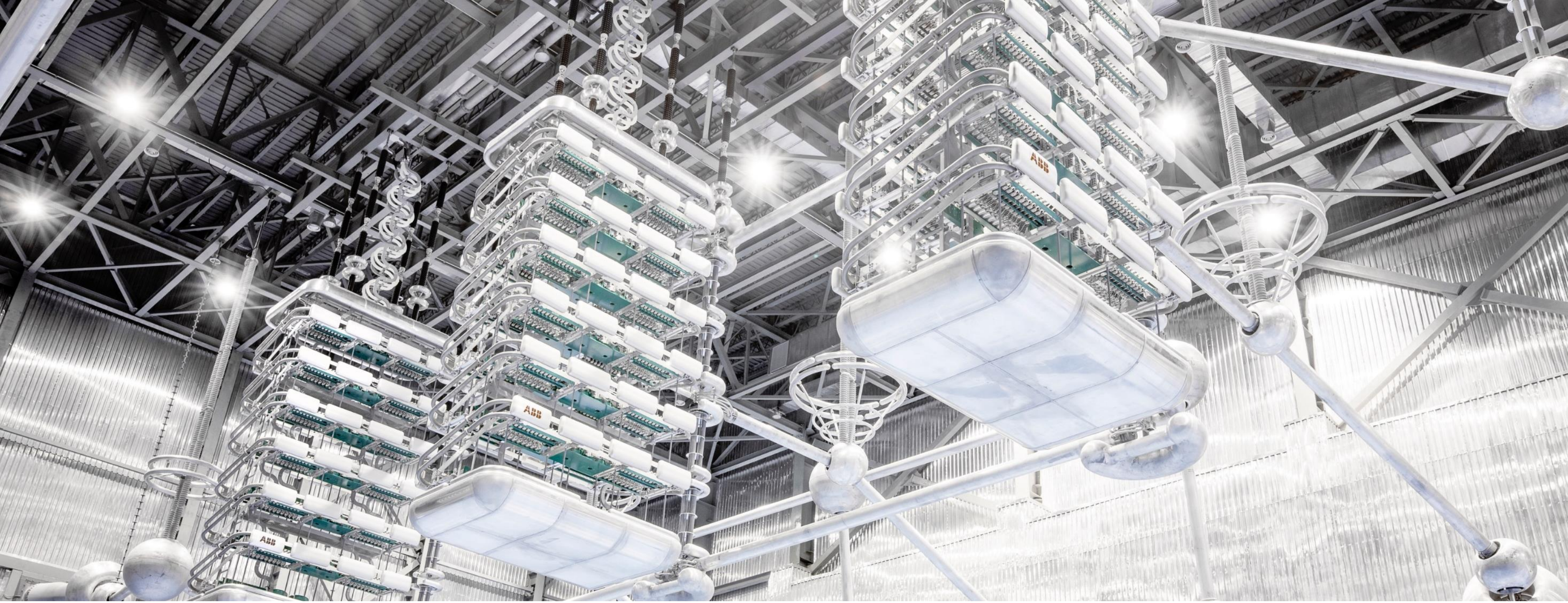
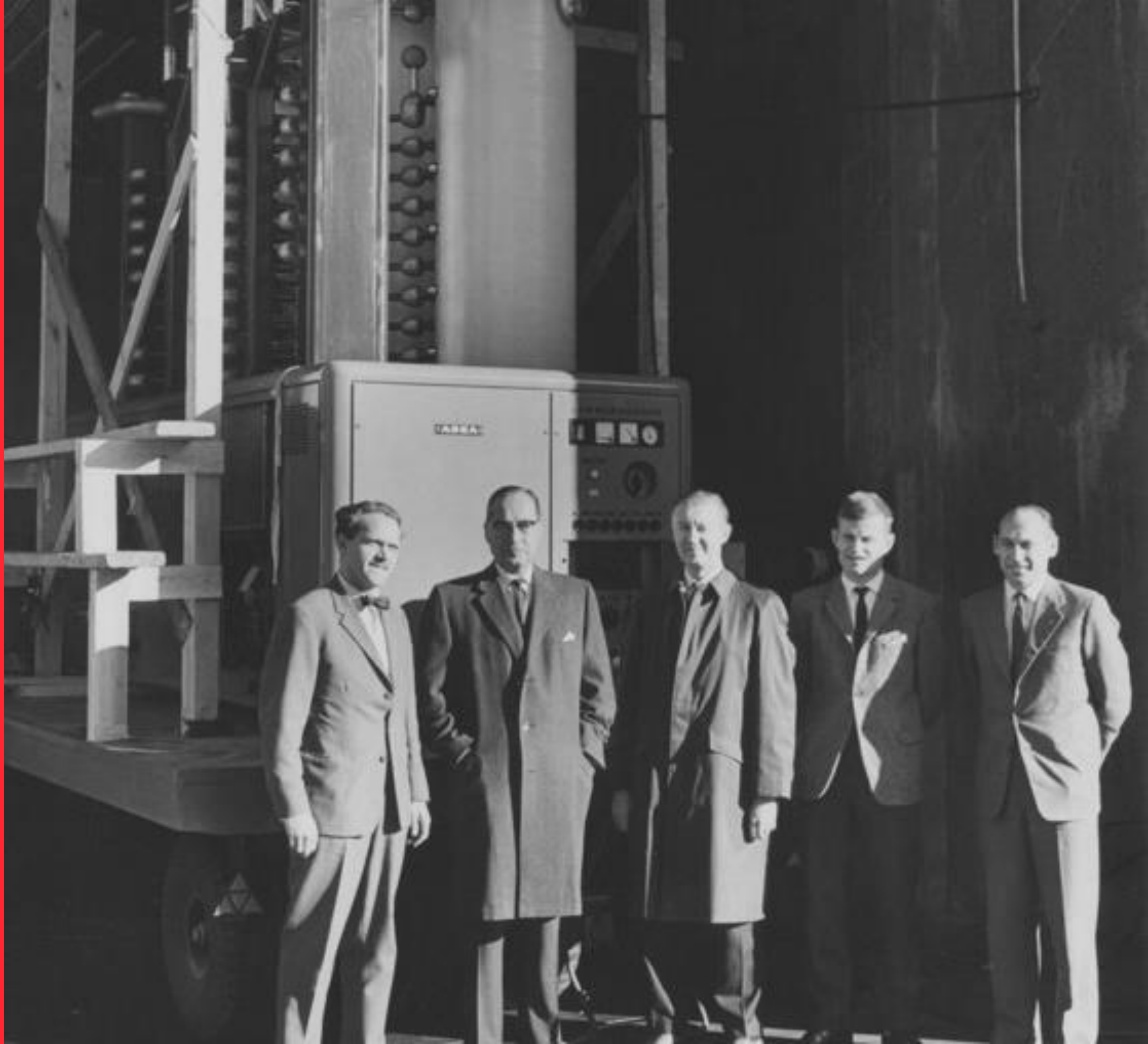


MAXWELL PINTO, MSc, JORNADAS TECNICAS, JULY 2019

ABB High Voltage Direct Current
Applications of a Well-proven System

1. **HVDC History**
   Reliable power to millions, for decades
2. **Near Future of HVDC in South America**
   An overview
3. **Skagerrak Project**
   A challenging history
4. **Maritime project**
   The first bipole HVDC Light solution
5. **Conclusion**
   HVDC flexibility



HVDC history

A proven track record of innovation

1893
ABB starts providing power to the mining industry

1928
Dr Uno Lamm began developing HVDC in Ludvika, Sweden

1954
The world's first commercial HVDC link at Gotland, Sweden

1960s
Mercury arc valves replaced with thyristor semiconductor valves

1997
The world's first VSC HVDC installation

2010
The world's first 800 kV UHVDC link at Xiangjiaba-Shanghai, China

2013
Hybrid HVDC Breaker, solving a 100-year old technology puzzle enabling the DC-grids of the future.

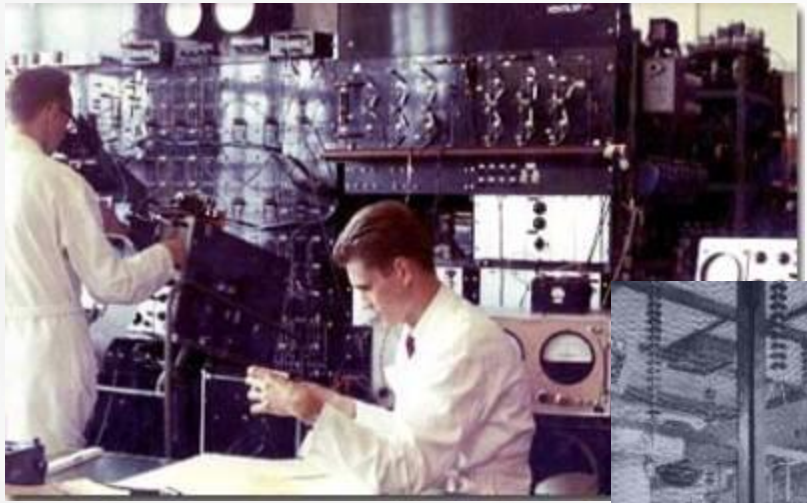
2014
Complete 1,100 kV UHVDC system developed.

2017
VSC HVDC highest performance ever – 3,000 MW, 640 kV, 2,000 km

The Future
DC support in AC grids
DC grids

"The best way to predict the future is to create it"
- *Abraham Lincoln*

The Birth of HVDC
Gotland



First commercial HVDC transmission in 1954 (100 kV, 20 MW)

Cable length: 100 km

Gotland – Swedish mainland

Case study
Itaipu

One of the largest HVDC transmissions in the world - two major ABB HVDC links that supply Sao Paulo.

6,300 MW

600 kV

1,590 km

Key facts

- The largest and most powerful HVDC transmission in the world for 20 years from 1990-2010.
- A considerable step forward in HVDC technology compared to the HVDC stations of the 1970s.

Case study
Rio Madeira

Integrating remotely located renewables, transmitting clean electricity, reliably and efficiently across a massive distance with minimum losses, to millions of consumers.

3,150 MW + 2x 400MW (BtB)
600 kV
2,375 km

Key facts

- Essential for the integration of vast hydro electric power from the Amazon Basin.
- Highly challenging remote location in the Amazon jungle.

Case study

North East Agra – ultrahigh-voltage DC, multi-terminal solution

The world's first ultrahigh-voltage multi-terminal HVDC link, a step towards a true DC grid.

6,000 MW

800 kV

1,775 km

Key facts

- Bulk 2-way transmission.
- Multi-terminal solution to integrate two generation locations.
- Minimum transmission corridor due to limited space.

Case study
Changji-Guquan – in execution

Due to set new world records on voltage level, transmission capacity and distance, supplying millions of people with reliable electricity.

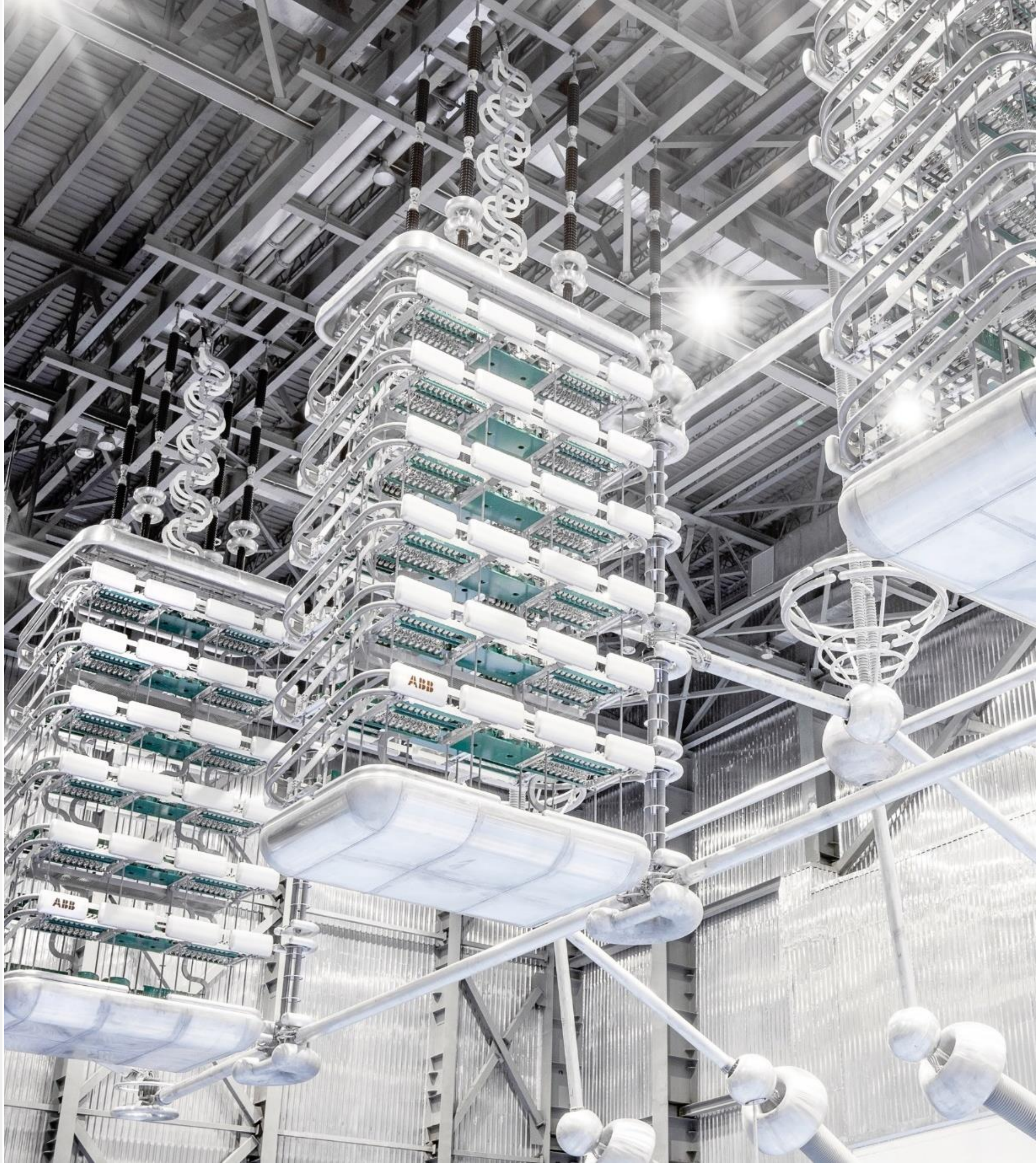
12,000 MW

1,100 kV

3,000 km

Key facts

- ABB was the first to successfully develop and test the, world record breaking, 1,100kV converter transformer technology.
- Key in integrating remote renewables on a large scale and transmitting power over greater distances.



HVDC Classic LCC
Cost effective, bulk transmission
(up to 12 GW+)

HVDC Classic from ABB:

- Low losses
- High reliability
- High availability
- World's largest greenfield project experience
- Extensive service and upgrade experience

Installed base

Over 120 projects and over 60 years experience

America

CU Upgrade	2019	Outaouais	2009	Chateauguay	1984
Maritime Link	2017	Sharyland	2007	Cu-project	1979
Quebec – New England Upgrade		Rapic City	2003	Nelson River 2	1978
Madawaska Upgrade	2016	Cross Sound	2002	Square Butte	1977
Celilo Upgrade	2016	Eagle Pass	2000	Eel River	1972
Railroad DC Tile	2016	Quebec – New England	1990	Pacific Intertie	1970
Oklaunion	2014	Pacific Intertie Expansion	1989	Vancouver Island Pole 1	1968
Mackinac	2014	Intermountain	1986		
IPP Upgrade	2014	Pacific Intertie Upgrade	1985		
Blackwater	2010	Madawaska	1985		
	2009	Highgate	1985		

Europe

North-sea Link	2021	Nordbalt	2015	Swepol	2000
Nordlink	2021	Litpol Link	2015	Gotland Light	1999
IFA2	2020	Skagerrak 4	2014	Hällsjön	1997
Kriegers Flak Cgs	2019	East West		Kontek	1995
Johan Svedrup	2019	Interconnector	2013	Baltic Cable	1994
Gotland Upgrade	2018	Sapei	2011	Fennoskan 1 & 2	1989
Caithness – Moray	2018	Valhall	2011	Dürnohr	1983
Kontek Upgrade	2016	Norned	2008	Skagerrak 1-3	1976
Troll 1 & 2, 3 & 4	2015	Estlink	2006	Gotland 1-3	1970
Borwin 1	2015	Italy – Greece	2001	Konti-skan	1965
Dolwin 1, 2	2015	Tjæreborg	2000	English Channel	1955
Åland	2015				

South America

Rio Madeira Back-to-back	2013
Rio Madeira	2013
Brazil – Argentina Interconnection I & II	1999
Itaipu	1984

Asia

Changji-Guquan	2019
Raigarh-Pugalur	2019
North East Agra	2016
Jinping - Sunan	2013
Mülünbeir – Liaoning	2010
Lingboa li Extension	2010
Xiangjiba – Shanghai	2010
Three Gorges – Shanghai	2006
Vizag Li	2005
Three Gorges – Guangdong	2004
Three Gorges – Changzhou	2002
Chapad	1999
Rihand-Delhi	1990
Gezhouba – Shanghai	1989
Vindyachai	1989
Sakuma	1965

Africa

Inga – Kolwezi Upgrade	2016
Cahora Bassa, Songo	2015
Caprivi Link	2010
Apollo Upgrade	2008
Inga – Kolwezi	1982
Cahora Bassa	1977

Australia and Oceania

Broken Hill	2013
Murraylink	2013
Directlink	
Leyte-Luzon	1999
NewZealand 1 & 2	1984

HVDC Light: 20 year of success!

Harmonic and Loss Reduction – Eliminating the Need for Harmonic Filters

Modulation principles

1997 – 2001
Two level converter

2002 – 2004
Three level converter

2005 – 2009
Two level converter,
optimized switching

2010 – 2015
Cascade two level converter

2016 –
Modular multi-level converter

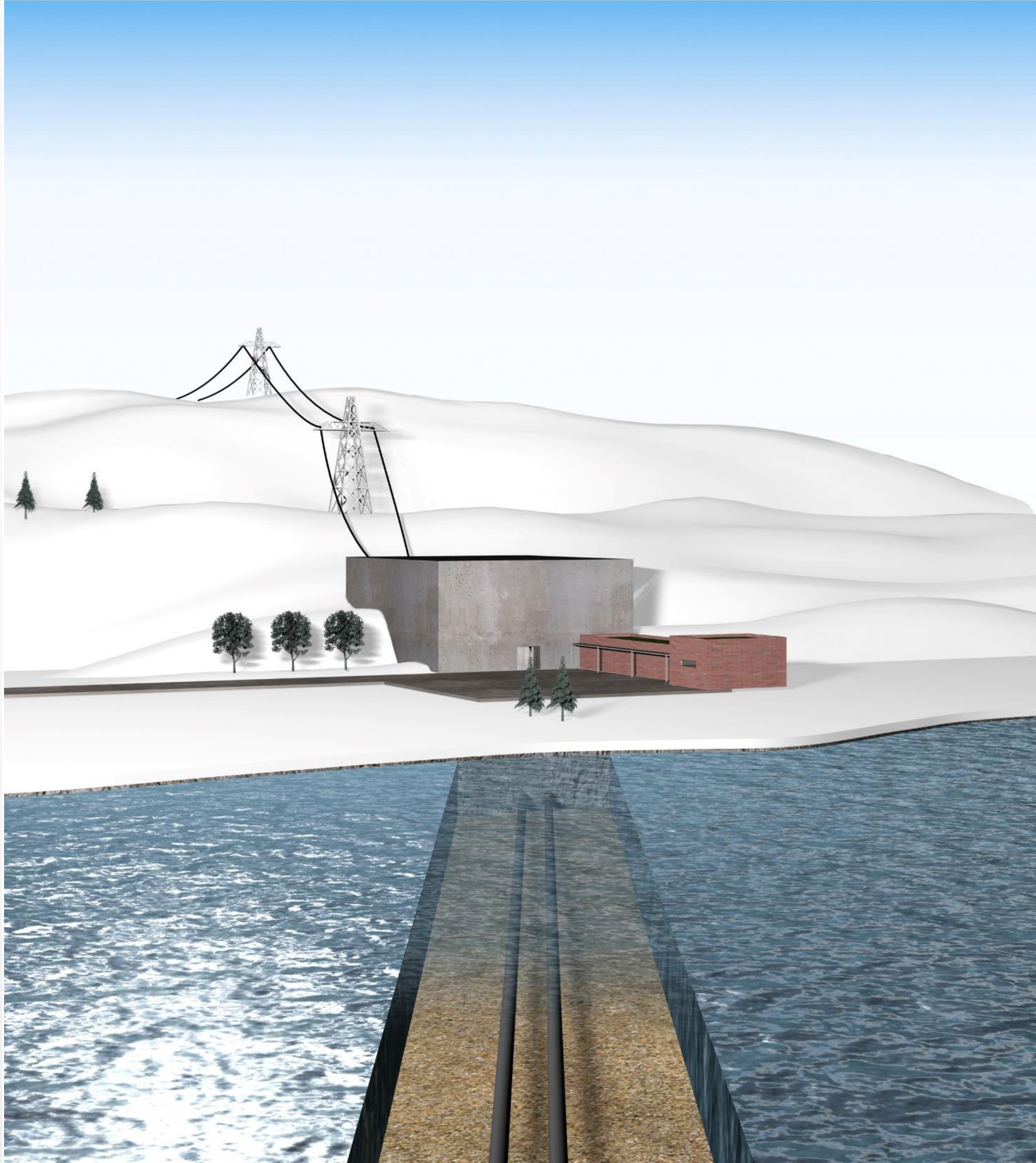
Case study
Nordlink – in execution

Interconnecting grids using HVDC technology helping our customers reach their targets for a renewable energy mix.

1,400 MW
525 kV
623 km

Key facts

- VSC bipole HVDC
- Balances intermittent wind power in Germany with controllable hydropower in Norway.
- Most powerful HVDC Light® system in construction, joint with NordLink.



VSC HVDC Light®
Up to 640 kV and 3,500 MW

Your grid challenges, solved by HVDC Light:

Weak network?

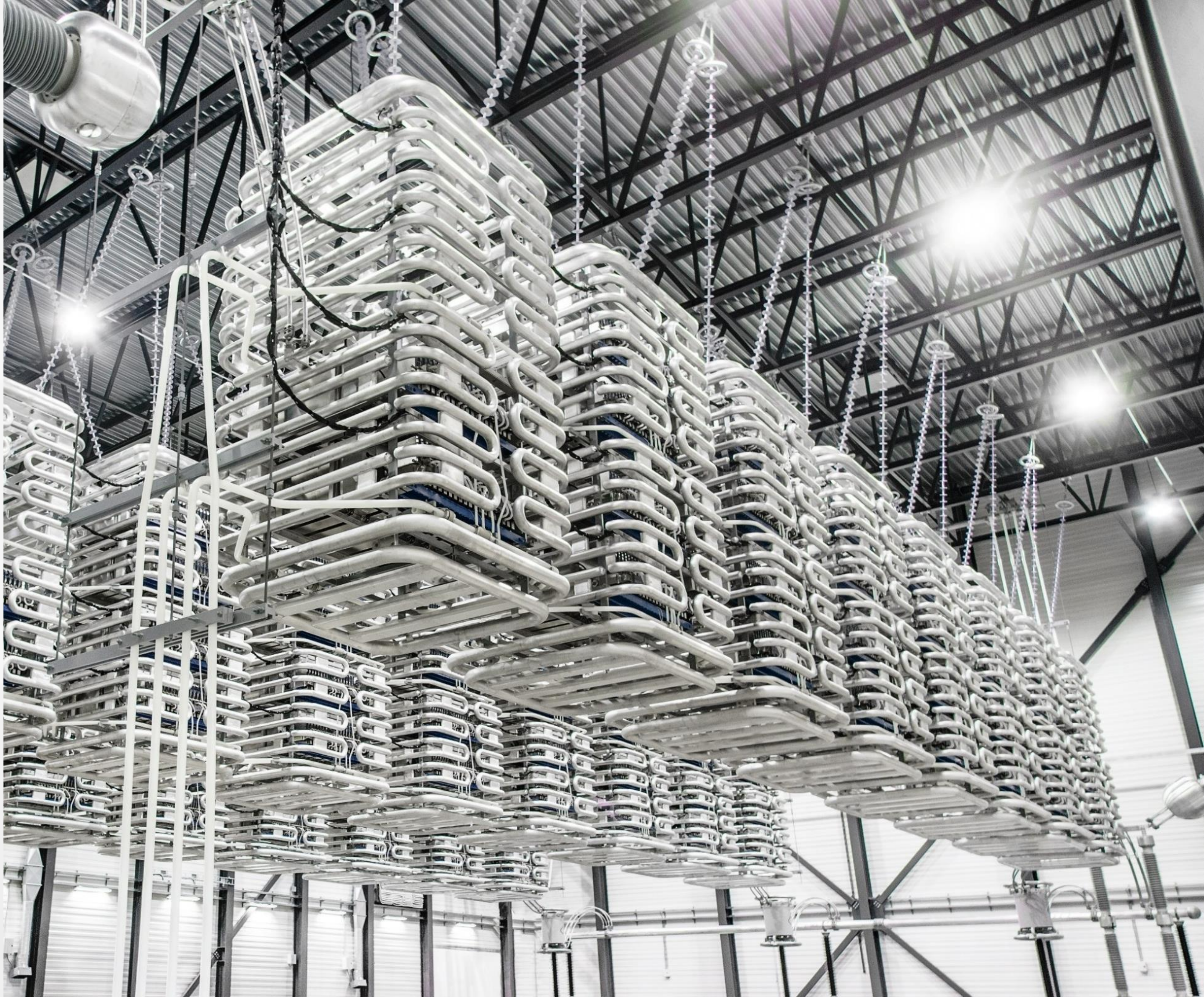
- Black start power restoration
- Active/reactive power control (statcom functionality)
- AC voltage and frequency stabilization (increasing AC grid utilization)

Bi-directional power trade?

- Fast power reversal

Integration of renewables?

- Power, voltage and frequency control



VSC HVDC Light

ABB supplied 70% of all VSC links in the world

- VSC-HVDC projects commissioned
- In construction

*VSC: Voltage sourced converter

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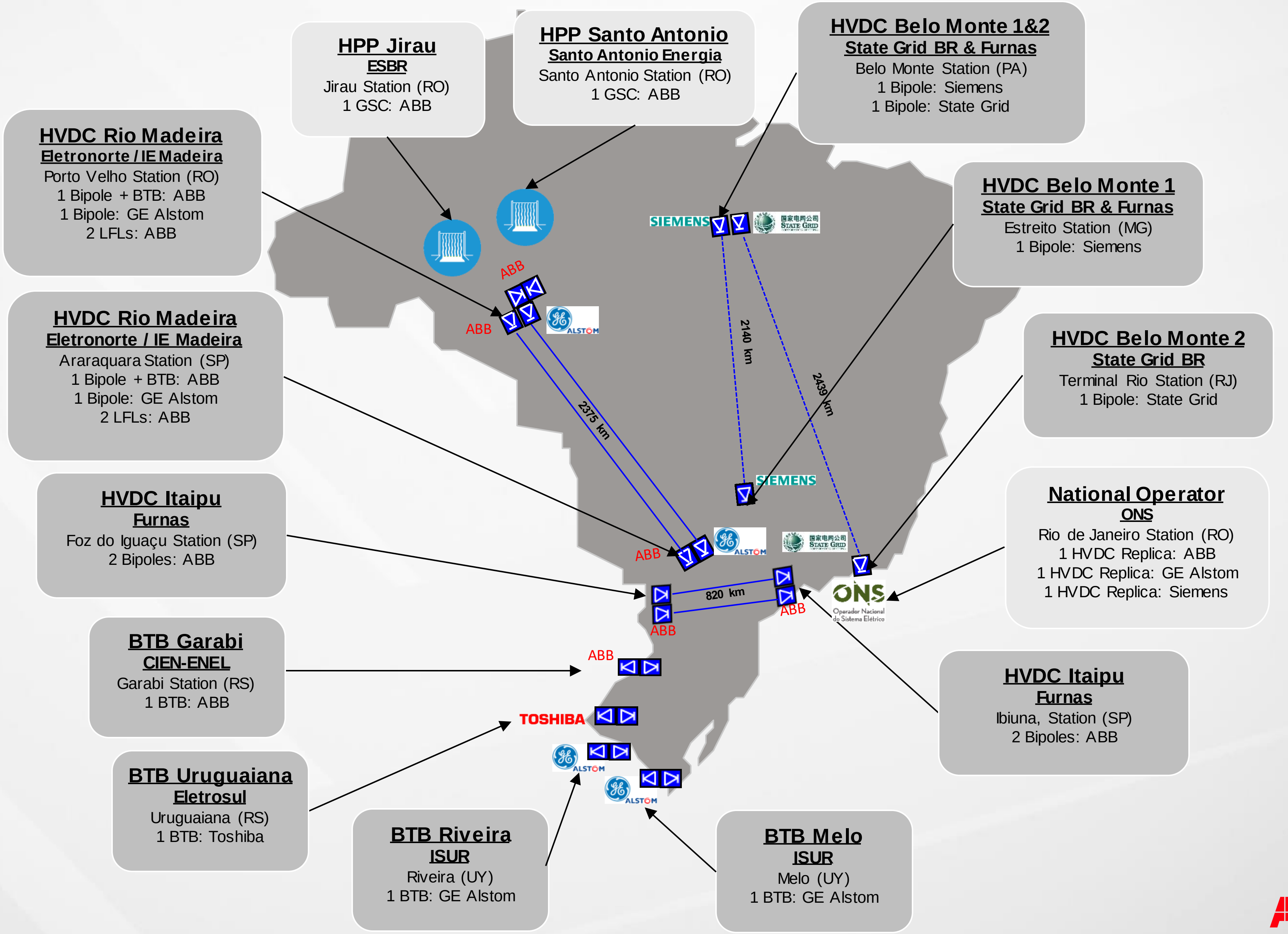
HVDC flexibility

HVDC Installed Base

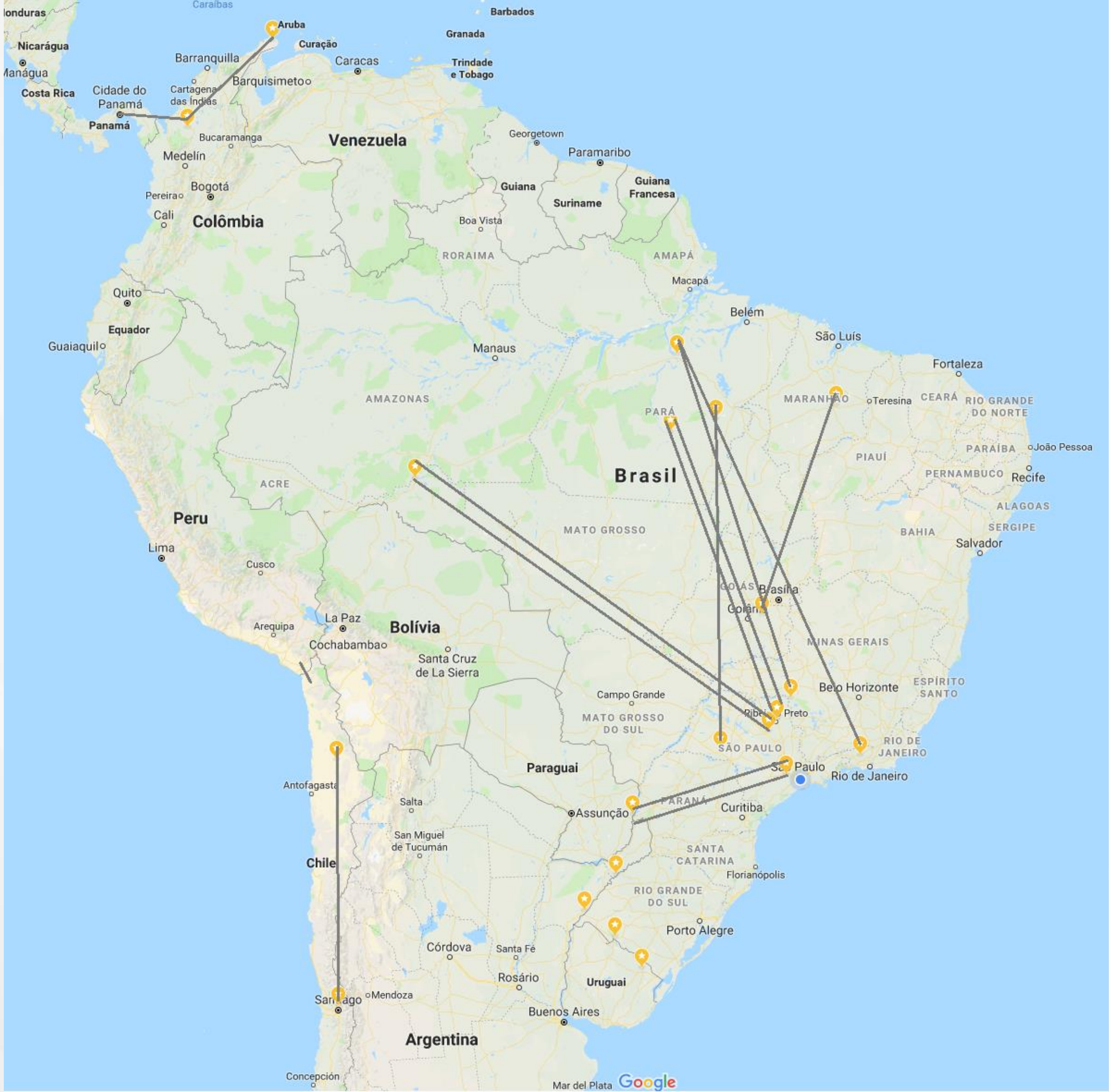
Brazil



ABB

HVDC Installed Base and Future Projects
South America

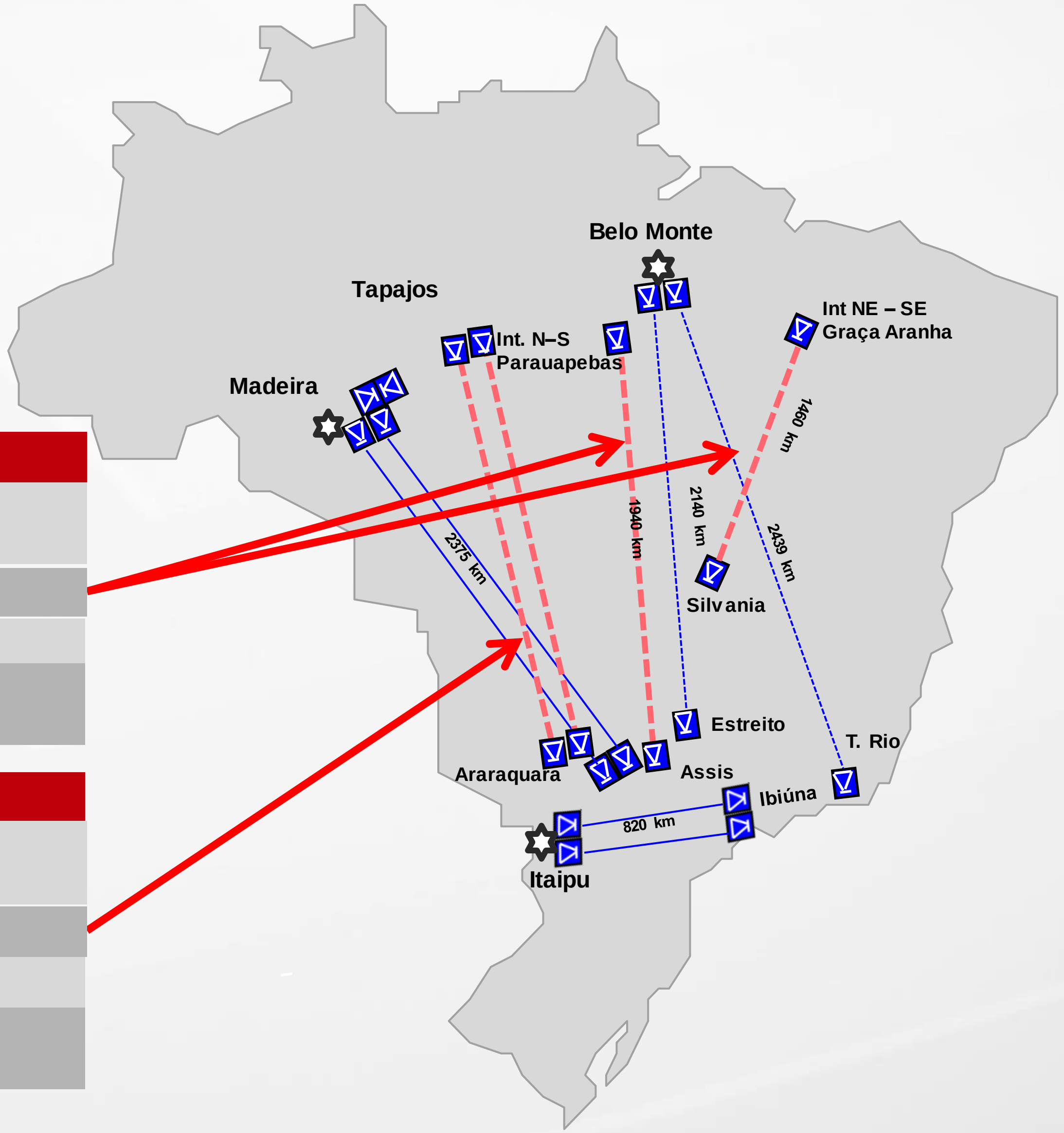
SAM in 2029



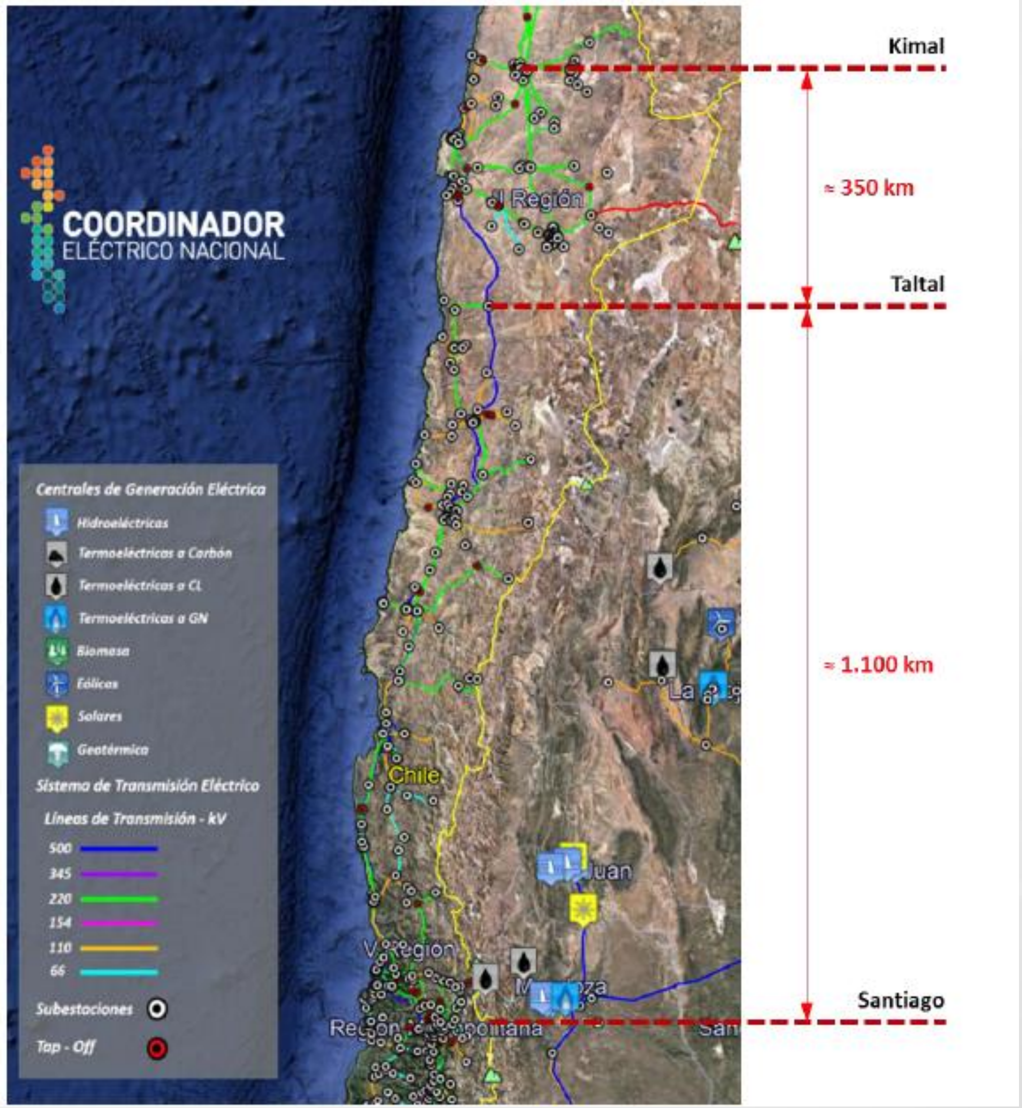
HVDC Future Projects
Brazil

N/SE and NE/SE Transmission Expansion	
Transmission Line:	2,100 km N/SE 1,500 km NE/SE
Voltage:	± 800 kV DC
Power:	8,000 MW for 2 bipoles
Expected Auction/Award:	2021 BP B 2023 BP A

HPP Tapajós Transmission System	
Transmission Line:	1,500 km BP1 2,500 km BP2
Voltage:	± 800 kV DC
Power:	8,000 MW for 2 bipoles
Expected Auction/Award:	2025 BP1 2027 BP2



HVDC Future Projects
Chile



3000 MW / ±600kV DC
To be in operation up to 2028

Source: CEN – Coordinador Electrico Nacional

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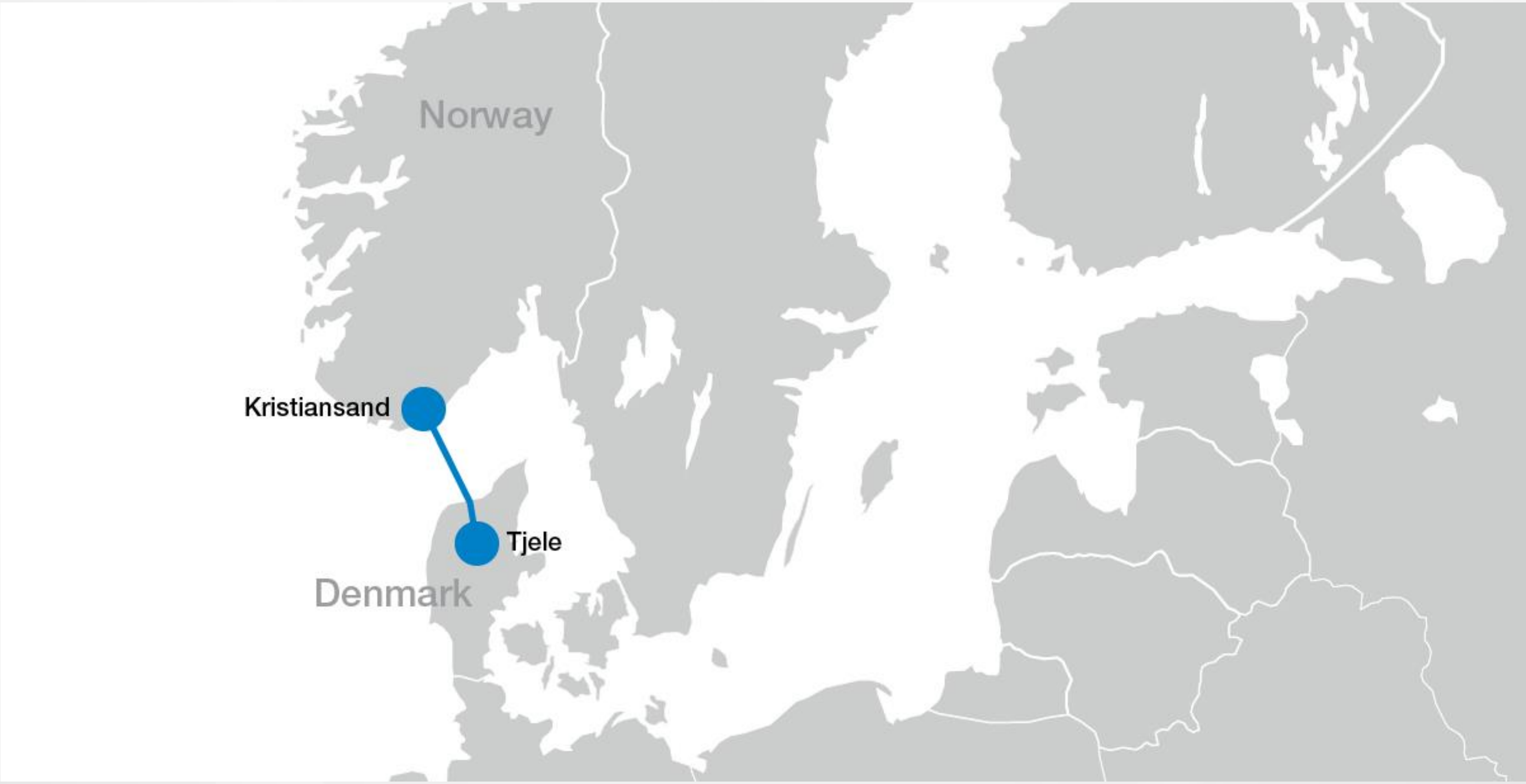
Skagerrak Project
A continuous evolution

General Information

- Connection between Kristiansand, Norway and Tjele, Denmark.
- The transmission system belongs to Statnett on the Norwegian side and to Energinet on the Danish side.
- Skagerrak 1 and 2 (SK 1 e SK 2) entered commercial operation in 1975/1976.
- Skagerrak 3 (SK 3) was commissioned in 1993.
- Skagerrak 4 (SK 4) is in operation since 2014.
- The distance between the substation is around 240 km.
- Hydroelectric power from Norway.
- Initially thermoelectric power form Denmark.
- Today Denmark has a considerable amount of windfarms.

Skagerrak Project
Connecting Norway and Denmark

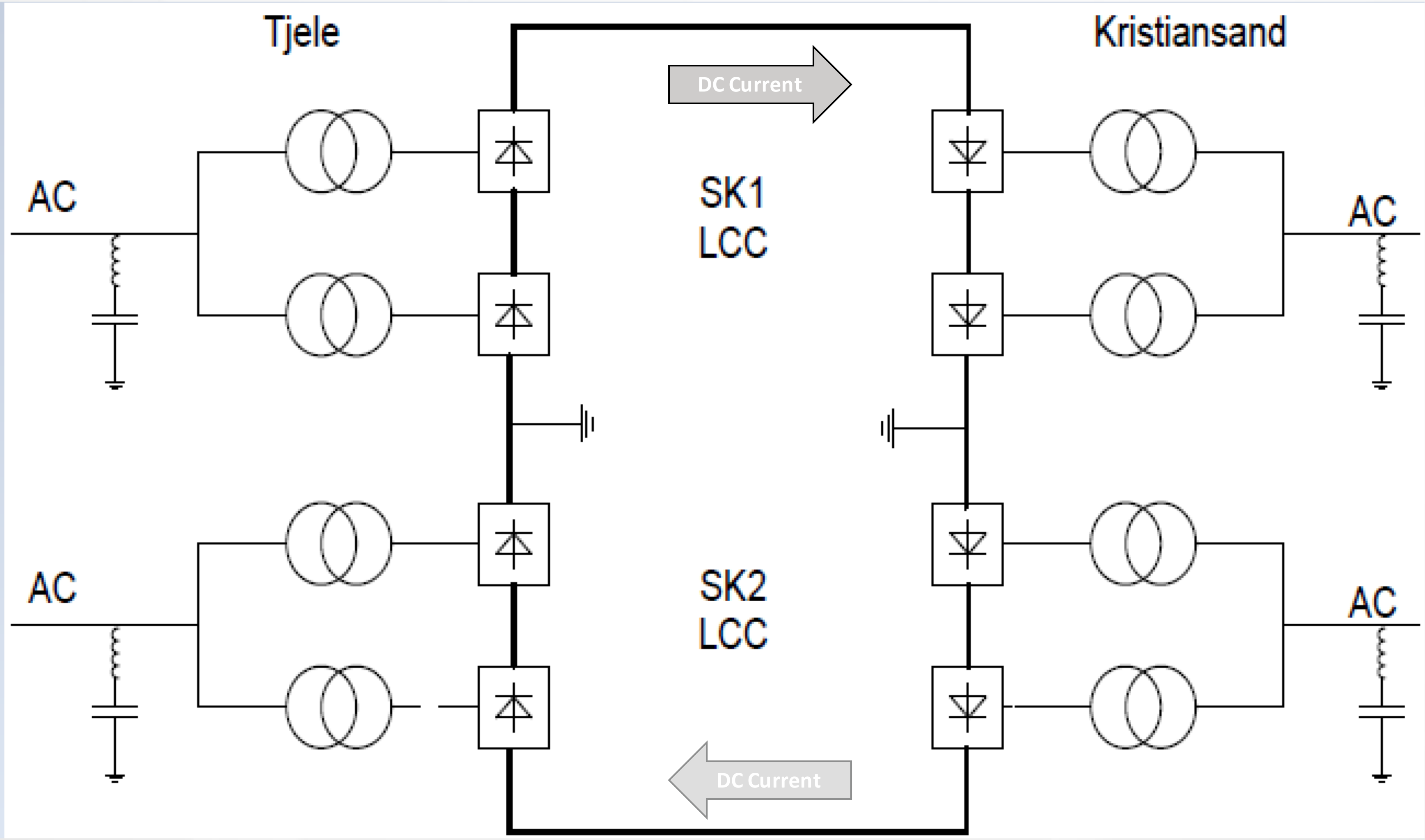


Skagerrak 1 & 2
The first bipole

General Information

- Bipole with Line-Commuted Converters (LCC).
- Uses thyristor in the converters.
- Voltage of ± 250 kV DC (until Skagerrak 3).
- Current of 1000 A.
- Total power of 500 MW.
- 127 km submarine cables and 113 km overhead lines.
- Earth electrode on both sides.
- Commissioned in 1975/1976.
- Revitalized in 2007.

Skagerrak 1 & 2
The first bipole



Skagerrak 3
The third pole. Changes were needed…

General Information

- Monopole with LCC converter.
- Voltage of 350 kV DC.
- Current of 1430 A.
- Power capacity of 500 MW.
- 127 km submarine cable and 113 km overhead line.
- Commissioned in 1993.

But…

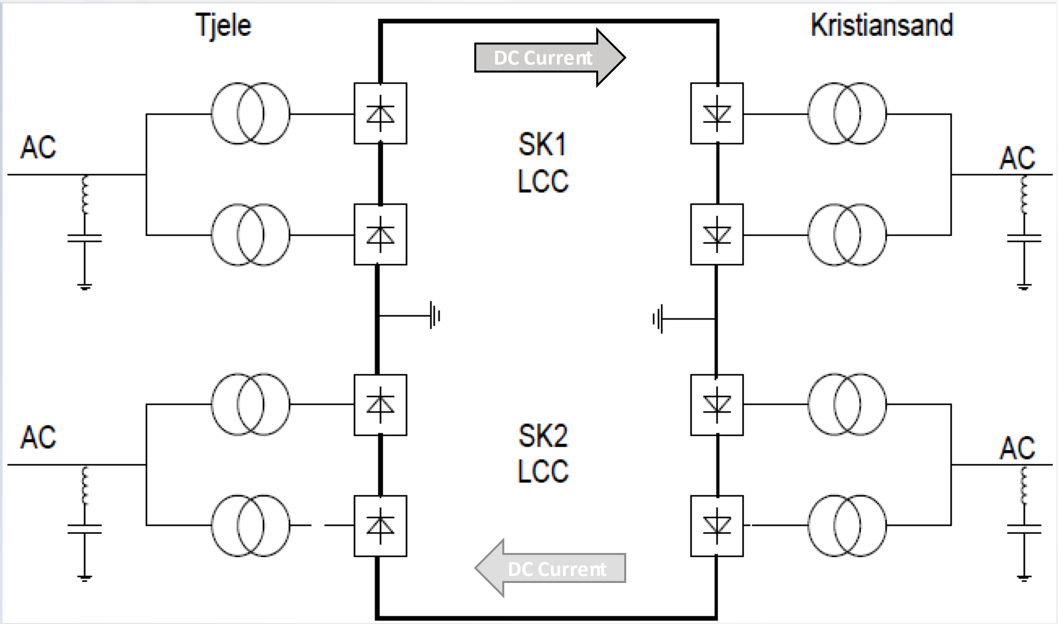
- No metallic return dedicated cable was built.
- There is a limitation to the amount of time the earth return can be used.
- The rated voltage, current and power for SK3 is different from SK 1 and 2.

How to operate the new system with a new pole with different specs?

Skagerrak 3
Adaptations

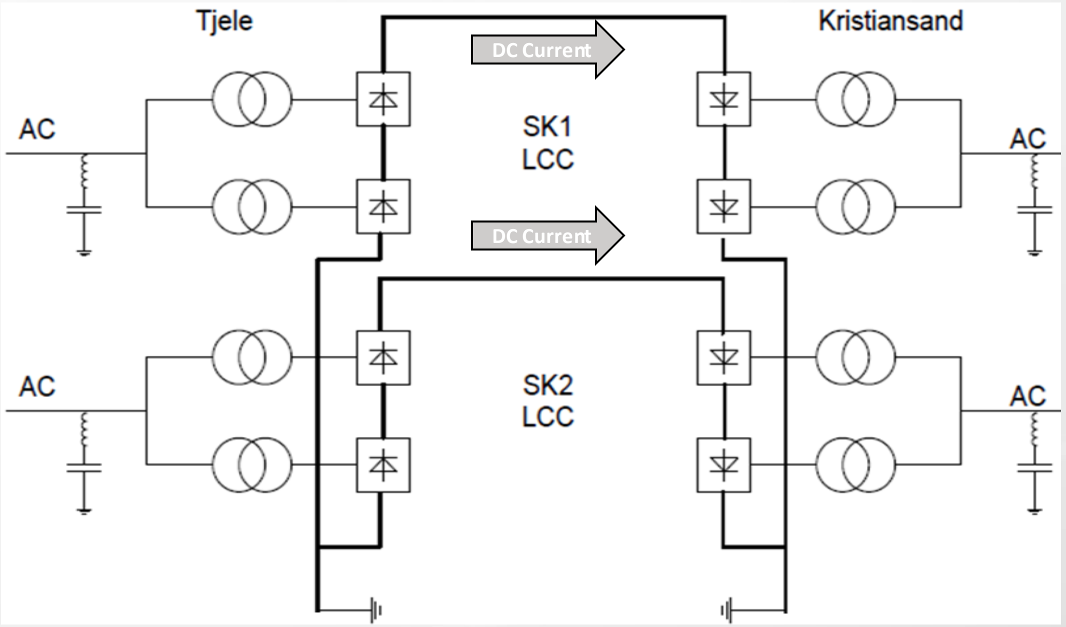
Before SK3

- SK1 and SK2 are two monopoles that form a bipole.
- SK1 and SK2 have different DC voltage polarities.
- SK1 and SK2 have DC currents flowing in opposite directions.



After SK3

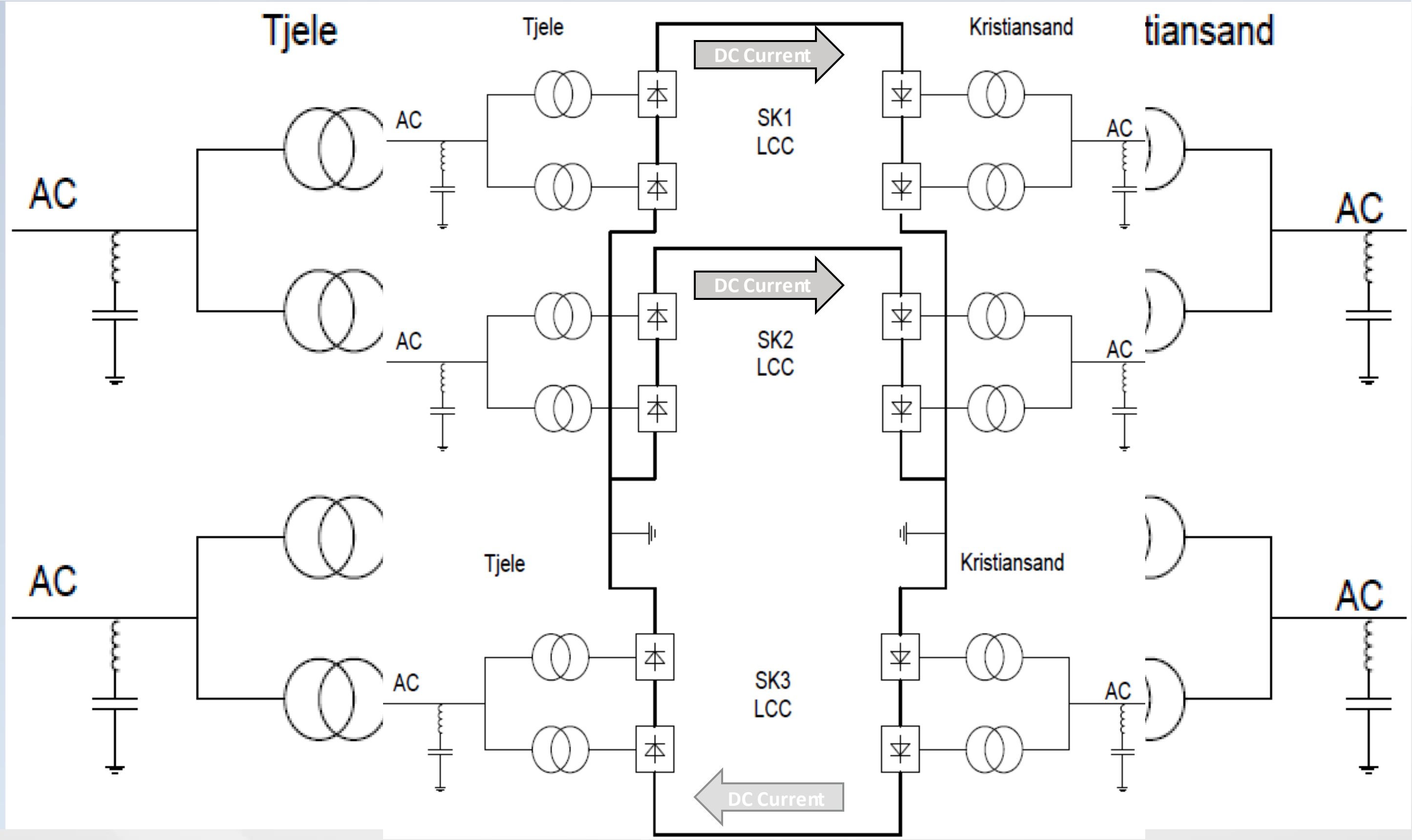
- SK1 and SK2 have their converters in parallel and form a monopole.
- SK1 and SK2 have the same DC voltage polarity.
- SK1 and SK2 have their DC currents flowing in the same direction.



Skagerrak 3
The addition of a new pole

With Skagerrak 3

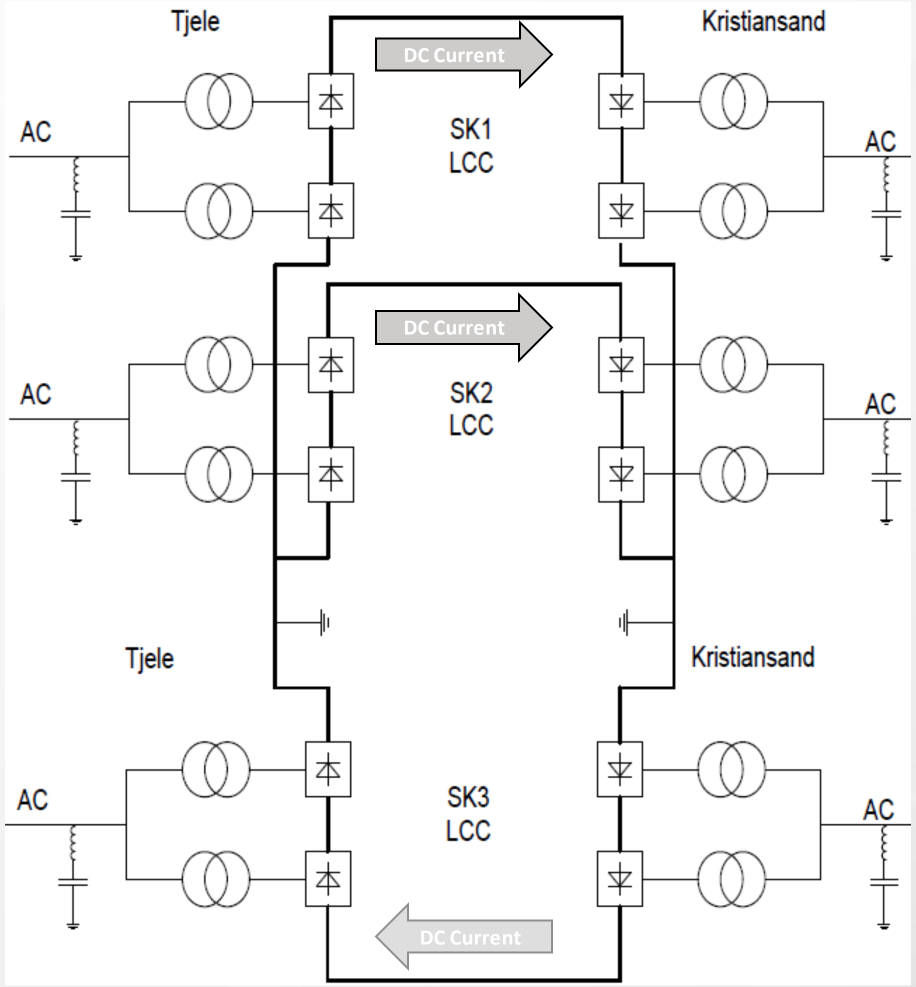
- SK3 operates with a DC voltage polarity to SK1 and SK2.
- SK3 has its DC current flowing in the opposite direction to SK1 and SK2.
- SK1 and SK2 operate as a monopole and, together with SK3, form a new bipole.



Skagerrak 3
With the new pole

From 1993 on….

- SK1 and SK2 operated with +250 kV DC e maximum current of 1000 A. The total power capability was 500 MW (250 MW per pole).
- SK3 operated with -350 kV DC and maximum current of 1430 A. The power capability was 700 MW.
- The new bipole has a total power capability of 1200 MW.
- Normally the power was distributed between the two poles so they had the same DC current in order to minimize the earth current.
- During the operation with full power, the current flowing to ground was 600 A.



Changes in the Danish System
Wind power: More changes were needed…

Norway

– The main energy source is hydroelectrical.

Denmark

– When SK1 and SK2 were commissioned, the Danish system had primarily thermal power sources.
– In the last decade, many windfarms have been built in the country.

Changes in the Danish System
Advantages of HVDC with renewable power

What was HVDC initially intended for?

- Initially the Skagerrak transmission system was designed for optimal economical energy dispatching among the two countries.
- Stabilization of the AC grids after contingencies.

What happened more recently?

- Wind generation in Denmark sometimes exceeds the consumption of the loads connected to it.
- The HVDC system compensates for swift variations in wind power and assures the balance between load and generation.
- Hydro power in Norway compensates for quick changes in windfarm output in Denmark.
- In some situations the active power in the HVDC link is inverted and Denmark exports energy to Norway.

Changes in the Danish System
The fourth pole

Why a forth pole?

- The need for an increase in the energy exchange capability between Norway and Denmark requires the construction of a new HVDC pole.

LCC or VSC?

- SK1, 2 and 3 are located electrically far away from big conventional generators.
- The LCC converters demand a minimum AC network short-circuit level to work properly.
- There are other two HVDC links (Norned and Konti-Skan) that are relatively close to Skagerrak and multi-infeed interactions might may appear.
- Voltage and electromechanical stability problems may occur and synchronous condensers were installed in Norway to increase the short-circuit level.
- A new HVDC pole using LCC technology would require the installation of a few synchronous condensers in both the Norwegiand and Danish systems.

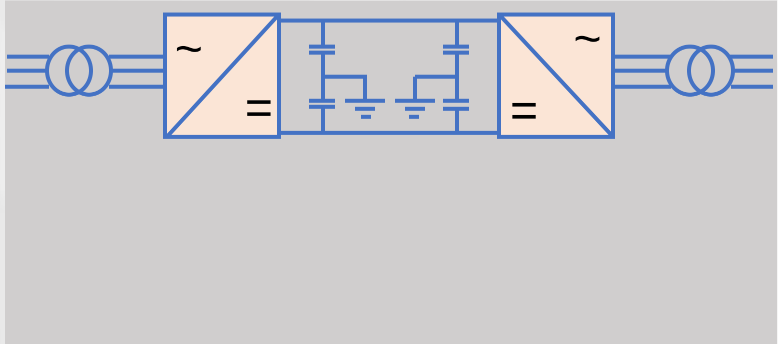
Skagerrak 4
The VSC pole

Advantages of a Voltage Source Converter

- No need of new synchronous condensers.
- The reactive power exchange between the converter and the AC network is controlled.
- The VSC converters can be used to control the AC voltage of both networks.
- Great increase in AC system stability.
- Black start capability.

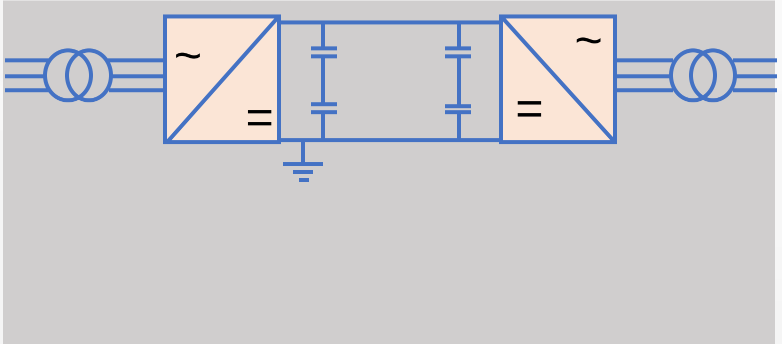
HVDC Light
System Configuration

Symmetric monopole



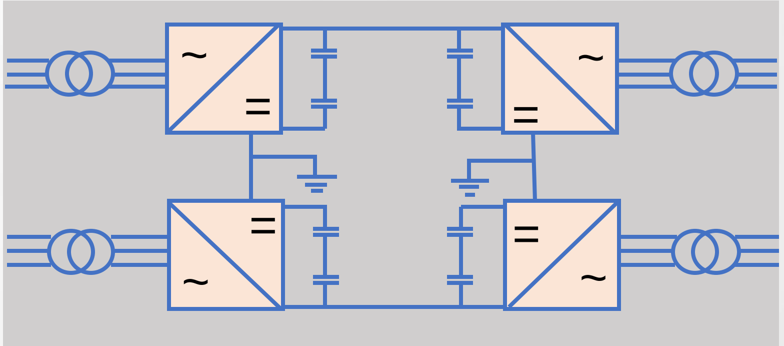
Positive
Low cost
Low transmission losses
Negative
Loss of 100 % power at trip

Asymmetric monopole



Positive
Only one high voltage cable
Bipole enabled
Negative
Less compact

Bipole



Positive
High Availability for half power
Negative
Temporary ground current (can be avoided at the expense of a metallic return conductor)

Skagerrak 4
Specifications

The new pole

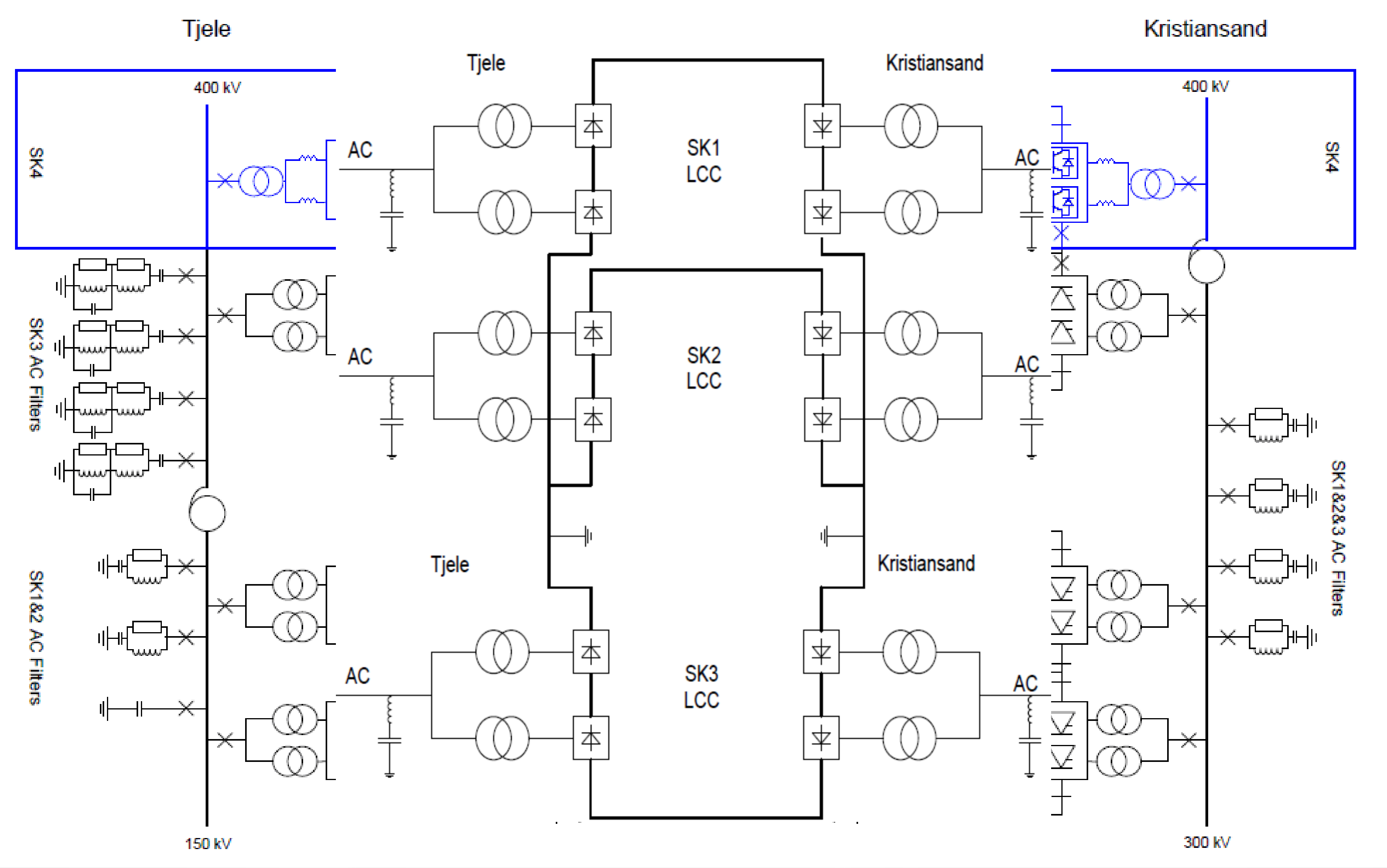
- VSC converter – asymmetric monopole
- Rated DC voltage of + 500 kV.
- DC current of 1400 A.
- Rated active power of 700 MW.
- 140 km submarine cable and 104 km overhead line.
- Commissioned in 2014.

Final Configuration
Two bipoles

Since 2014....

- SK1 and SK2 operate once again as two poles of a bipole.
- SK3 and SK4 operate now as an hybrid bipole, as the fisrst one is a LCC monopole and the second one is an asymmetric monopole with VSC technology.
- Both bipoles use the same earth electrode.
- SK3 and SK4 have different power ratings and rated DC voltages, but their rated DC currents are very similar, which results in low currents to ground.

Final Configuration
Two bipoles



Final Configuration
How flexible and HVDC transmission can be…

		Poles 1 & 2	Pole 3	Pole 4
Rated Power	MW	2 x 250	500	700
DC Voltage	kV	250	350	500
DC Current	A	1000	1430	1400
Converter Technology		LCC	LCC	VSC
AC Voltage (Kristiansand, NO)	kV	300	300	400
AC Voltage (Tjele, DK)	kV	150	400	400
DC Submarine Cables	km	127	127	140
DC Overhead Lines	km	113	113	-
DC underground Cables	km	-	-	104
Comissioning Year		1976 - 1977	1993	2014

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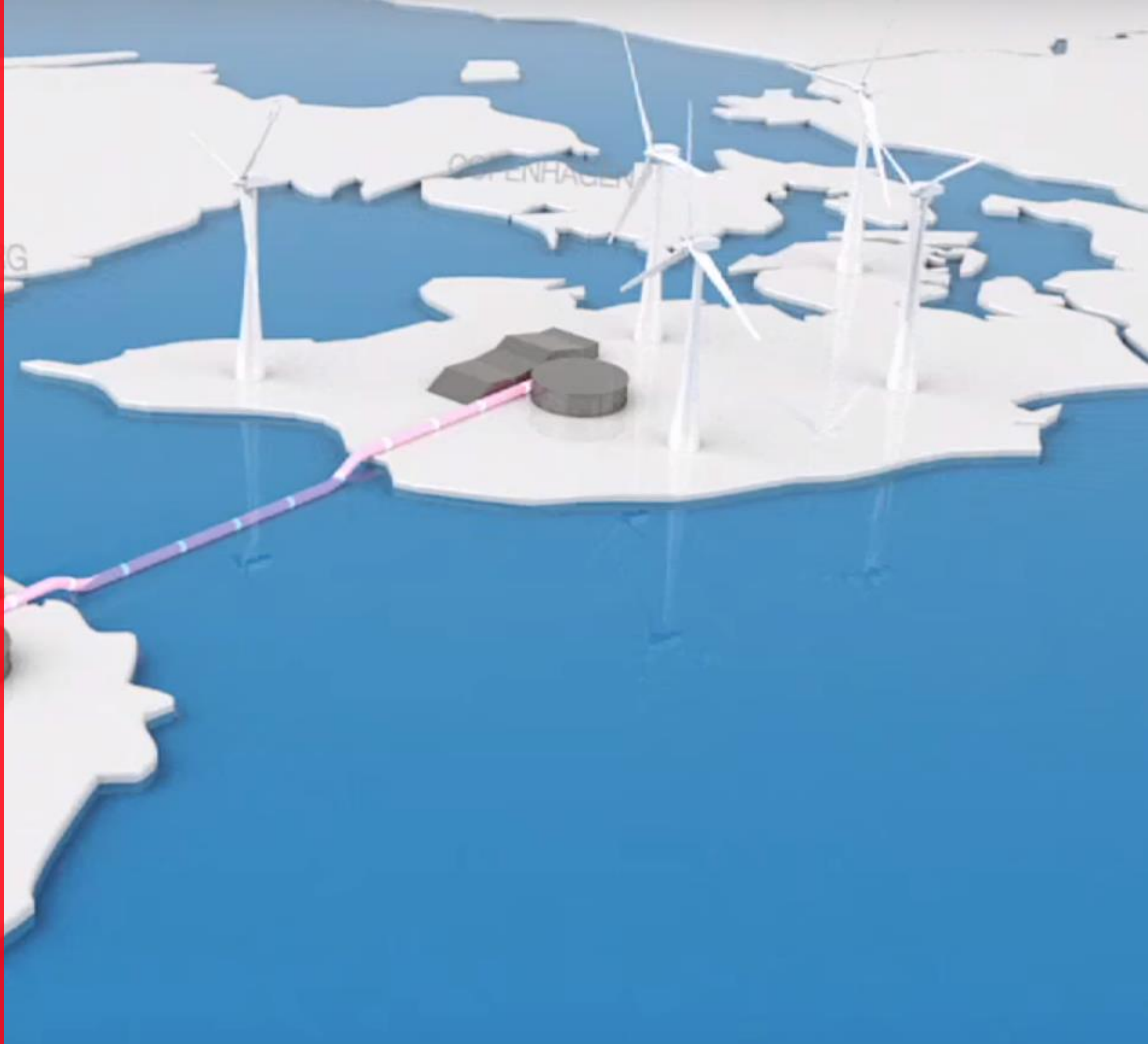
HVDC flexibility



Maritime Link
Canada

Main data

Customer	NSP Maritime Link (Emera)
Customer needs	• Integrate renewable generation into the the North American grid
ABB's response	• Bipole HVDC Light solution • Two 500 MW HVDC Light stations • Two AC substations at 230 kV • One AC substation at 345 kV
Customer benefits	• Improved grid stability • Power sharing enabled
Year	• 2017

Maritime Link
Canada

Case study
Maritime

Enabling clean, renewable electricity generated in Newfoundland and Labrador to be transmitted to the North American grid in Nova Scotia.

500 MW
200 kV
360 km

Key facts

- World's first VSC bipole HVDC interconnection overcoming unique control challenges.
- Demanding environment.
- Unique socio-economic and environmental requirements.

Case study
Nordlink – in execution

Interconnecting grids using HVDC technology helping our customers reach their targets for a renewable energy mix.

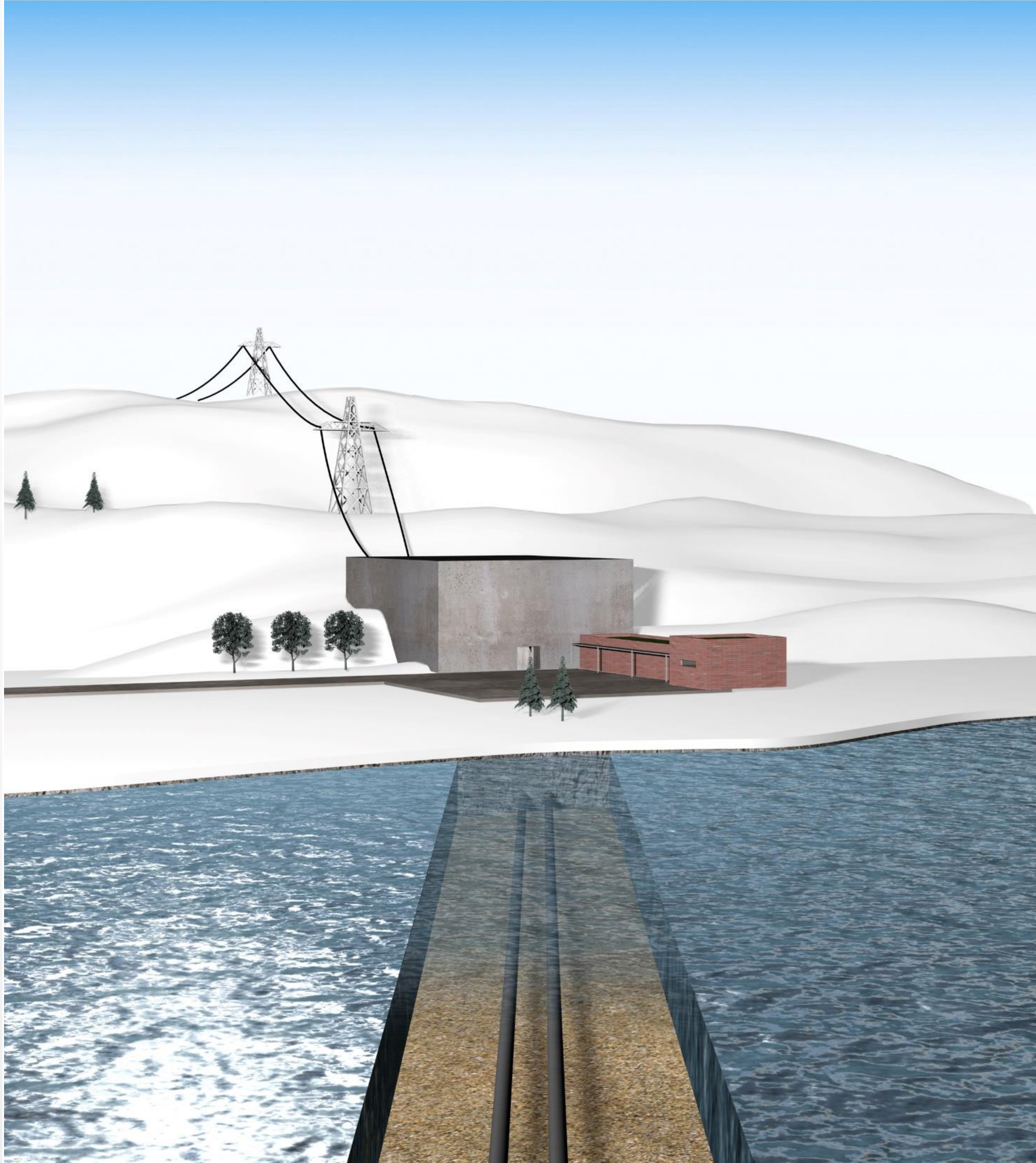
1,400 MW

525 kV

623 km

Key facts

- VSC bipole HVDC
- Balances intermittent wind power in Germany with controllable hydropower in Norway.
- Most powerful HVDC Light® system in construction, joint with NordLink.



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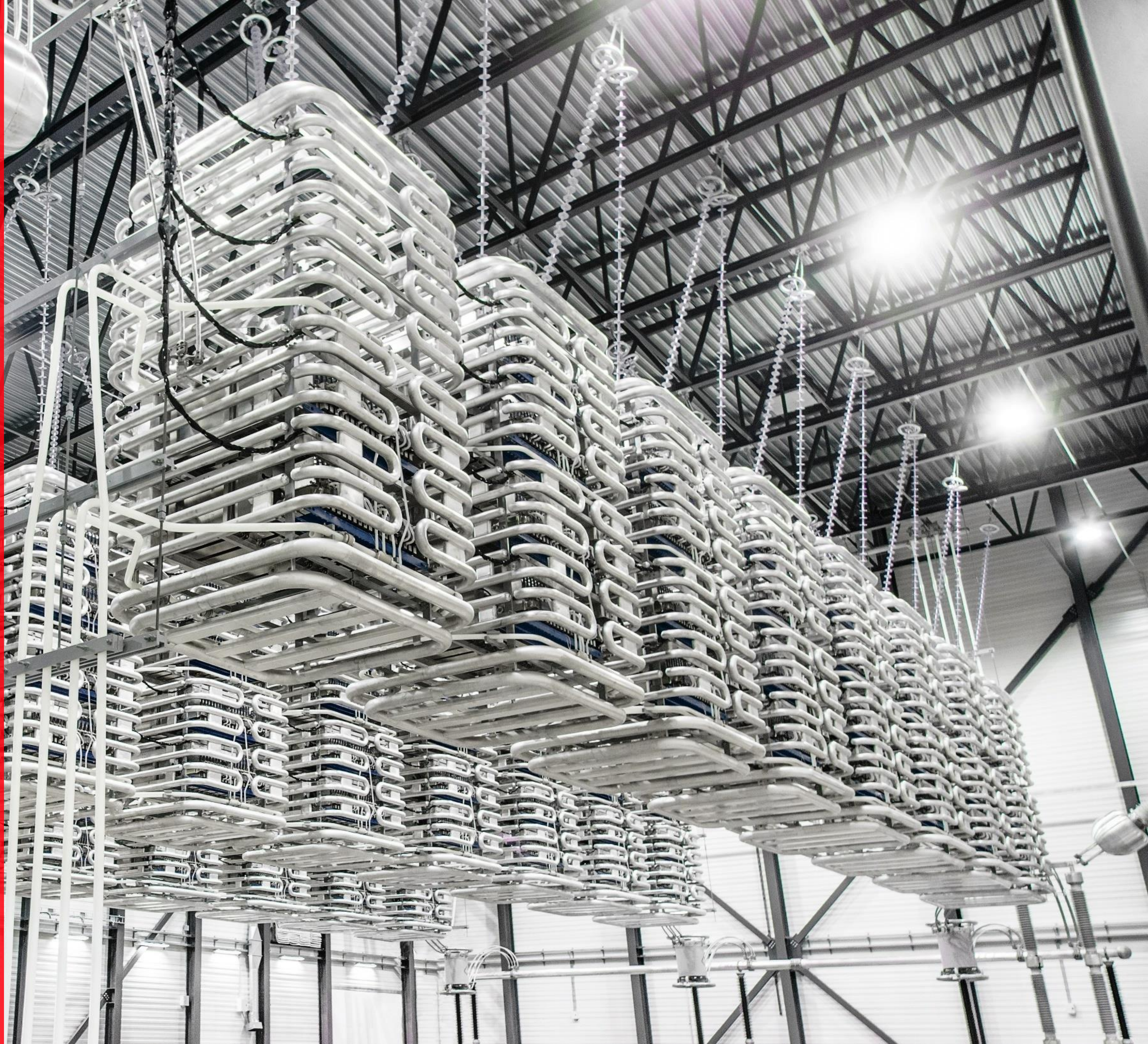
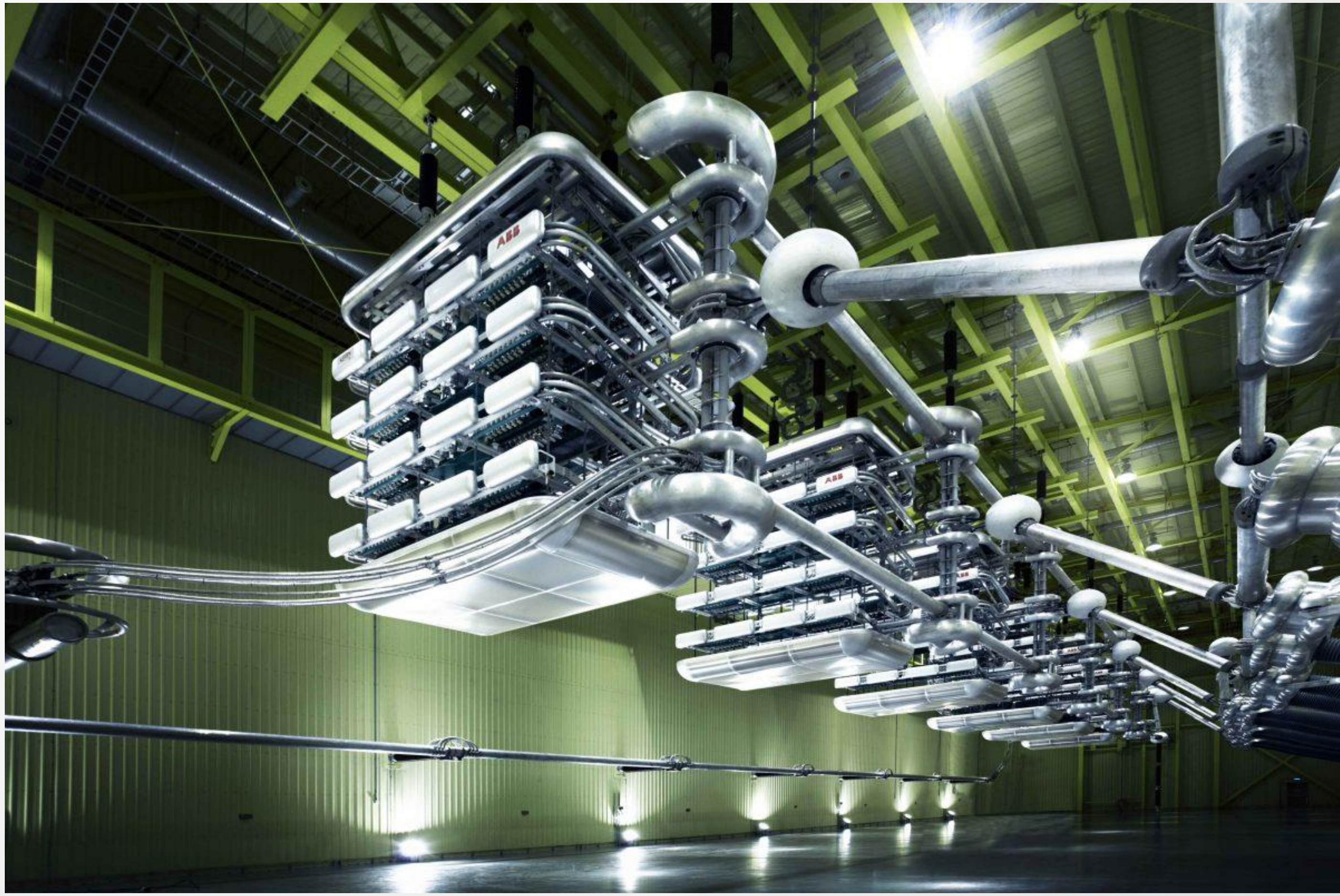


Conclusion
HVDC Flexibility

HVDC systems are ideal for connecting renewable generations as they compensate for power fluctuations that are typical to this kind of energy source.

HVDC converters can adapt to different needs from the transmission grid in different stages of its lifespan which is perfect for a power generation system that will change over time.



ABB