

Recent status and progress on the HTS application of AC and DC power transmission in Korea



Minwon Park, Seok Ju Lee, In-Keun Yu; **Changwon National University**
Youngin Won, Yangho Kwak, Hyungsuk Yang; **KEPCO**
Jin Bae Na, Cheol Hyui Lyu, Seung Ki Park; **LS cable**

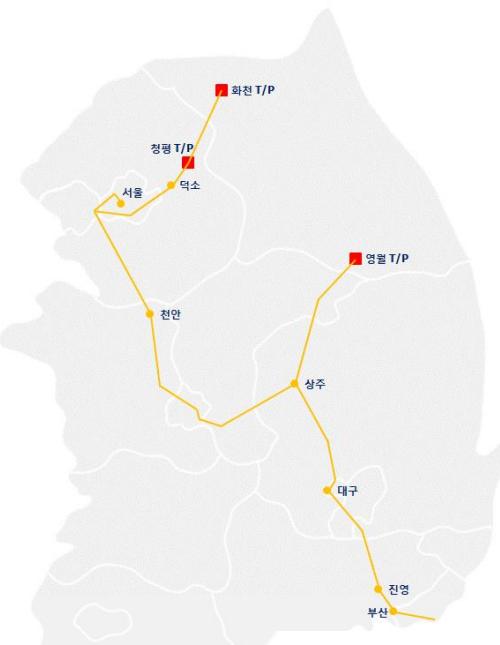
What was changed during last 50 years in Korea?

➤ Development of Korean power network

Ref. 1) www.kepco.co.kr

2) 제7차 전력수급기본계획

Power system in 1965



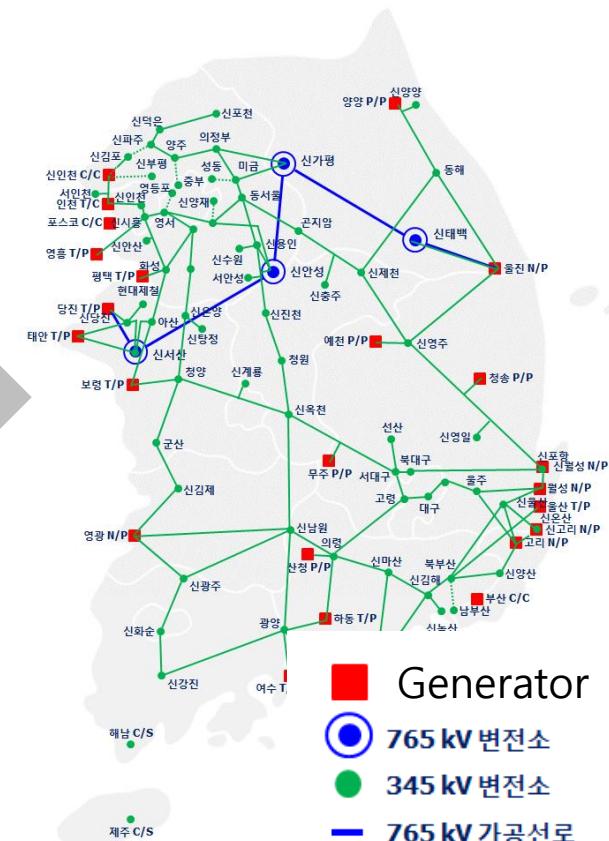
- Generator
- 154 kV
- 154 kV

Power system in 1975



- Generator
- 154 kV
- 154 kV

Power system in 2016



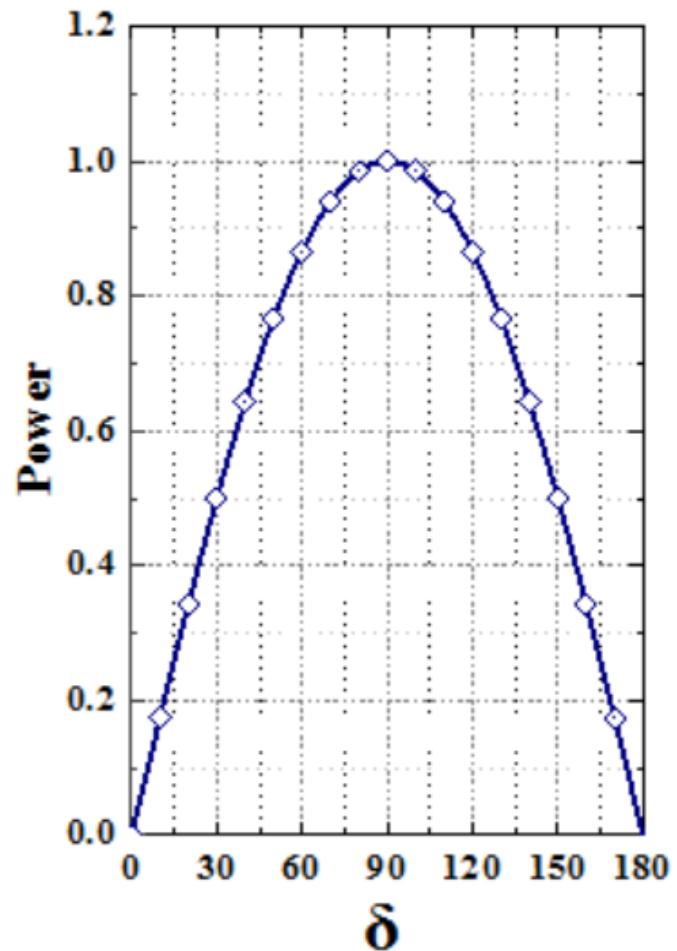
- Generator
- 765 kV 변전소
- 345 kV 변전소
- 765 kV 가공선로
- 345 kV 가공선로
- 345 kV 지중선로

History of the technology development of electricity

$$\mathbf{P} = \mathbf{V} \times \mathbf{I}$$

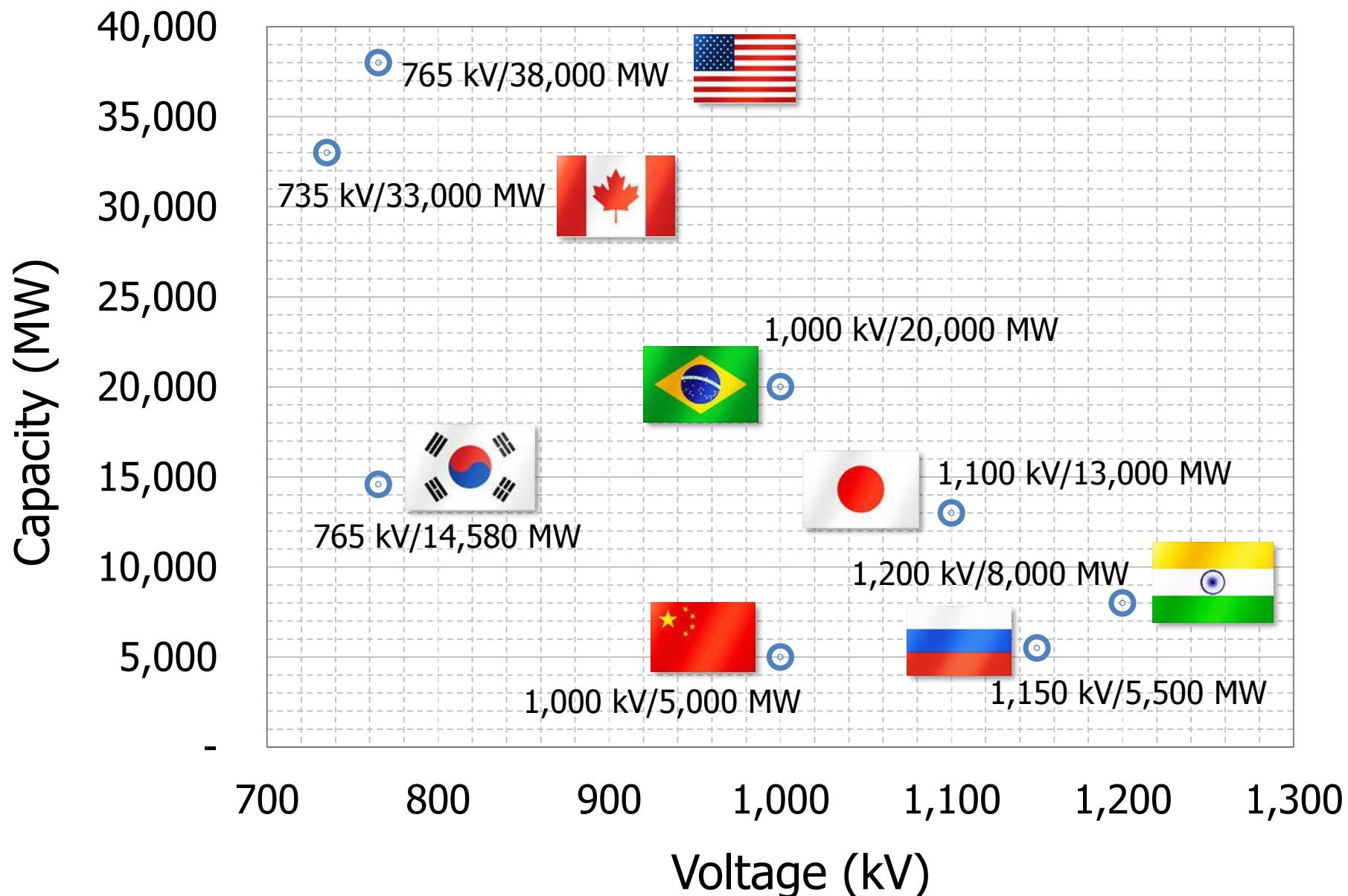
Power loss
 $= r(\mathbf{Cu} \& \mathbf{Al}) \times I^2$

$$\mathbf{P} = \frac{\mathbf{V}_r \times \mathbf{V}_s}{\mathbf{X}_l} \sin\delta$$

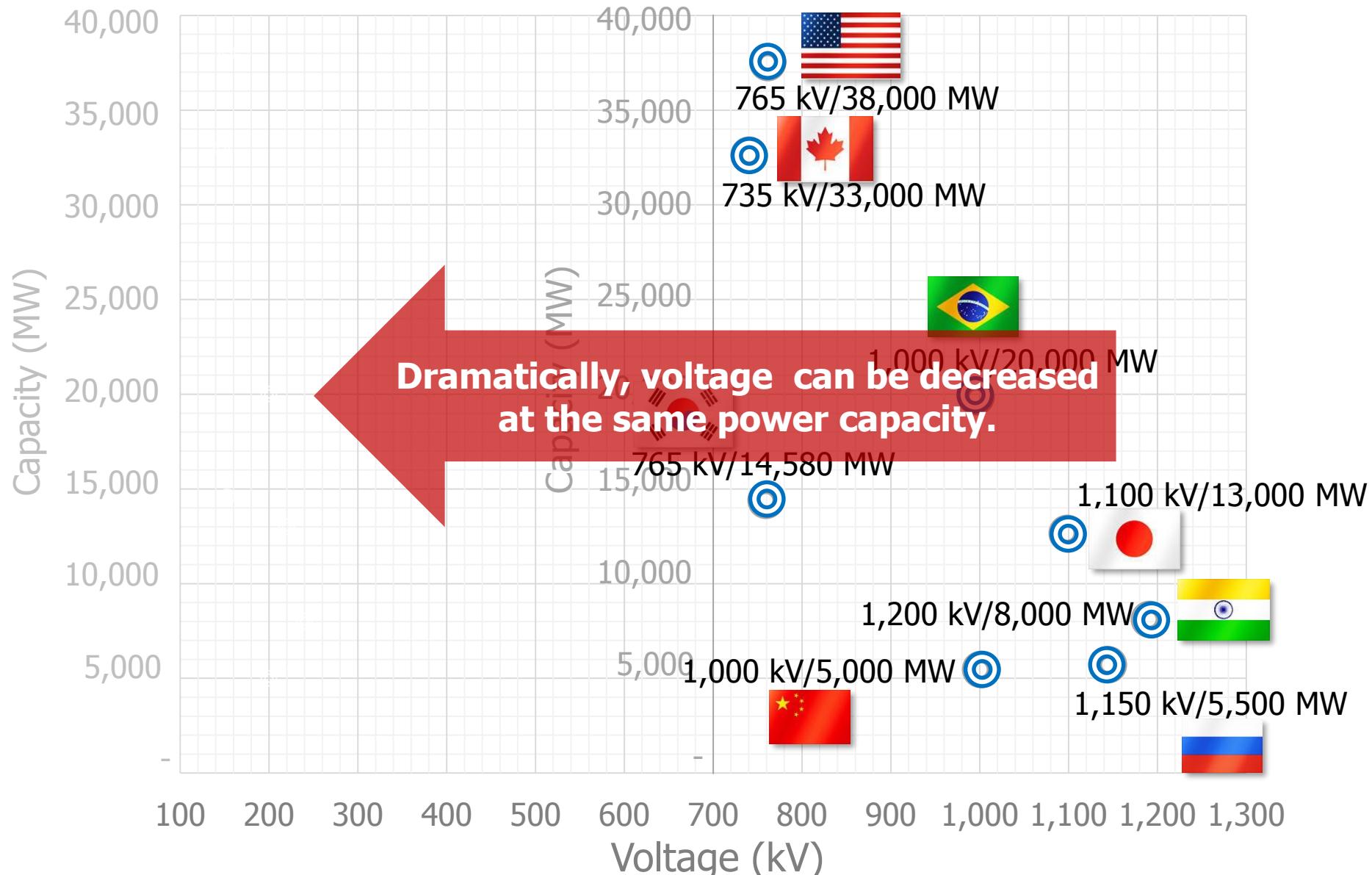


Utility has concentrated on the **increasing of voltage level**.

Worldwide highest voltage level



Just using HTS, 5 times more current without any resistivity in use⁵



Paradigm shift by utility

- Implications of Korean power network
 - Current status and the direction for the future

In technological and scholarly characteristics of power system

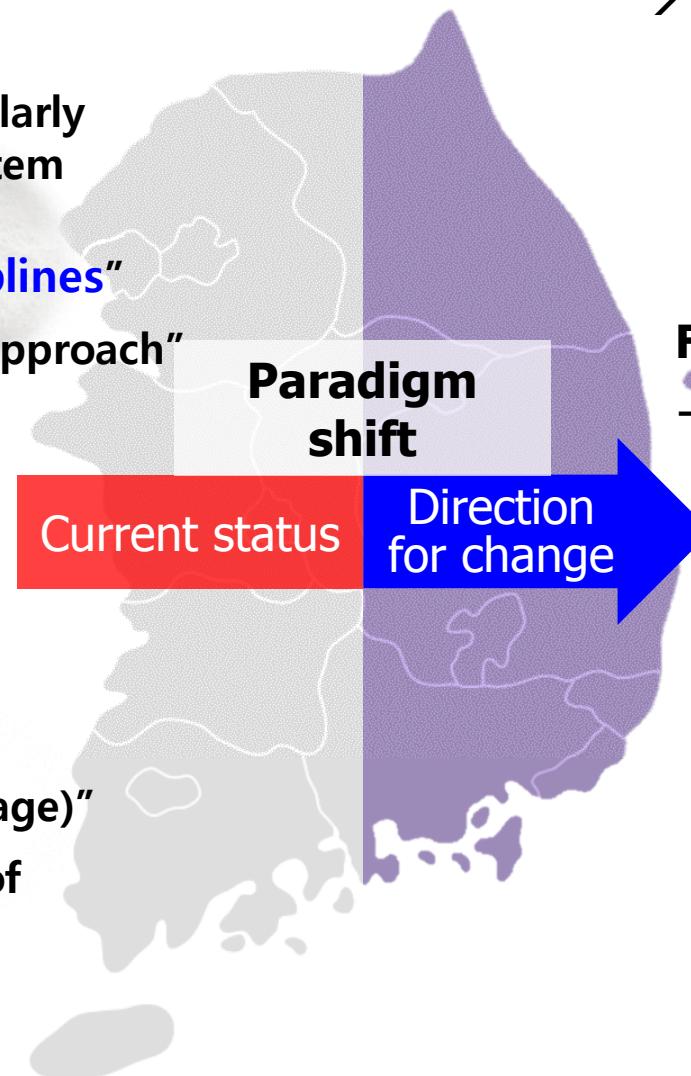
"Image of traditional disciplines"

→ "Trends of conservative approach"

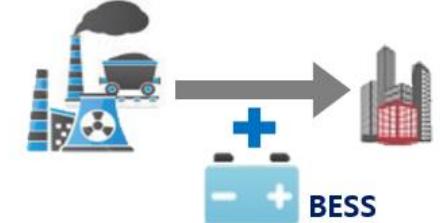
In power application

"Consistent direction (Voltage)"

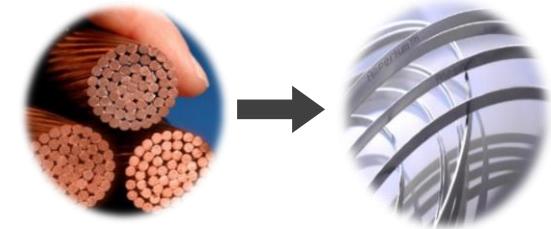
→ "Emphasis on efficiency of power"



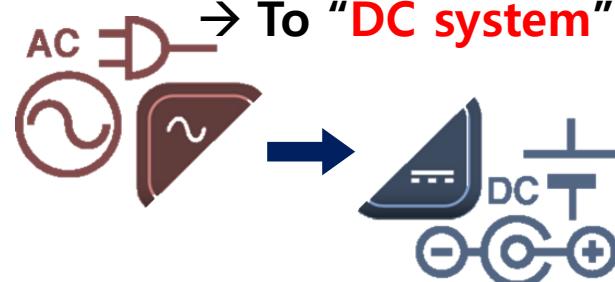
From "Forthright consumption"
→ To "Energy storage"



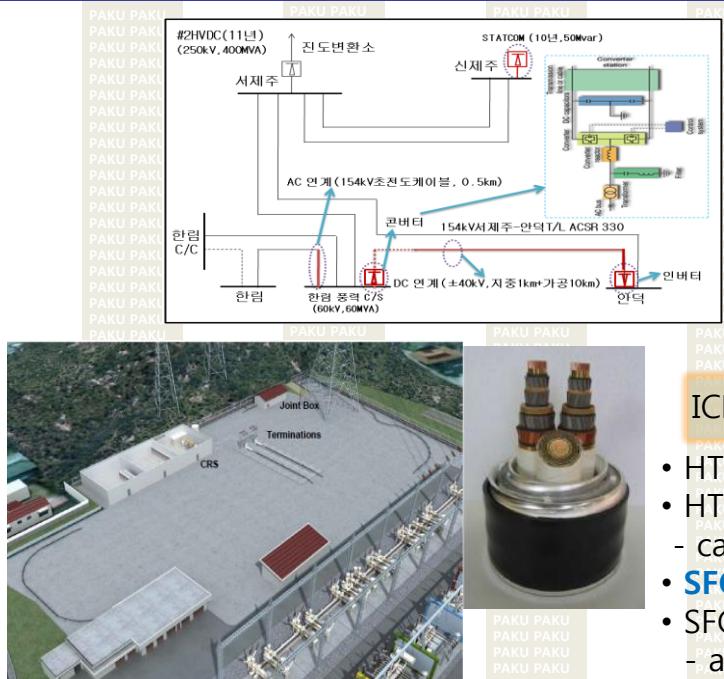
From "Copper & aluminum"
→ To "Ceramic (HTS wire)"



From "AC system"
→ To "DC system"



HTS power application R&D in Korea last 15 years (2001~2016)



DAPAS(2001.06~2011.03), 10M\$/yr

- HTS Power **cable**; 22.9kV and 154kV class (KERI, LS, KEPRI, etc.)
- HTS **Xsfm**; 154kV class core technology (KPU, etc.)
- **SFCL**; 22.9kV, 600A and 3kA class, 154kV core tech. (KEPRI, LS, etc.)
- HTS **Motor**; 5MVA class (DHI, KERI, etc.)
- **2G wire**; 1km, 500A/cm_width (KERI, SuNam, etc.)
- **CAST (Project Management)**

ICHEON(2009.01~2013.12), 5M\$/yr

- HTS Power **cable**; 22.9kV, 50MVA, 500m (KEPRI, LS, KERI, etc.)
- HTS Power cable; 22.9kV, 150MVA 100m
 - cable all grid connection
- **SFCL**; 22.9kV, 630A class (KEPRI, LS, etc.)
- SFCL; 22.9kV, 3kA class
 - all grid connection
- **KEPCO (funded and grid opened)**, Korea has only one utility company



JEJU Project(2011.07~2016.10), 10M\$/yr, 5yrs

- HTS DC Power cable; 80kV, 60MVA, 500m
- HTS AC Power cable; 154kV, 500m
 - cable all grid connection to deliver wind farm power
- SFCL is also considered to connected to grid
- **KEPCO (funded and grid opened)**

What was changed last 15 years

- **3 HTS power cables**(AC 22.9kV, AC 154kV, DC 80kV) were installed in real test grid.
- 1 HTS power cable(AC 22.9kV) is ready to be commercially available.
- **2 SFCL**(AC 22.9kV, 154kV) were connected to the real test grid.



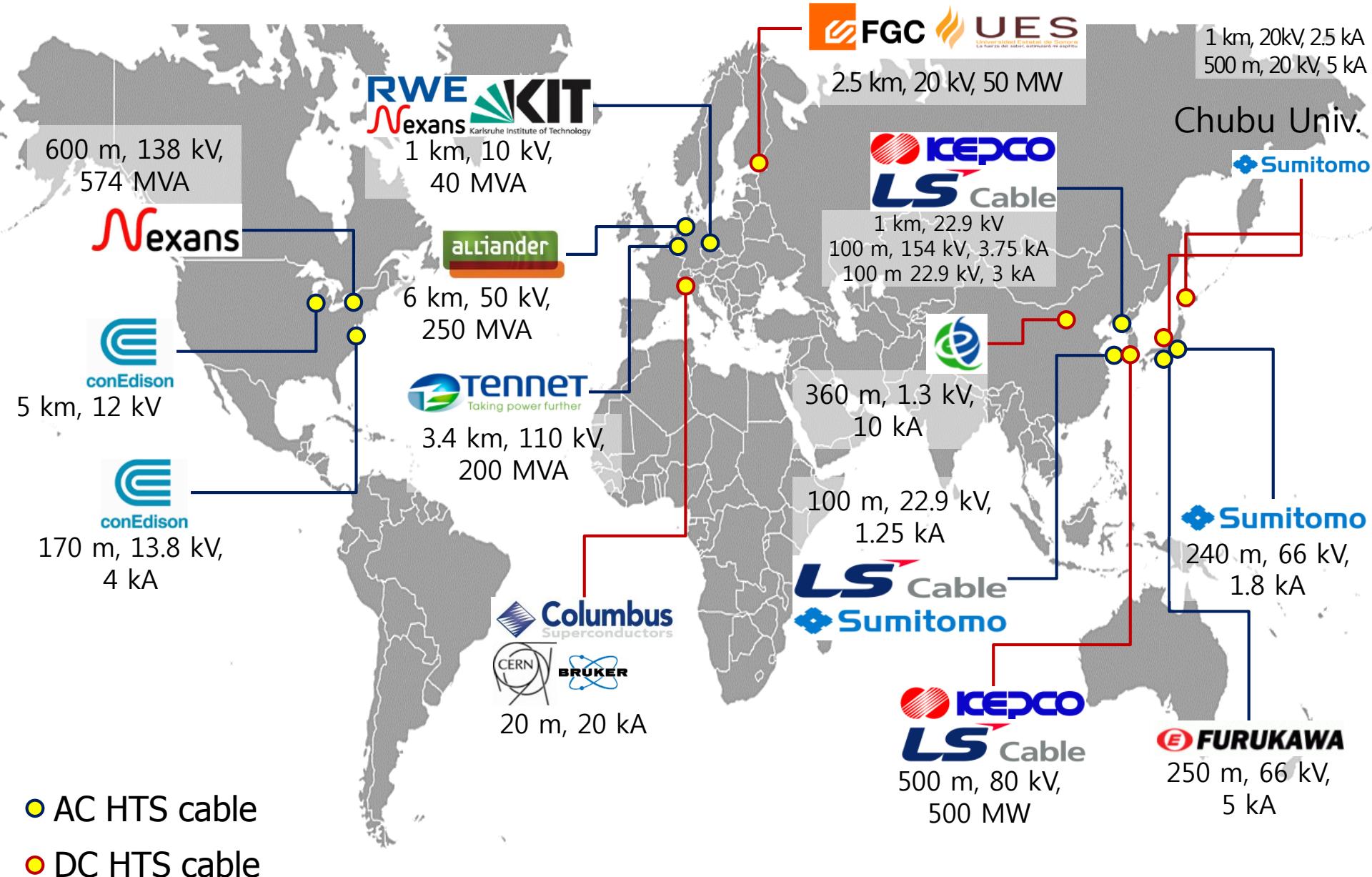
- World class 2G HTS wire company(SuNAM) was established.



HTS Power Cable



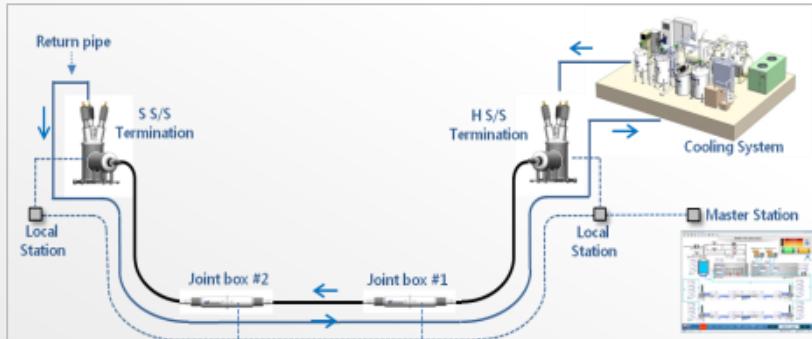
Worldwide HTS power cable projects



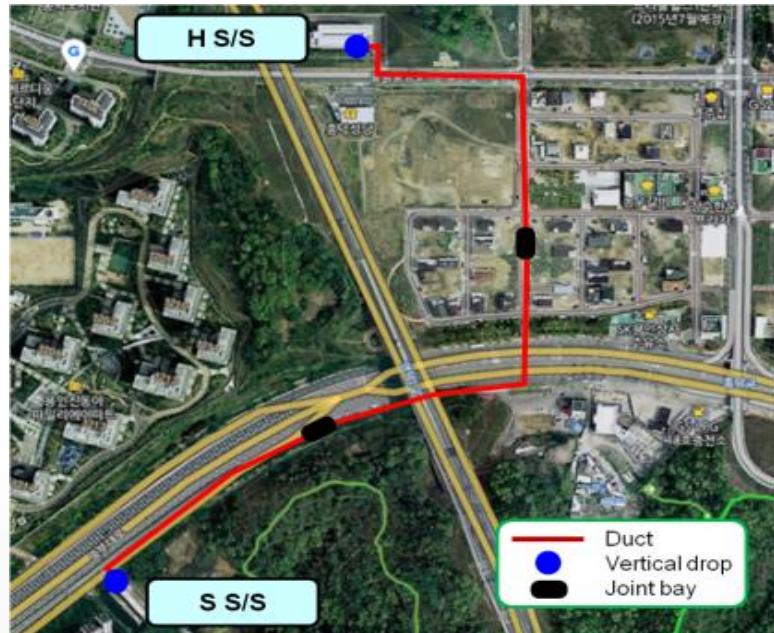
R&D in advance ▶ Pilot demonstration ▶ Commercialization

First commercialization

- Shingal project: **100% funded by KEPCO**
 - Project period: Sep., 2016 ~
 - System configuration: AC23kV 50MVA, 1km-cct + 7.5kW @69K Turbo Brayton Cooling system
 - Project cost: USD10M
 - Type test in progress

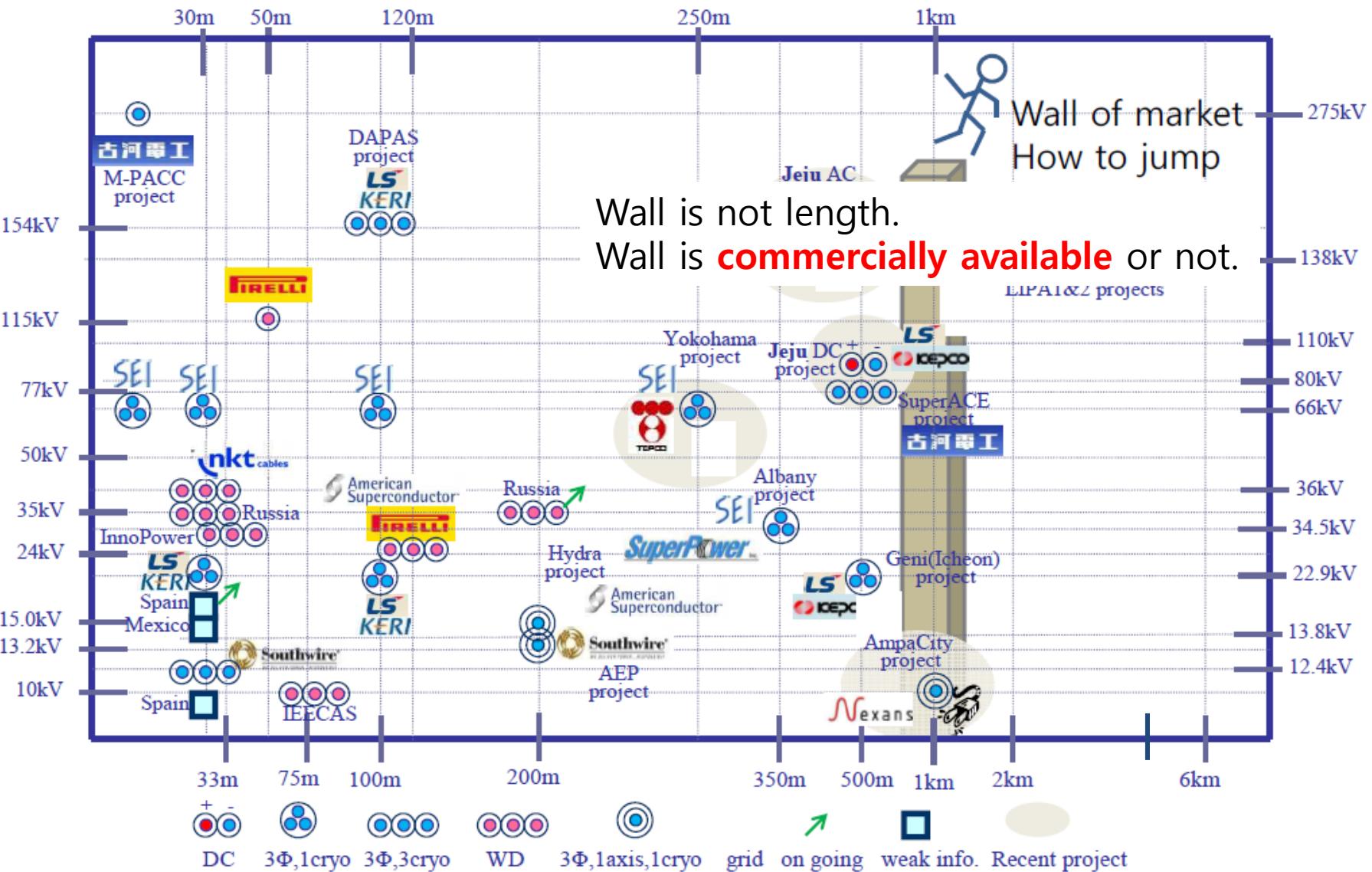


System configuration



Installation Site

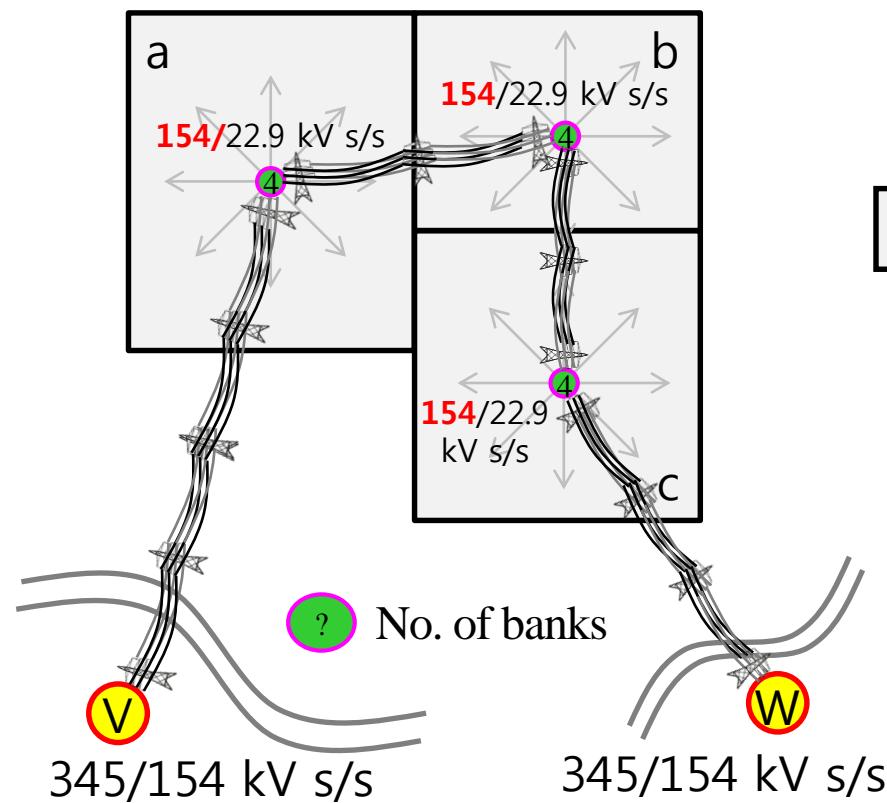
HTS power cable graph (Length x Voltage)



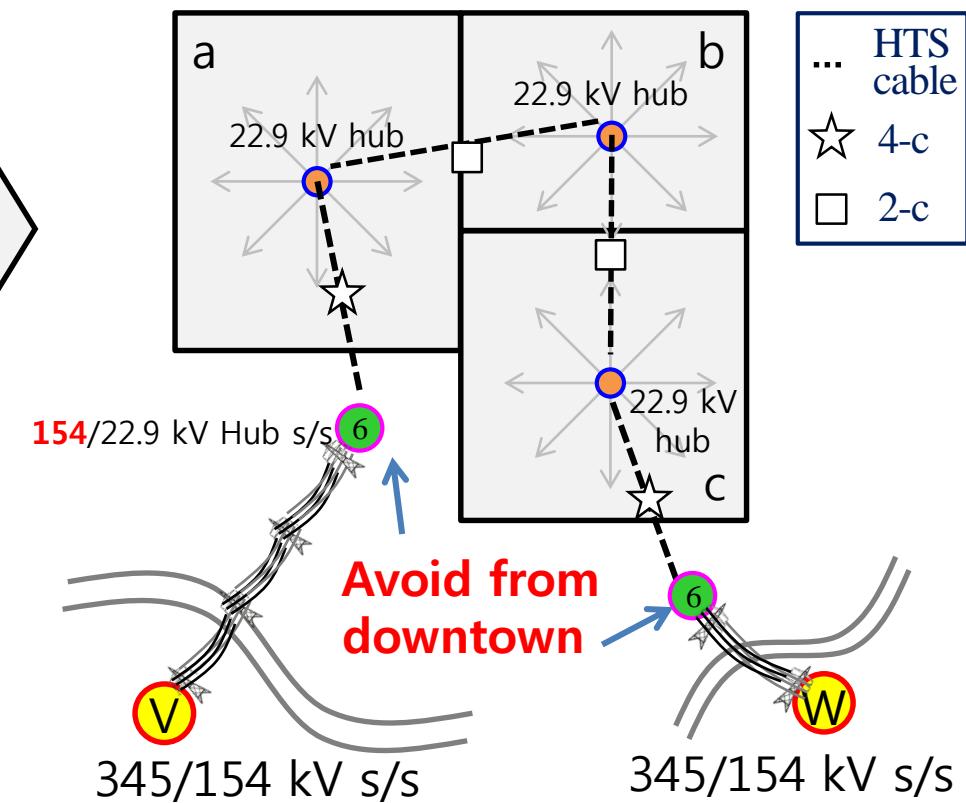
Concept of 23kV HTS power cable application for commercialization

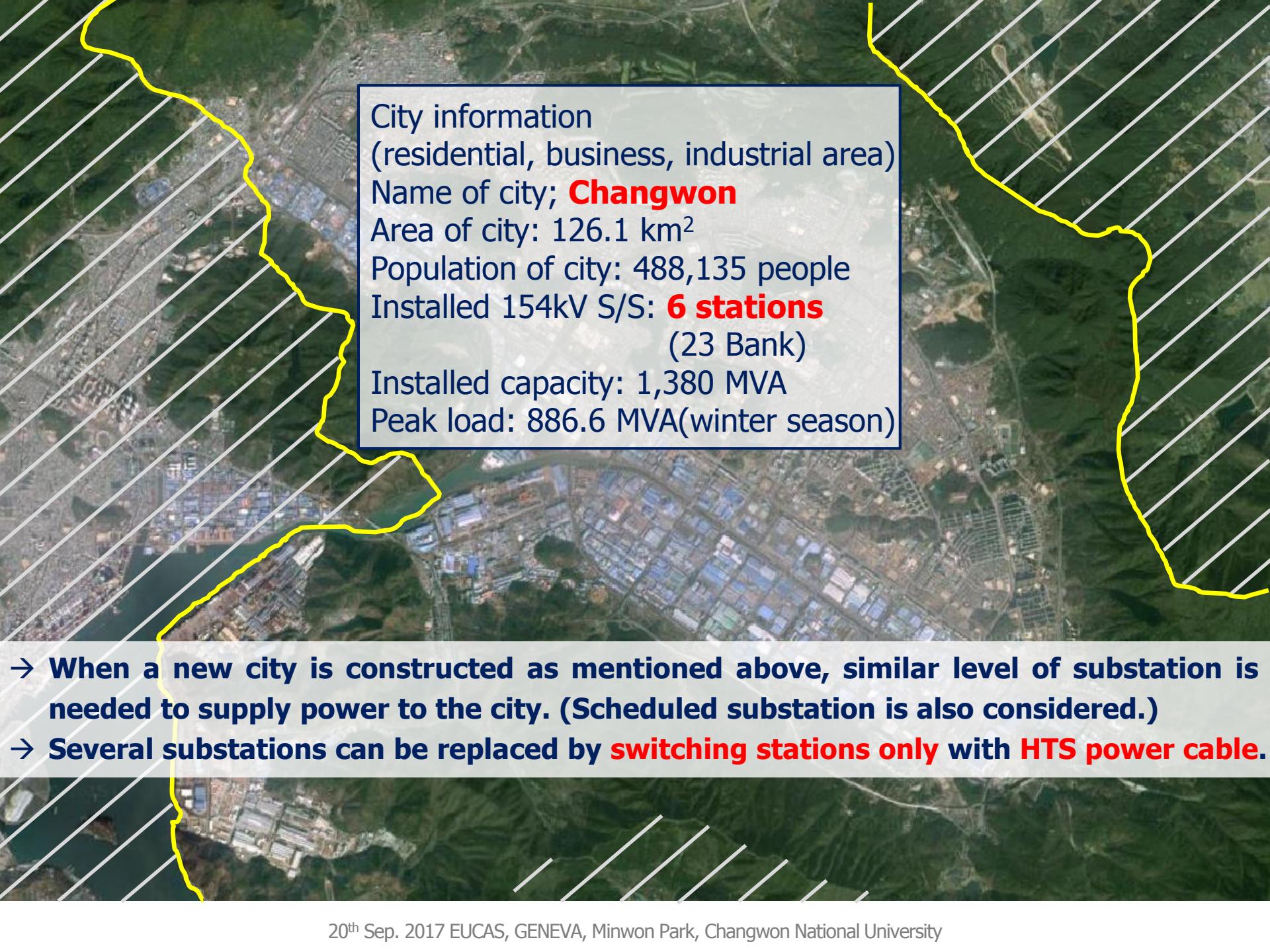
- In order to achieve the economic advantage of HTS power cable,
- a new concept of 23kV HTS power cable was proposed.
- And, more detail economic benefit from analysis was done.

Conventional power network



HTS power network
(3 s/s → 2 hub s/s)





City information
(residential, business, industrial area)
Name of city; **Changwon**
Area of city: 126.1 km²
Population of city: 488,135 people
Installed 154kV S/S: **6 stations**
(23 Bank)
Installed capacity: 1,380 MVA
Peak load: 886.6 MVA(winter season)

- When a new city is constructed as mentioned above, similar level of substation is needed to supply power to the city. (Scheduled substation is also considered.)
- Several substations can be replaced by switching stations only with HTS power cable.

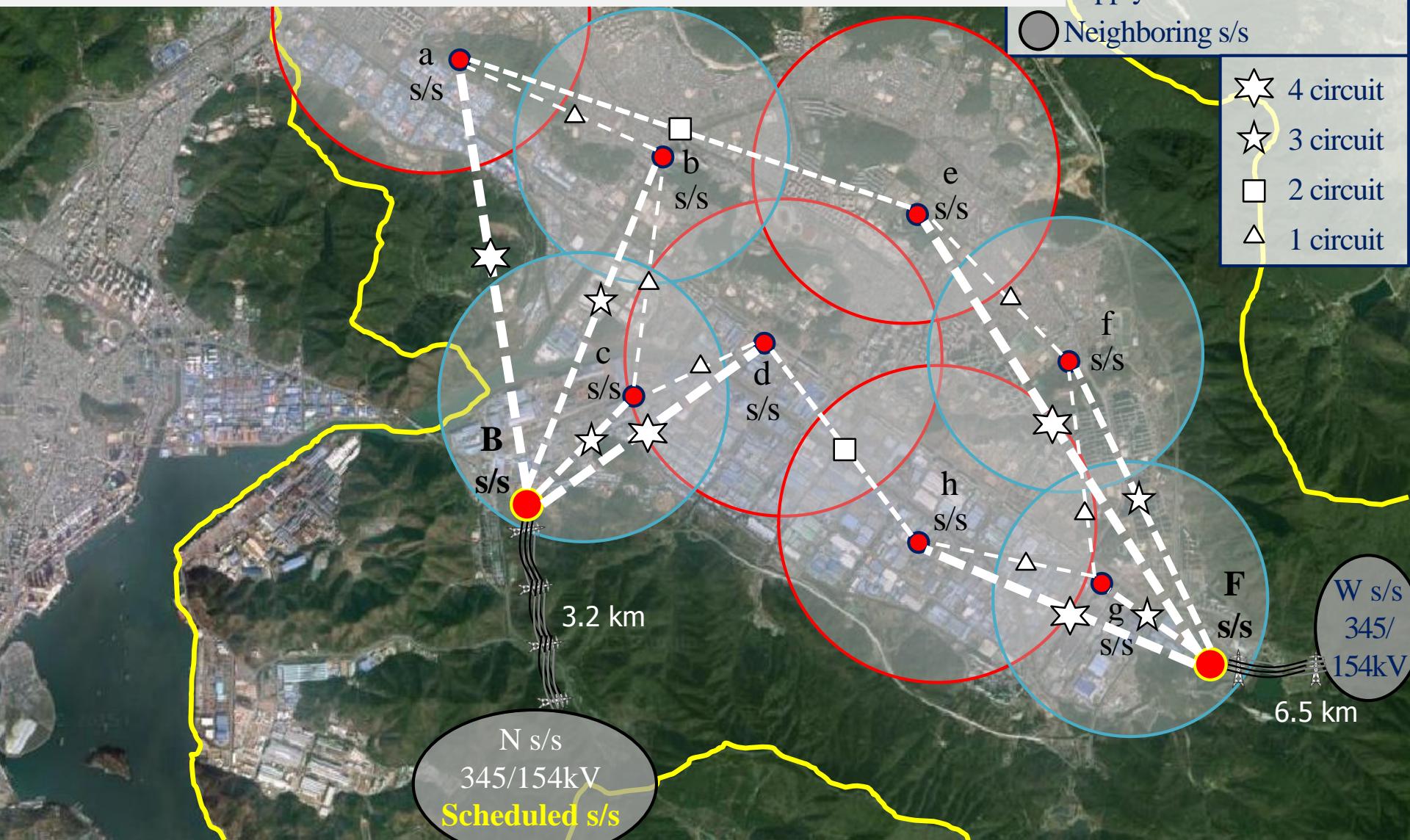


HTS station using tri-axial HTS power cable

5km is very enough length to cover the distance of S/S to S/S.
This is one of the next targets of HTS power cable.

- 154/22.9 kV Hub substation
- 22.9 kV switching substation
- Supply area
- Supply area

Neighboring s/s

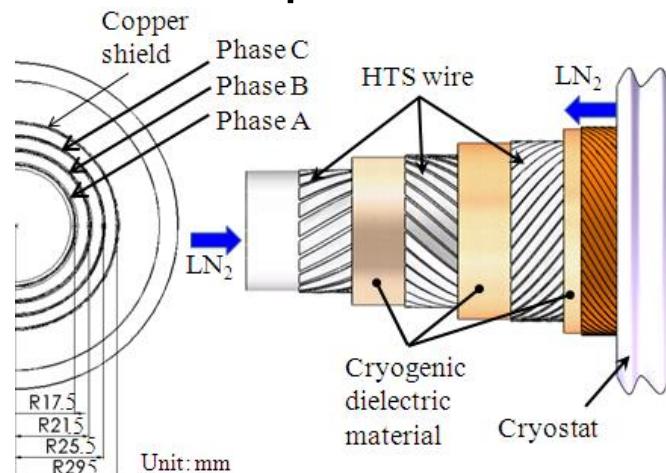
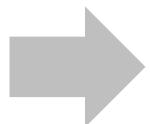
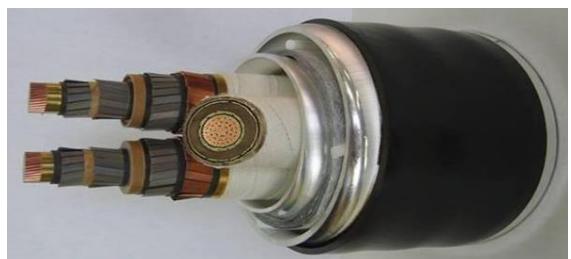


→ The city receives electric power based on two hub-stations with tri-axial HTS power cables.

2km class tri-axial HTS power cable project



- Period; 2017~2021 (5 years)
- Budget: 30M USD/5yrs (fully funded by KEPCO)
- Participants: KEPCO, KEPRI, LS cable(cable supplier), and Changwon National University(core design)
- Scope
 - 23kV, 50MVA, Co-axial HTS power cable development
 - 3km class cooling system development for power cable
 - 23kV HTS power network protection algorithm development
 - 100m HTS power cable test
 - ~2km HTS power cable installation in real power network



New project roadmap of HTS power cable was established.

Now, here



Why utility company is interested in HTS power cable in Korea



Public nuisance along with voltage



Milyang city 765kV strong resistivity
2 people suicided
7 years construction stopped
(2007-2014)



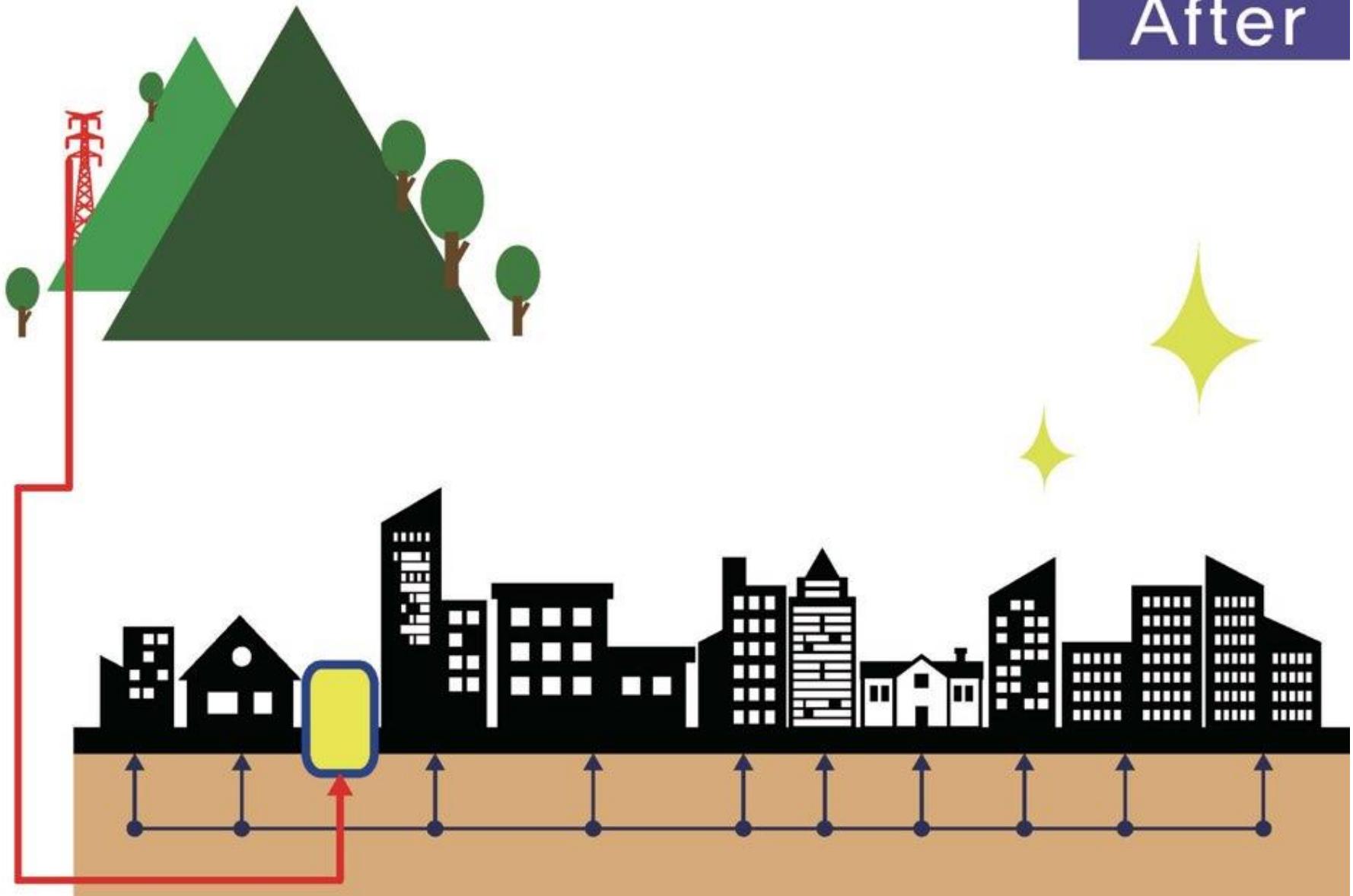
Now power line in downtown

Before



Future in downtown

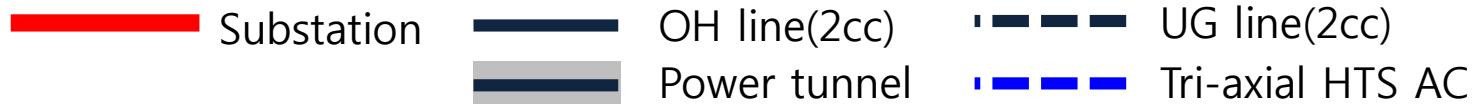
After



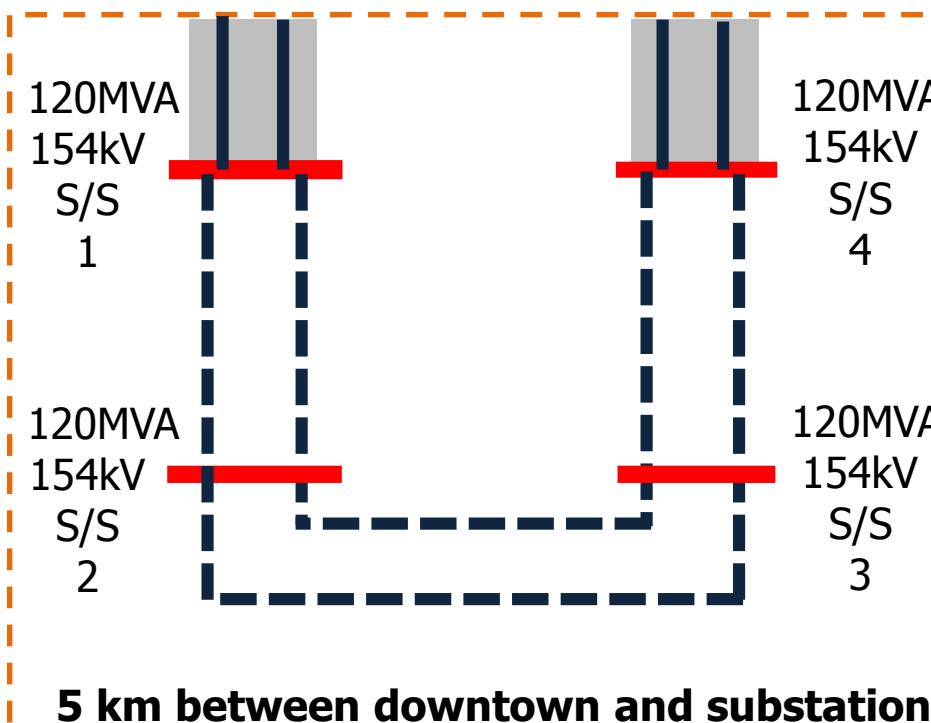
Move substation back behind mountain and avoid downtown

2~3km is enough to get the economical benefit.

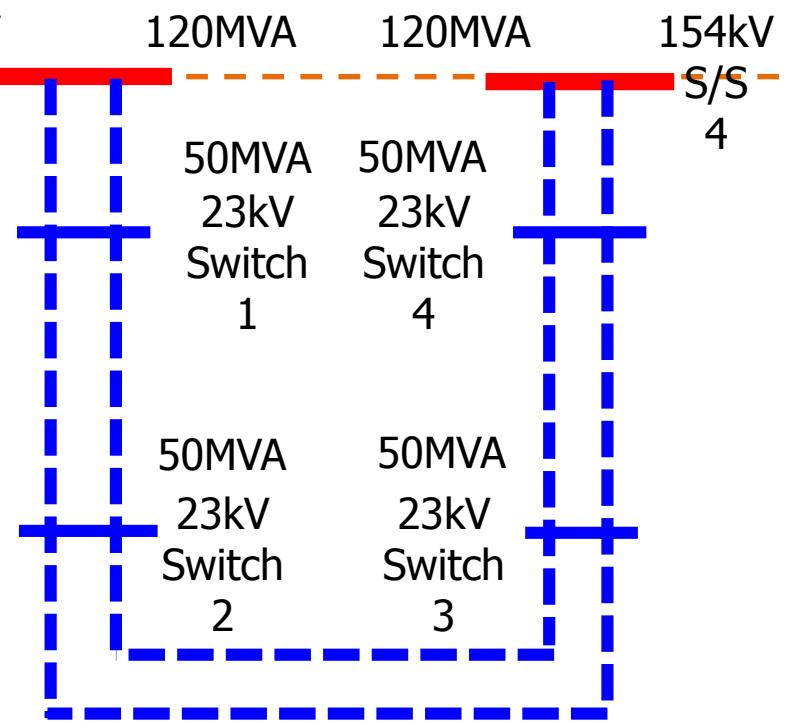
- No power tunnel(154kV), using power duct(23kV), and very cheap substation land



Conventional network



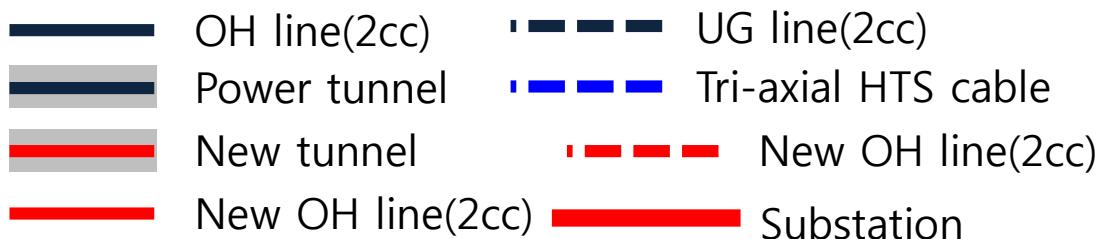
Superconductivity platform



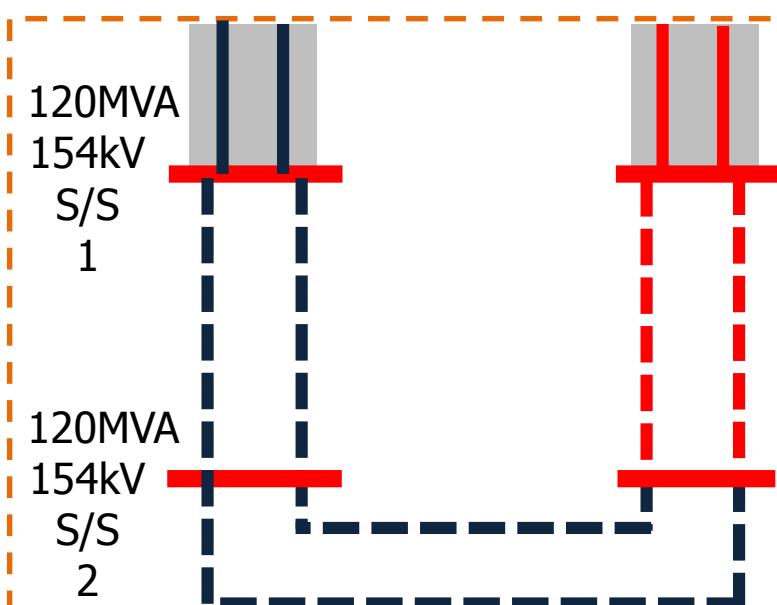
5 km between downtown and substation

Newly required substation; one HTS cable and one OH

More power from superconductivity platform

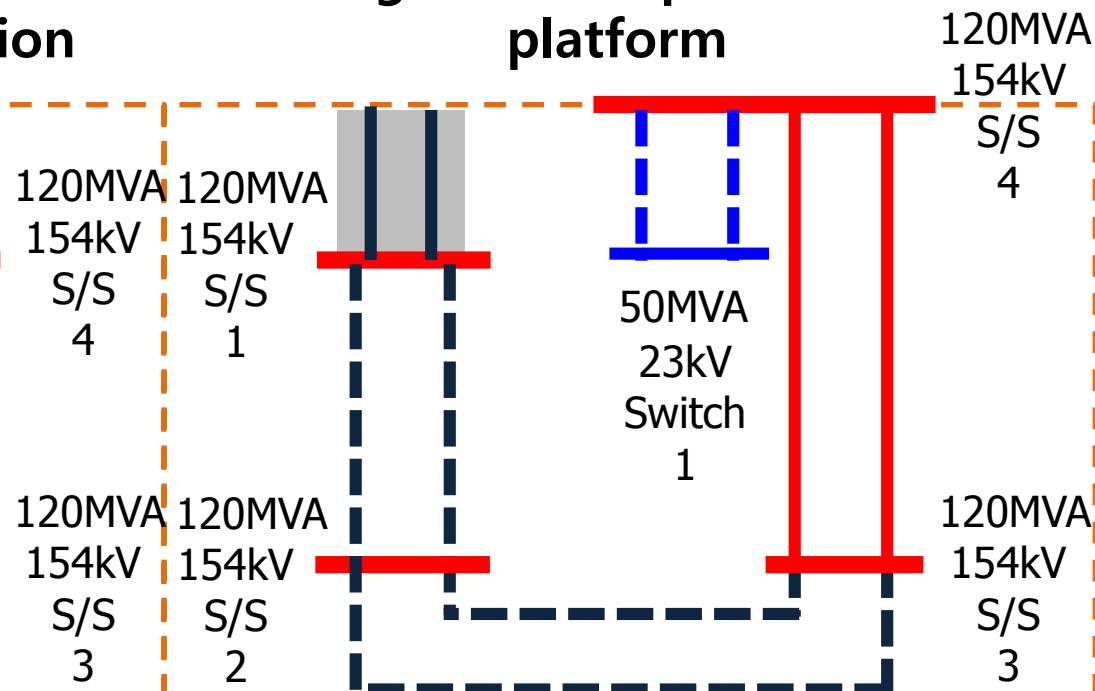


Conventional network ; needs one more substation



5 km between downtown and substation

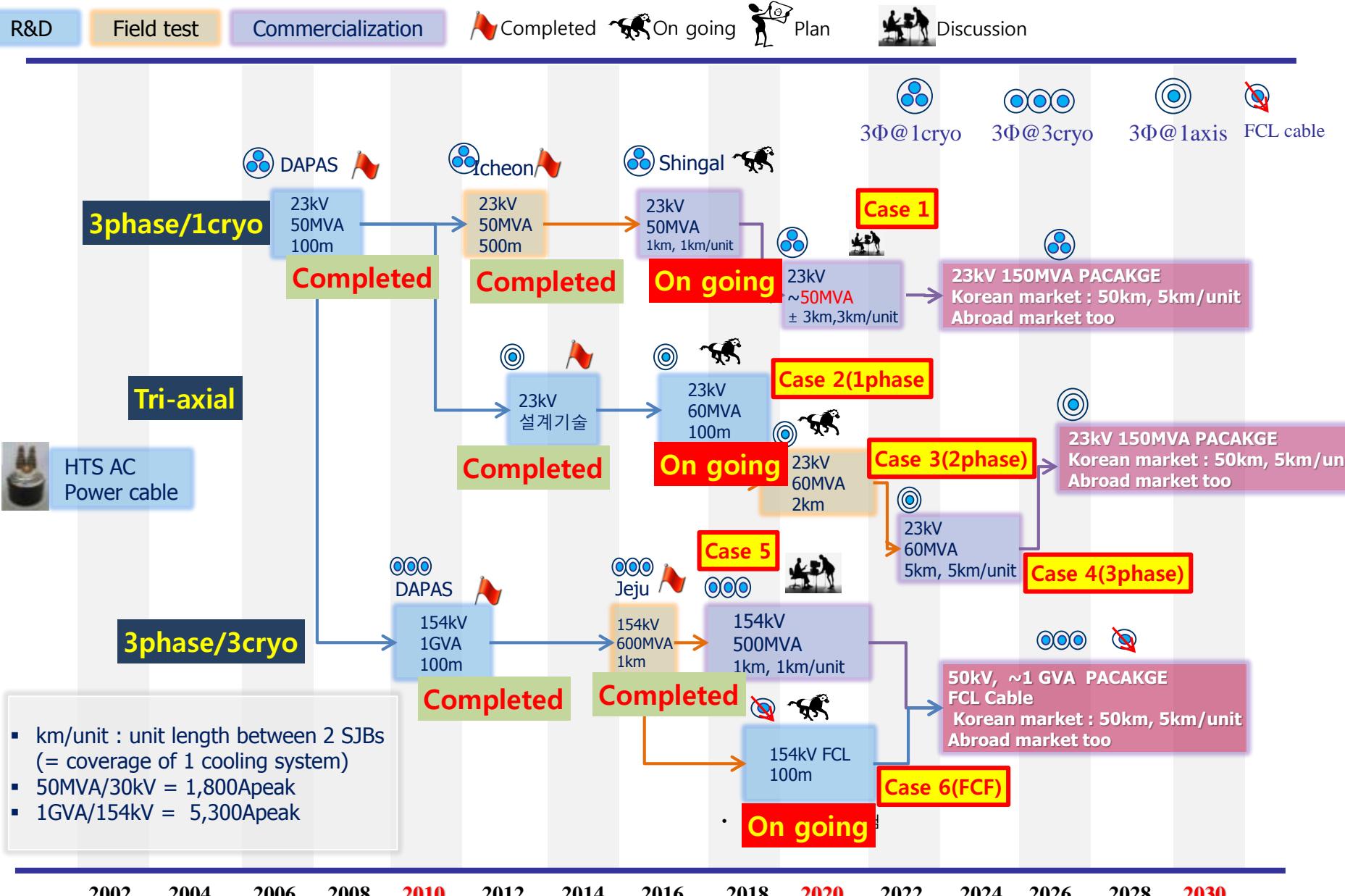
Using one HTS power cable platform



Planning of HTS power cable in Korea



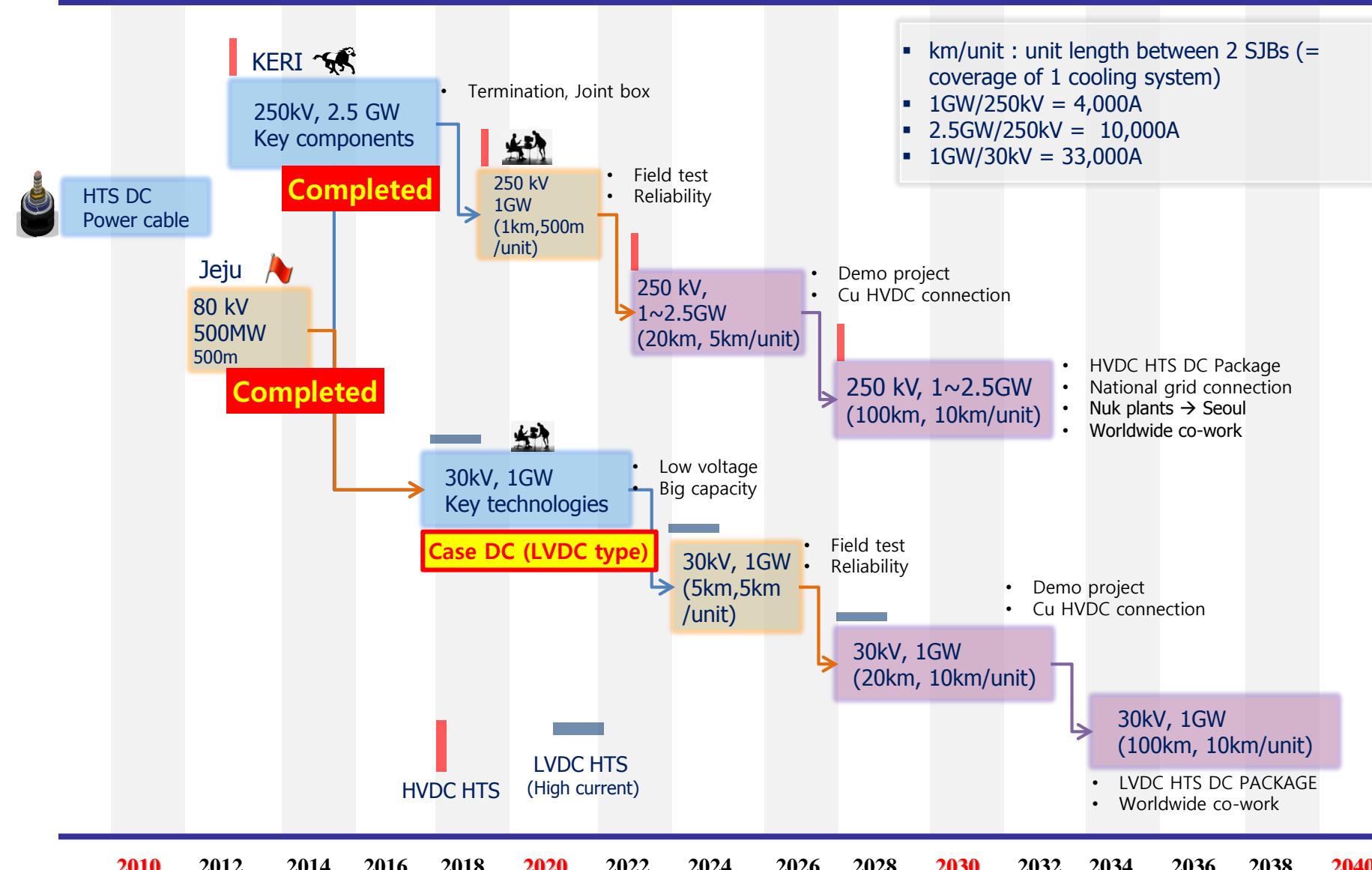
AC HTS power cable roadmap



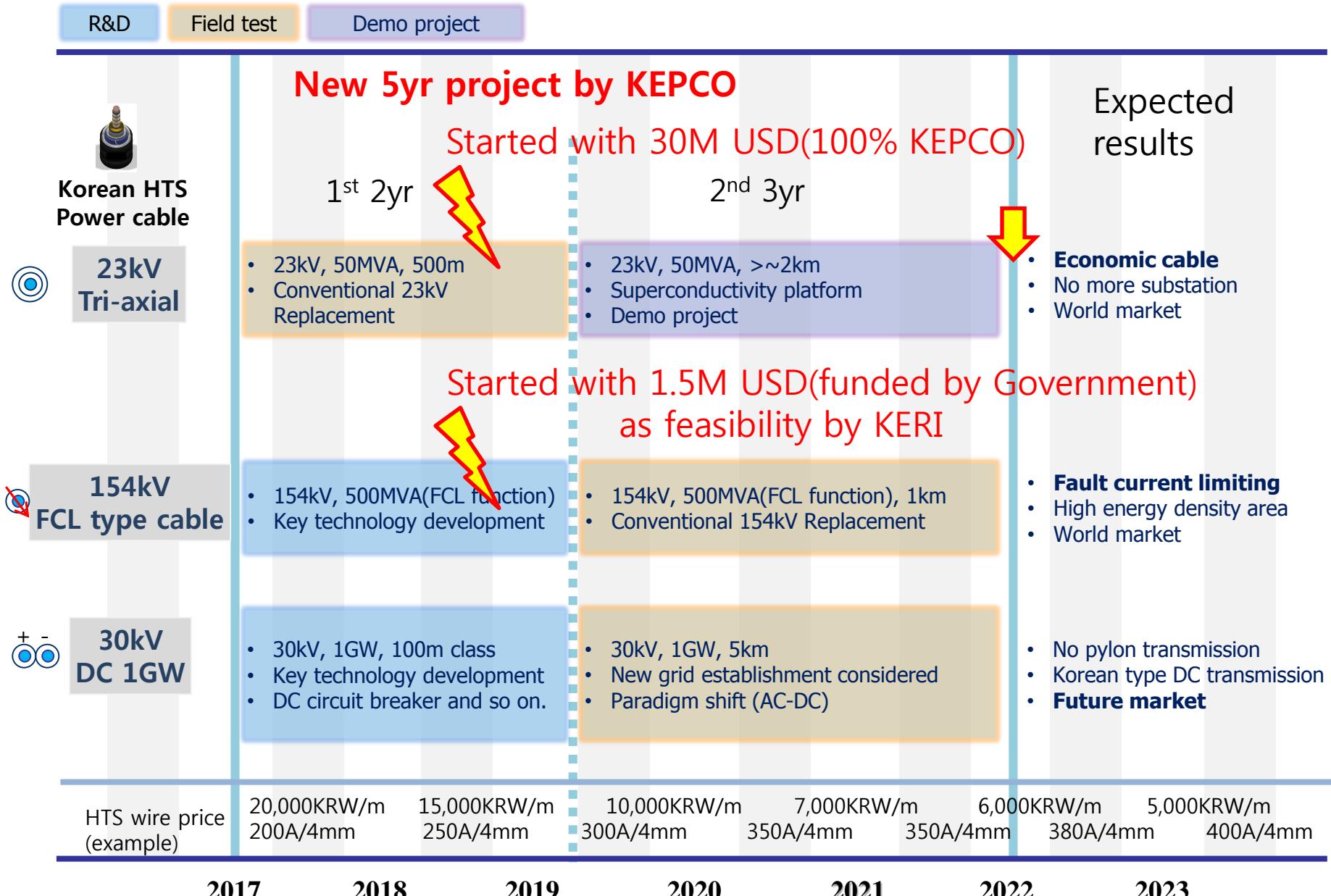
20th Sep. 2017 EUCAS, GENEVA, Minwon Park, Changwon National University

DC HTS power cable roadmap

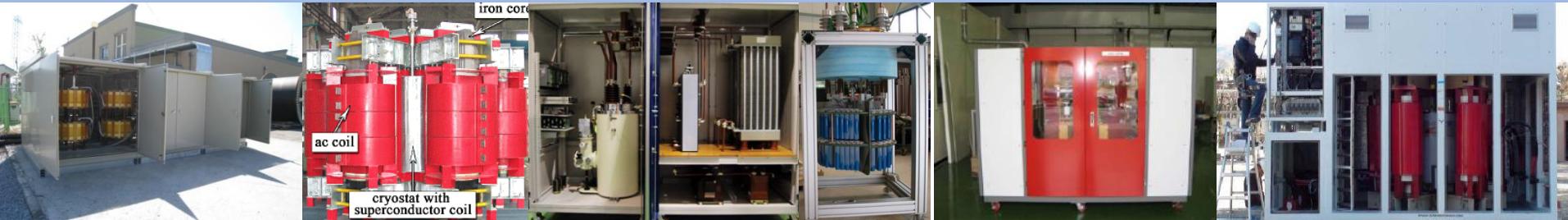
R&D Field test Commercialization Completed On going Plan Discussion



DAPAS → Icheon → Jeju → New project(Proposed 2016)



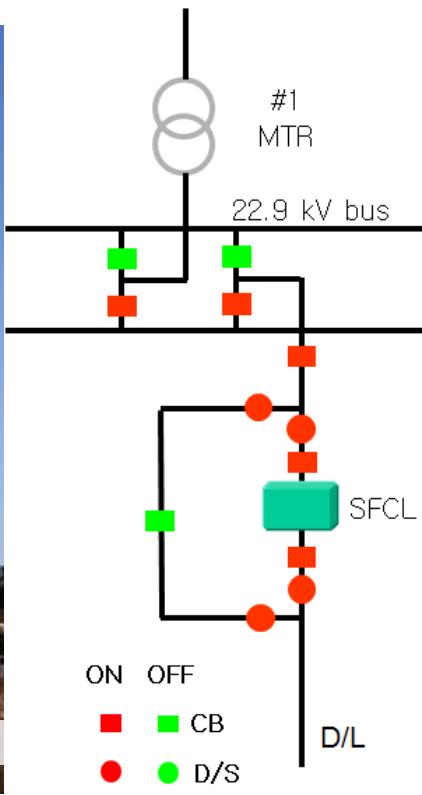
HTS Fault Current Limiter



➤ HTS SFCL in 22.9 kV grid at Icheon substation

- SFCL operation (commercial operation)
 1. Dec. 2010 – SFCL installation
 2. 23 Aug. 2011 - energized
 3. Currently under commercial operation
(To protect a 22.9 kV feeder)
 4. Fault (Feb. 2012) – SFCL properly worked

- SFCL
 1. 22.9 kV, 630 A, hybrid SFCL
 2. SFCL interruption under fault current
 1. < 1.2 kArms : No action
 2. > 1.4 kArms : Instantaneous action
 3. Limiter impedance : 400 mΩ



154kV SFCL installed in real grid for testing

- 154 kV/2,000 A class HTS SFCL (Withstand voltage tests)



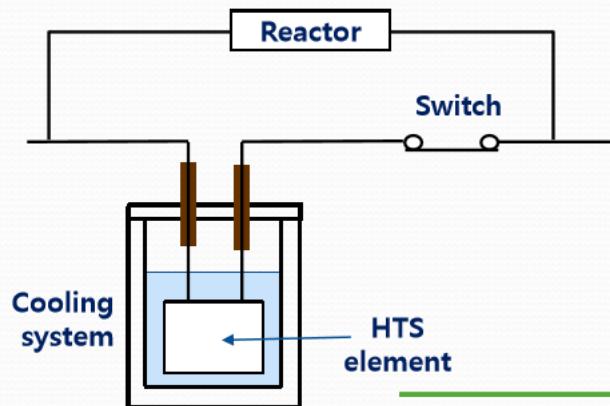
It is waiting for real fault current even now.



- A resistive type combined with normal-conducting components

- Components of the SFCL

- HTS element: detects and limits fault current
- Cooling system: cools the HTS element
- Switch: protects the HTS
- Reactor: limits the fault current



Parameter	Specification
Rated voltage (rms)	170kV
Rated current (rms)	2,000 A
Rated power frequency	60 Hz
Rated AC withstand voltage (rms)	325 kV
Rated impulse withstand voltage	750 kV. BIL
Rated short circuit current (rms)	50 kA
Operation temperature (K)	71 K



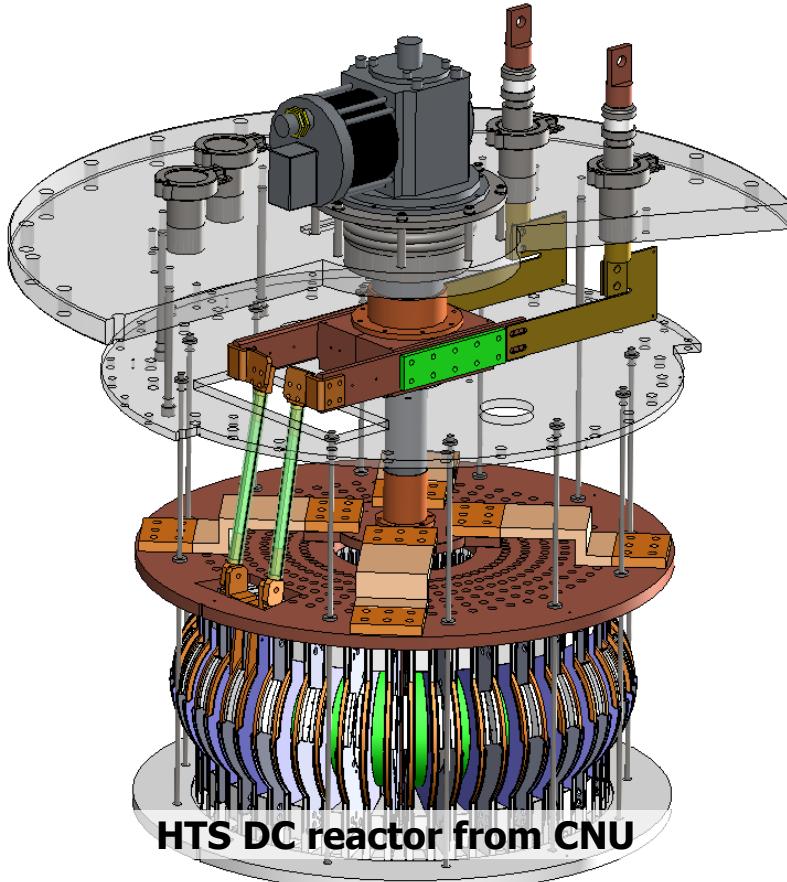
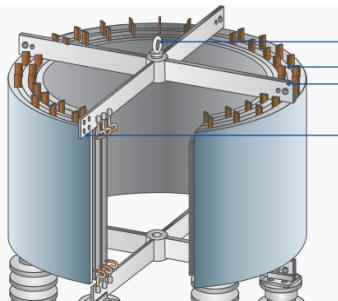
- Now, more than several months very stable operation.
- Single phase 154kV SFCL, design, fabrication, installation, and operation.
- Three phase system will be developed soon.
- Real grid demonstration might be around 2019.

HTS DC reactor



Concept of the HTS DC reactor

- Shape of the conventional reactor



- Conductor of the reactor magnet

- Conventional reactor



< Copper or aluminium >

- HTS DC reactor



< HTS wire >

- Characteristics of the HTS DC reactor
 - Operation condition : DC
 - Conductor type : HTS wire
 - Magnet type : Air dry core & toroid-type
 - Operation temperature : < 77 K
 - **No electrical loss (Zero electric resistance)**
 - **No Flux leakage (toroid-type)**
 - Reduce the reactor's size, weight and space

Advantage of the HTS DC reactor

- Size advantage of HTS DC reactor (Same scale, without insulator)

Ref : SIEMENS



Basically a “mechanical” Issue

HTS DC reactor is **one of the solution**
for **support load problem** of large scale DC reactor

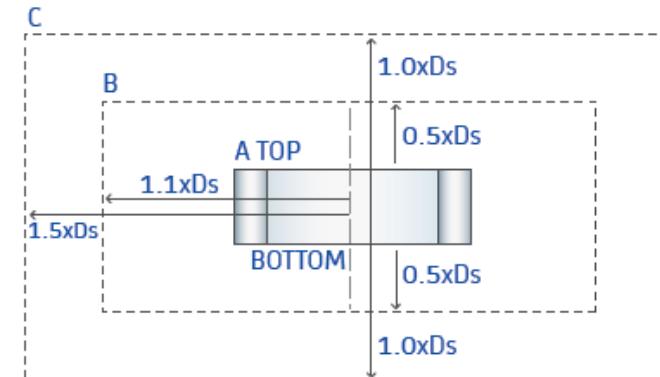
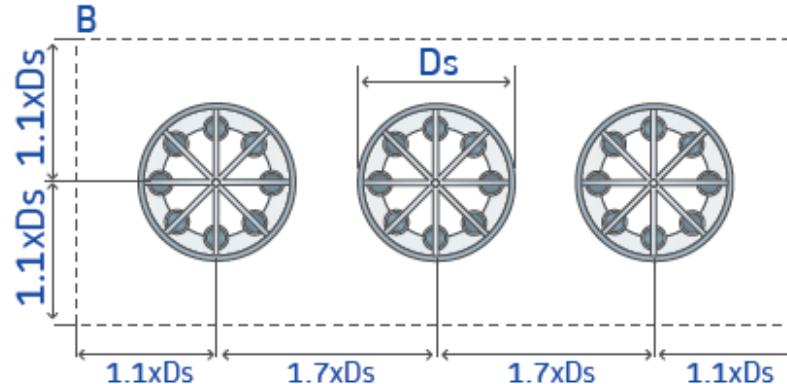
Advantage of the HTS DC reactor

- Install space of the reactor considered magnetic clearances (ref : ALSTOM)

→ A : Reactor outer surface, D_s : Reactor outer diameter

→ Keep metallic parts not forming closed loops out side B

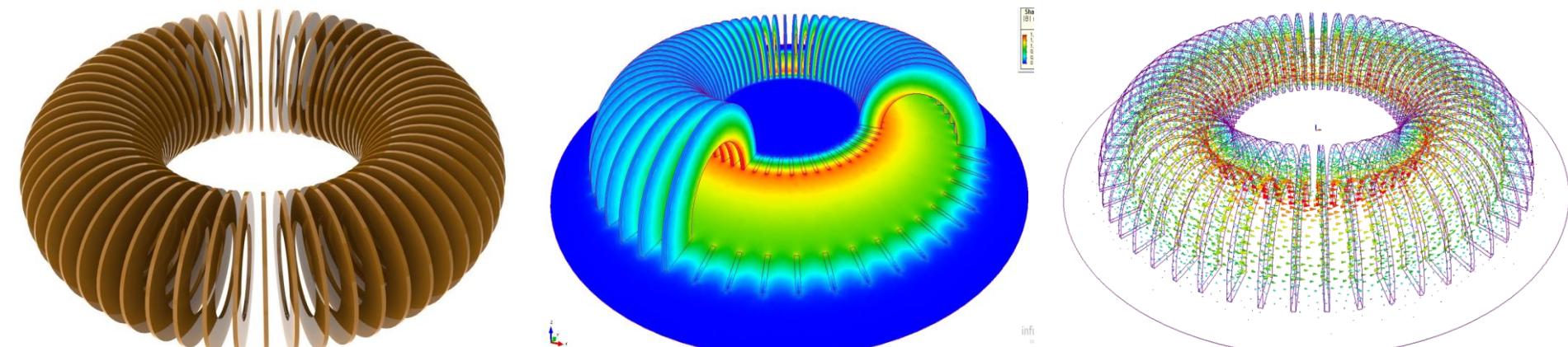
→ Keep metallic parts forming closed loops or large metallic parts outside C



- Magnetic field distribution of the HTS DC reactor (toroid-type)

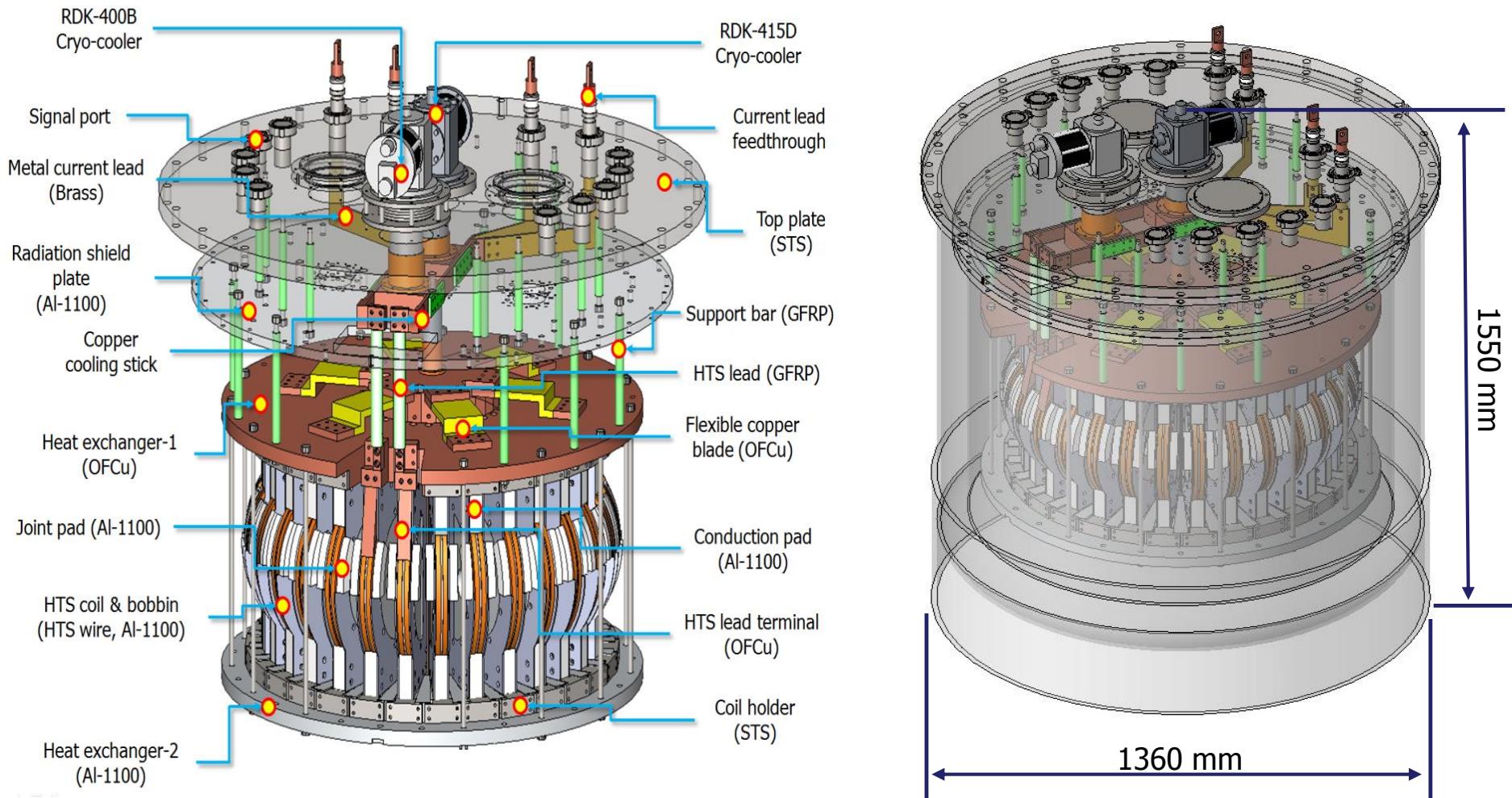
→ The toroid-type HTS DC reactor magnet has a much lower leakage flux

→ Most magnetic flux line patterns are formed by the shape of the toroid magnet



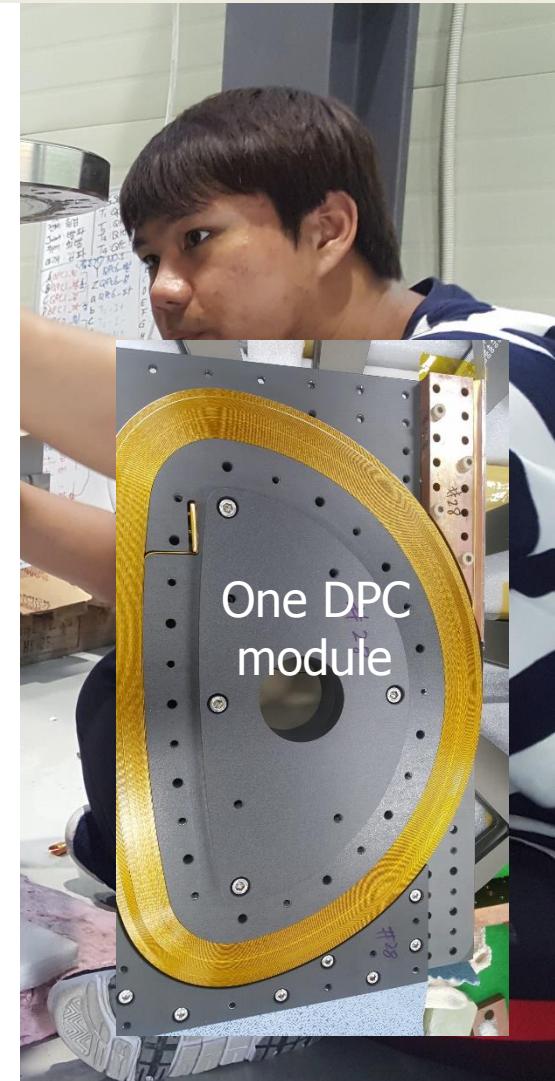
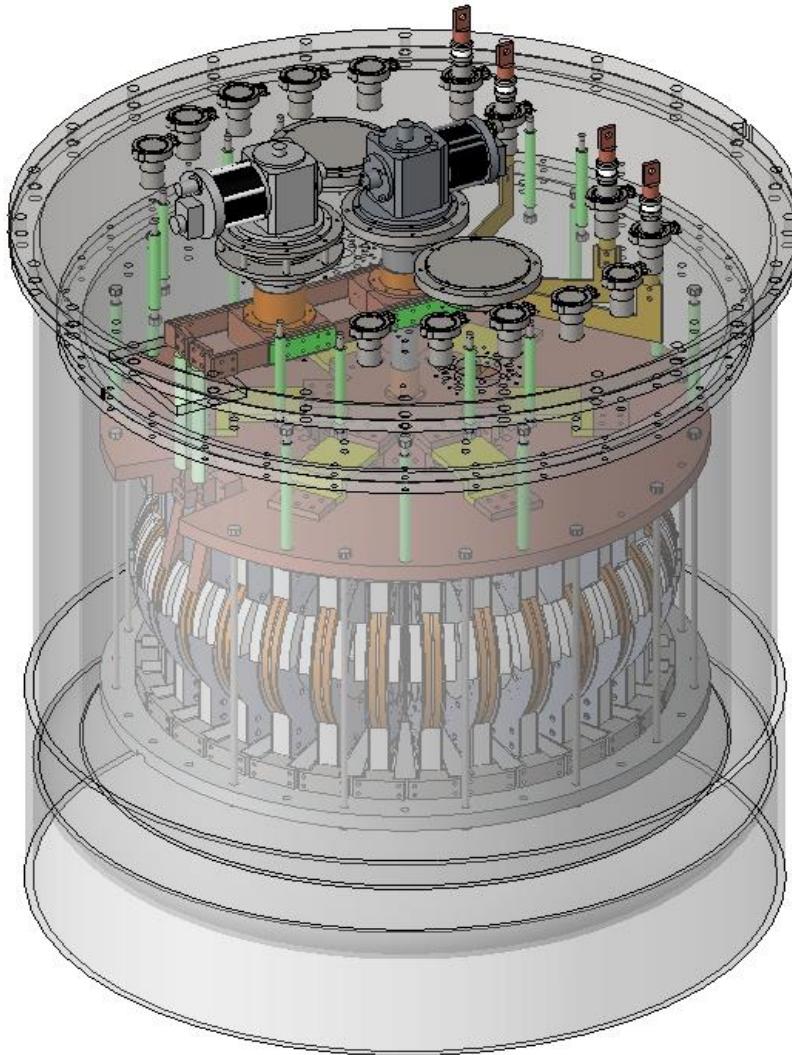
HTS DC reactor (400 mH, 1,500 A)

- Design results of the 400 mH, 1,500 A class HTS DC reactor using coated conductor
- 400 mH, 1,500 A HTS DC reactor will be operated **within a few weeks**.



HTS DC reactor (400mH, 1,500A)

SuNAM, KERI, CNU 38



400mH, 400A class
successfully completed
with good test results

400mH, 1,500A
will be tested soon

Done

- 23kV(3Φ) AC cable 100m
- 23kV(3Φ) AC cable 500m
- 154kV(3Φ) AC cable 1km
- 80kV DC cable 500m
- 23kV(3Φ) SFCL
- 154k(1Φ) SFCL
- 400mH, 400A DC reactor

Thank you for your attention

On going HTS project or business of AC and DC transmission in Korea

AC 23kV HTS power cable

Brief specification

1km, 23kV, commercial installation

AC 23kV tri-axial HTS power cable

100m, ~2km, 23kV, demo project

AC 154kV SFCL

Real grid installation within 2019

AC 154kV FCL function HTS power cable

Feasibility R&D

DC reactor

400mH, 1,500A fabrication

DC 250kV power cable

Terminal design and test

by

KEPCO (plan, power network)

KEPRI (R&D)

LS cable (supplier)

Changwon National University (core design)

KERI, and so on

- Back data

분석결과1 - 154kV 변전소/120MVA 신규설치 대비 22.9kV 3상동축초전도 케이블/50MVA 적용

구분	발생비용	기존전력공급 계통			Biz1 신규변전소 외곽위치		
		값	비용 (억)	비율 (%)	값	비용 (억)	비율 (%)
154kV 변전소/120MVA	100.1 억/개소	1	100.1	38%	1	100	38%
154kV 변전소/180MVA	118.1 억/개소	0	-	0%	0	-	0%
154kV 변전소/240MVA	136.2 억/개소	0	-	0%	0	-	0%
154kV 변전소/300MVA	154.3 억/개소	0	-	0%	0	-	0%
154kV 변전소 대지구입(택지개발지구 기준)	13.0 억/개소	0	-	0%	1	13	5%
154kV 변전소 대지구입(기존도심지 기준)	33.0 억/개소	1	107	40%	0	-	0%
소합계(억원)			207.1	78%		113	43%
지중송전 전력구 154kV 인입 거리	0.1 km						
154kV 지중송전 전력구	63.5 억/km	1	31.7	12%	0	-	0%
154kV 지중송전 전력 케이블/4Bank	51.4 억/km	1	25.7	10%	0	-	0%
소합계(억원)			57.5	22%			
154kV 변전소간 연계 거리	5.0 km						
154kV 가공선로 케이블/4Bank	23.0 억/km	0	-	0%	0	-	0%
154kV 지중송전 관로/4Bank	77.8 억/km	0	-	0%	0	-	0%
154kV 지중송전 전력구/4Bank	114.9 억/km	0	-	0%	0	-	0%
소합계(억원)				- 0%			
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-0.1km	52.9 억				0	-	0%
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-0.5km	60.3 억				2	121	45%
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-1km	72.0 억				0	-	0%
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-3km	132.0 억				0	-	0%
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-5km	186.5 억				0	-	0%
22.9kV 3상동축초전도 케이블/100MVA (22.9kV 지중배전관로)-0.1km	54.3 억				0	-	0%
22.9kV 3상동축초전도 케이블/100MVA (22.9kV 지중배전관로)-0.5km	72.5 억				0	-	0%
22.9kV 3상동축초전도 케이블/100MVA (22.9kV 지중배전관로)-1km	91.0 억				0	-	0%
22.9kV 3상동축초전도 케이블/100MVA (22.9kV 지중배전관로)-3km	185.2 억				0	-	0%
22.9kV 3상동축초전도 케이블/100MVA (22.9kV 지중배전관로)-5km	259.3 억				0	-	0%
소합계(억원)						121	45%
22.9kV 배전개폐소	31.5 억/개소				1	32	12%
총합계(억원)			265			265	

분석결과1 - 154kV 변전소/120MVA 신규설치 대비 22.9kV 3상동축초전도 케이블/50MVA 적용

: 154kV 변전소 루프연결 : 지중송전 – 가공선로 적용에 따른

구분	발생비용	기준전력공급 계통			Biz1 신규변전소 외곽위치		
		값	비용 (억)	비율 (%)	값	비용 (억)	비율 (%)
154kV 변전소/120MVA	100.1 억/개소	1	100.1	12%	1	100	26%
154kV 변전소/180MVA	118.1 억/개소	0	-	0%	0	-	0%
154kV 변전소/240MVA	136.2 억/개소	0	-	0%	0	-	0%
154kV 변전소/300MVA	154.3 억/개소	0	-	0%	0	-	0%
154kV 변전소 대지구입(택지개발지구 기준)	13.0 억/개소	0	-	0%	1	13	3%
154kV 변전소 대지구입(기존도심지 기준)	33.0 억/개소	1	107	13%	0	-	0%
소합계(억원)			207.1	25%		113	30%
지중송전 전력구 154kV 인입 거리	0.1 km						
154kV 지중송전 전력구	63.5 억/km	1	31.7	4%	0	-	0%
154kV 지중송전 전력 케이블/4Bank	51.4 억/km	1	25.7	3%	0	-	0%
소합계(억원)			57.5	7%		-	0%
154kV 변전소간 연계 거리	5.0 km						
154kV 가공선로 케이블/4Bank	23.0 억/km	0	-	0%	1	115	30%
154kV 지중송전 관로/4Bank	77.8 억/km	0	-	0%	0	-	0%
154kV 지중송전 전력구/4Bank	114.9 억/km	1	575	68%	0	-	0%
소합계(억원)			574.6	68%		115	30%
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-0.1km	52.9 억				0	-	0%
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-0.5km	60.3 억				2	121	32%
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-1km	72.0 억				0	-	0%
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-3km	132.0 억				0	-	0%
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-5km	186.5 억				0	-	0%
22.9kV 3상동축초전도 케이블/100MVA (22.9kV 지중배전관로)-0.1km	54.3 억				0	-	0%
22.9kV 3상동축초전도 케이블/100MVA (22.9kV 지중배전관로)-0.5km	72.5 억				0	-	0%
22.9kV 3상동축초전도 케이블/100MVA (22.9kV 지중배전관로)-1km	91.0 억				0	-	0%
22.9kV 3상동축초전도 케이블/100MVA (22.9kV 지중배전관로)-3km	185.2 억				0	-	0%
22.9kV 3상동축초전도 케이블/100MVA (22.9kV 지중배전관로)-5km	259.3 억				0	-	0%
소합계(억원)						121	32%
22.9kV 배전개폐소	31.5 억/개소				1	32	8%
총합계(억원)			839			380	

Biz 1 선정조건 - 154kV 변전소/120MVA 신규설치 대비 22.9kV 3상동축초전도 케이블/50MVA 적용

→ 지중송전 전력구 인입거리 0.1 km 일 경우,

154 kV 변전소 도심지 대지구입비용 (변전소 대지구입비용(택지개발지구 기준)대비) **138억 이상** 일 것.

→ 즉, 154kV 도심 변전소 대지구입 시, 125억(138억 – 13억 = 125억) 이상 추가비용 발생할 것.

구분	발생비용	기존전력공급 계통			Biz1 신규변전소 외곽위치		
		값	비용 (억)	비율 (%)	값	비용 (억)	비율 (%)
154kV 변전소/120MVA	100.1 억/개소	1	100.1	40%	1	100	40%
154kV 변전소 대지구입(택지개발지구 기준)	13.0 억/개소				1	13	5%
154kV 변전소 대지구입(기존도심지 기준)	138 억/개소	1	138	55%			
소합계(억원)			238.1	95%		113	45%
지중송전 전력구 154kV 인입 거리	0.1 km						
154kV 지중송전 전력구	63.5 억/km	1	6.3	3%			
154kV 지중송전 전력 케이블/4Bank	51.4 억/km	1	5.1	2%			
소합계(억원)			11.5	5%			
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-0.1km	52.9 억				2	106	42%
22.9kV 배전개폐소	31.5 억/개소				1	32	13%
총합계(억원)			250			250	

Biz 1 선정조건-154kV 변전소/120MVA 신규설치 대비 **22.9kV 3상동축초전도 케이블/50MVA 적용**

→ 지중송전 전력구 인입거리 **0.5 km** 일 경우,

154 kV 변전소 도심지 대지구입비용 (변전소 대지구입비용(택지개발지구 기준)대비) **107억 이상** 일 것.

→ 즉, 154kV 도심 변전소 대지구입 시, **94억(107억 – 13억 = 94억)** 이상 추가비용 발생할 것.

구분	발생비용	기존전력공급 계통			Biz1 신규변전소 외곽위치		
		값	비용 (억)	비율 (%)	값	비용 (억)	비율 (%)
154kV 변전소/120MVA	100.1 억/개소	1	100.1	38%	1	100	38%
154kV 변전소 대지구입(택지개발지구 기준)	13.0 억/개소				1	13	5%
154kV 변전소 대지구입(기존도심지 기준)	138 억/개소	1	107	40%			
소합계(억원)			207.1	78%		113	43%
지중송전 전력구 154kV 인입 거리	0.5 km						
154kV 지중송전 전력구	63.5 억/km	1	31.7	12%			
154kV 지중송전 전력 케이블/4Bank	51.4 억/km	1	25.7	10%			
지중송전 전력구 건설비용 소합계(억원)			57.5	22%			
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-0.5km	60.3 억				2	121	45%
22.9kV 배전개폐소	31.5 억/개소				1	32	13%
총합계(억원)			265			265	

Biz 1 선정조건 - 154kV 변전소/120MVA 신규설치 대비 22.9kV 3상동축초전도 케이블/50MVA 적용

→ 지중송전 전력구 인입거리 **1 km** 일 경우,

154 kV 변전소 도심지 대지구입비용 (변전소 대지구입비용(택지개발지구 기준)대비) 74억 이상
일 것.

→ 즉, 154kV 도심 변전소 대지구입 시, 61억(74억 – 13억 = 61억) 이상 추가비용 발생할 것.

구분	발생비용	기존전력공급 계통			Biz1 신규변전소 외곽위치		
		값	비용 (억)	비율 (%)	값	비용 (억)	비율 (%)
154kV 변전소/120MVA	100.1 억/개소	1	100.1	35%	1	100	35%
154kV 변전소 대지구입(택지개발지구 기준)	13.0 억/개소				1	13	5%
154kV 변전소 대지구입(기존도심지 기준)	138 억/개소	1	74	26%			
소합계(억원)			174.1	60%		113	40%
지중송전 전력구 154kV 인입 거리	0.5 km						
154kV 지중송전 전력구	63.5 억/km	1	63.5	22%			
154kV 지중송전 전력 케이블/4Bank	51.4 억/km	1	51.4	18%			
지중송전 전력구 건설비용 소합계(억원)			114.9	40%			
22.9kV 3상동축초전도 케이블/50MVA (22.9kV 지중배전관로)-1.0km	72.0 억				2	144	50%
22.9kV 배전개폐소	31.5 억/개소				1	32	13%
총합계(억원)			289			289	