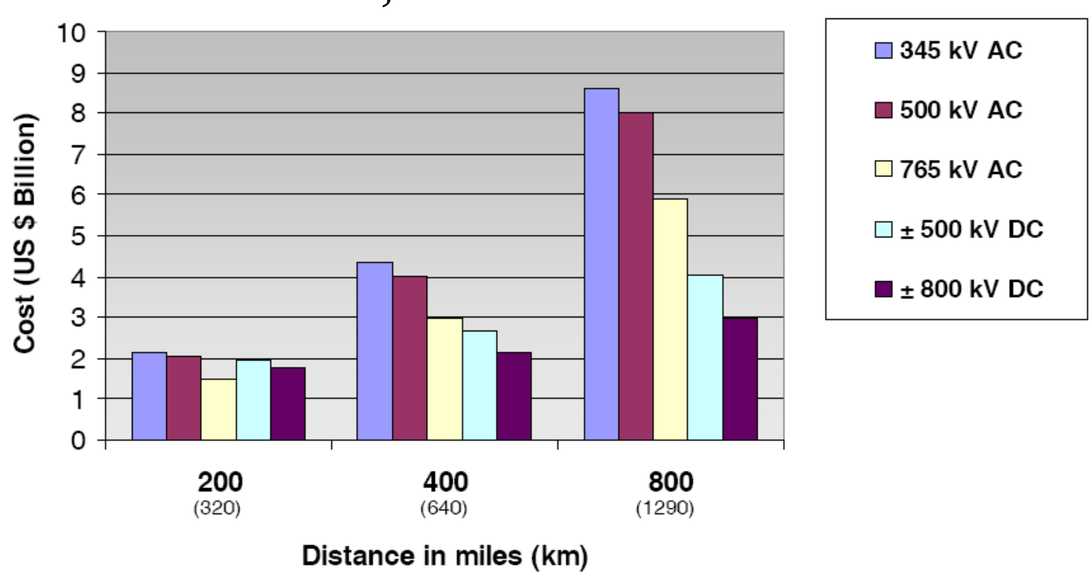


Fig. 23

Figure 24 compares the different alternatives in terms of tower heights.

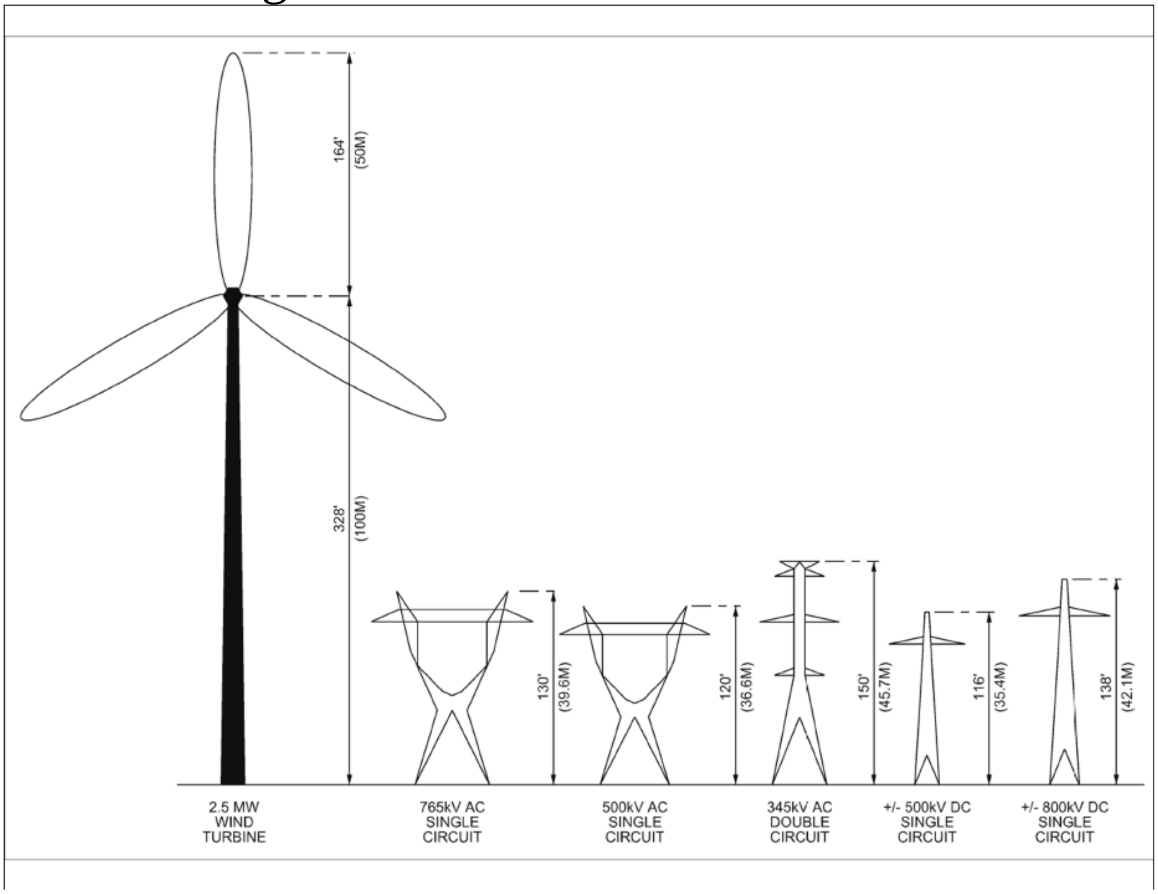


Fig. 24

Finally, Figs. 25 and 26 provide overlay designs described in the paper.

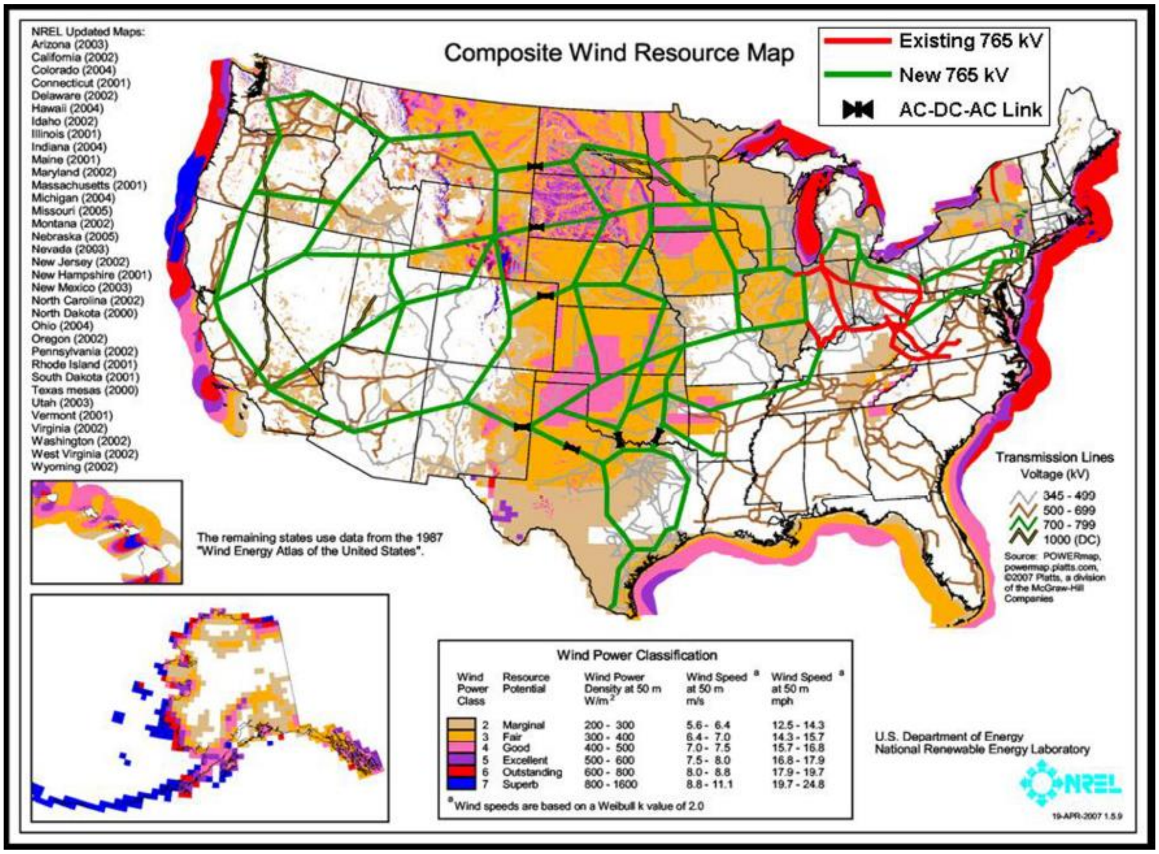

Composite Wind Resource Map
Existing 765 kV
New 765 kV
AC-DC-AC Link
NREL Updated Maps:
Arizona (2003)
California (2002)
Colorado (2004)
Connecticut (2001)
Delaware (2002)
Hawaii (2004)
Idaho (2002)
Illinois (2001)
Indiana (2004)
Maine (2001)
Maryland (2002)
Massachusetts (2001)
Michigan (2004)
Missouri (2005)
Montana (2002)
Nebraska (2005)
Nevada (2003)
New Jersey (2002)
New Hampshire (2001)
New Mexico (2003)
North Carolina (2002)
North Dakota (2000)
Ohio (2004)
Oregon (2002)
Pennsylvania (2002)
Rhode Island (2001)
South Dakota (2001)
Texas mesas (2000)
Utah (2003)
Vermont (2001)
Virginia (2002)
Washington (2002)
West Virginia (2002)
Wyoming (2002)
The remaining states use data from the 1987 "Wind Energy Atlas of the United States".
Transmission Lines
Voltage (kV)
345 - 499
500 - 699
700 - 799
1000 (DC)
Source: POWERmap, powermap.platts.com, ©2007 Platts, a division of the McGraw-Hill Companies
Wind Power Classification
Wind Power Class | Resource Potential | Wind Power Density at 50 m W/m² | Wind Speed a at 50 m m/s | Wind Speed a at 50 m mph
2 Marginal 200 - 300 5.6 - 6.4 12.5 - 14.3
3 Fair 300 - 400 6.4 - 7.0 14.3 - 15.7
4 Good 400 - 500 7.0 - 7.5 15.7 - 16.8
5 Excellent 500 - 600 7.5 - 8.0 16.8 - 17.9
6 Outstanding 600 - 800 8.0 - 8.8 17.9 - 19.7
7 Superb 800 - 1600 8.8 - 11.1 19.7 - 24.8
a Wind speeds are based on a Weibull k value of 2.0
U.S. Department of Energy
National Renewable Energy Laboratory
NREL
19-APR-2007 1.5.9

Fig. 25

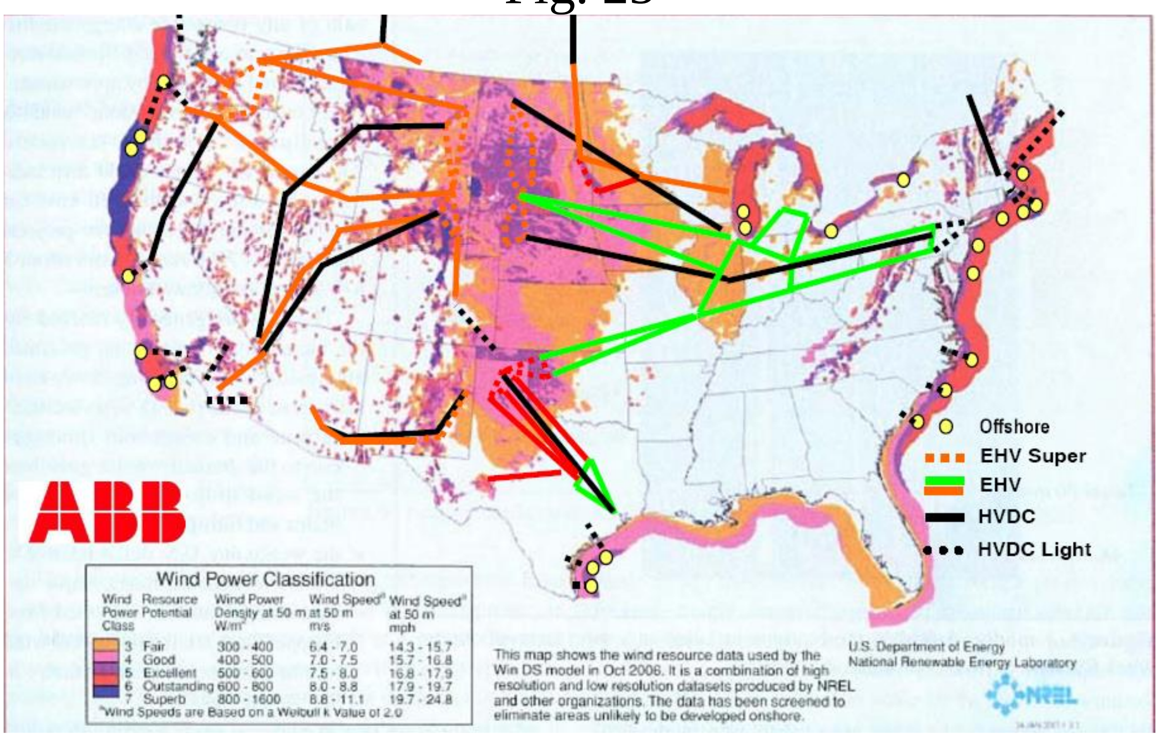

Offshore
EHV Super
EHV
HVDC
HVDC Light
Wind Power Classification
Wind Power Class | Resource Potential | Wind Power Density at 50 m W/m² | Wind Speed a at 50 m m/s | Wind Speed a at 50 m mph
3 Fair 300 - 400 6.4 - 7.0 14.3 - 15.7
4 Good 400 - 500 7.0 - 7.5 15.7 - 16.8
5 Excellent 500 - 600 7.5 - 8.0 16.8 - 17.9
6 Outstanding 600 - 800 8.0 - 8.8 17.9 - 19.7
7 Superb 800 - 1600 8.8 - 11.1 19.7 - 24.8
a Wind Speeds are Based on a Weibull k Value of 2.0
This map shows the wind resource data used by the Win DS model in Oct 2006. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data has been screened to eliminate areas unlikely to be developed onshore.
U.S. Department of Energy
National Renewable Energy Laboratory
NREL

Fig. 26

The paper ends with "A System Approach to Transmission Planning," which states:

"To implement the grid that is required for the future, collaborative planning is needed using a long term, system perspective. We know where the wind is, and we know where the loads are. Jointly, we can identify strategic broad-based interstate system plans to harvest renewable resources before the individual projects develop. Rather than project by project, piecemeal solutions, we must develop and justify an integrated system. In order to capture the full scale of benefits that high capacity technologies such as 765-kV and HVDC provide, the system must be examined on an interregional scale that matches the reach of those benefits. Some keys to success include: adoption of interconnection wide planning criteria and assumptions focusing on broad system solutions; proper balance in evaluating EHV plans to ensure long term system benefits; and development of planning criteria and assumptions for the "feeder" connections to renewable (or other) resources. Naturally such "technical planning" approaches cannot occur without the requisite regulatory and cost support for the required EHV system."

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