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Development of Superconducting Cable with Energy Storage Function for Mass Utilization Society of Renewable Energy

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KYUSHU UNIVERSITY

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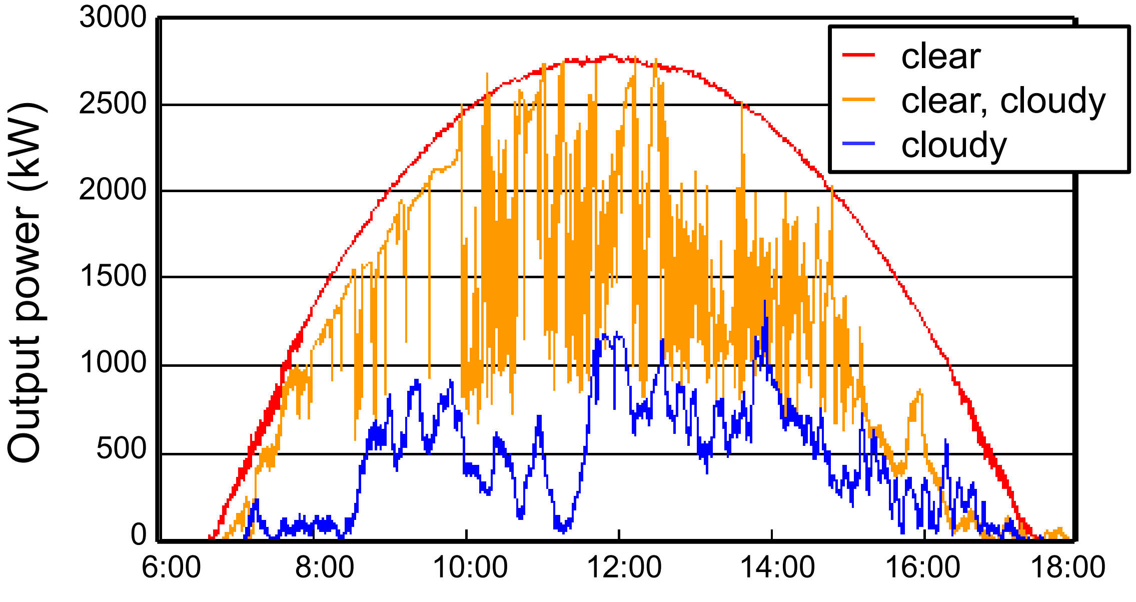
Background: Necessity of Power Fluctuation Compensation

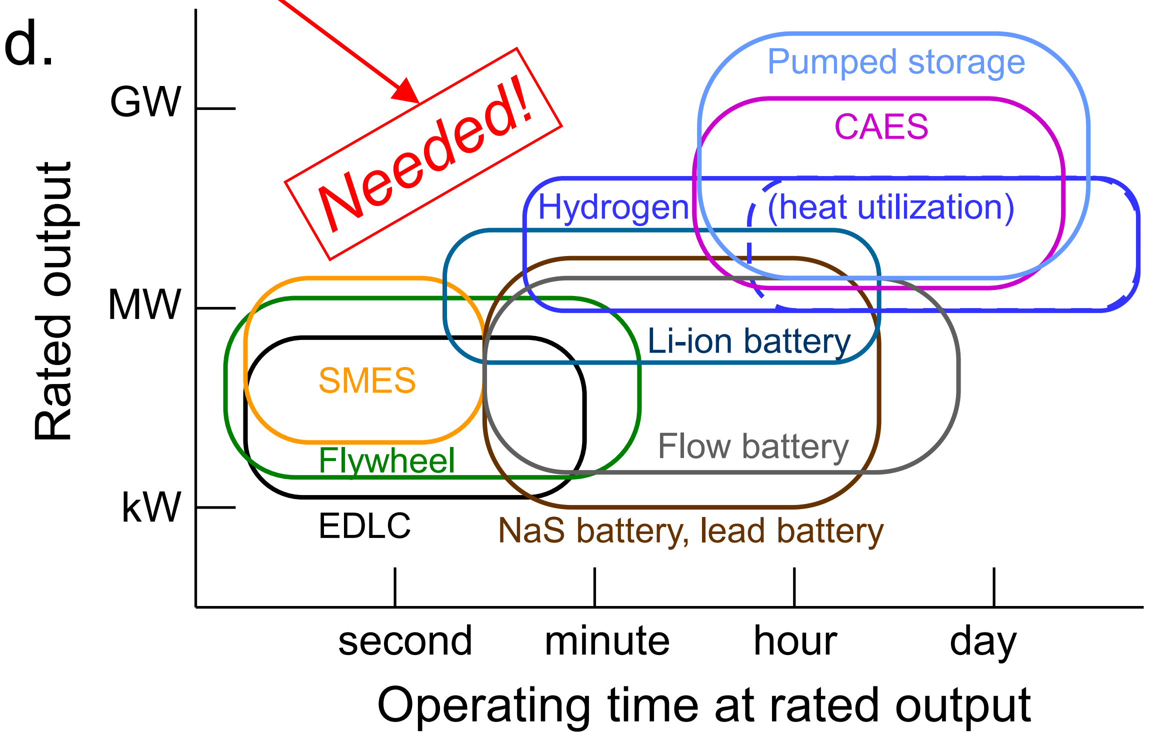
Large-scale utilization of renewable energies is a key issue for sustainable society.

Power fluctuation compensation is one of the most critical issues.

High-power and high-speed energy storage is indispensable especially for photovoltaic (PV) power generation when used as a main power source of a micro-grid.

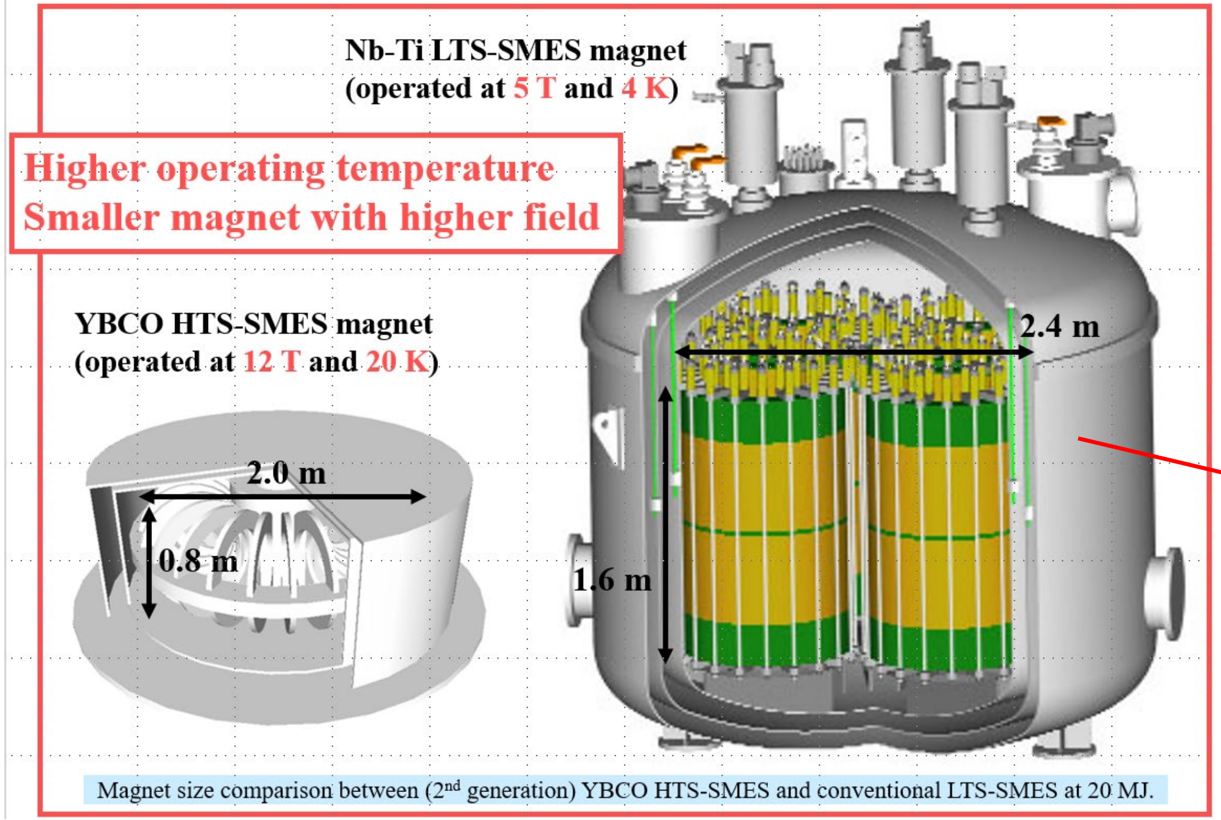


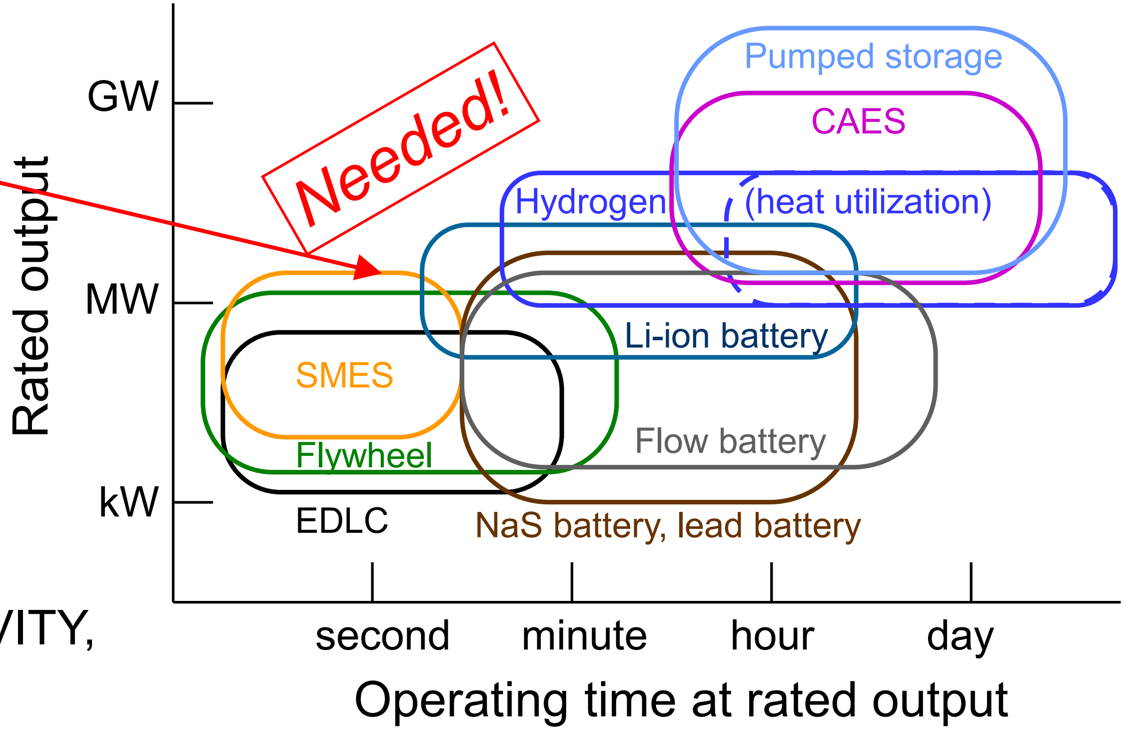
（電気事業連合会資料より）



Background: Limitation of SMES

My Ph.D. thesis was on the design of HTS SMES…





K. Higashikawa et al.,
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 17, NO. 2, JUNE 2007

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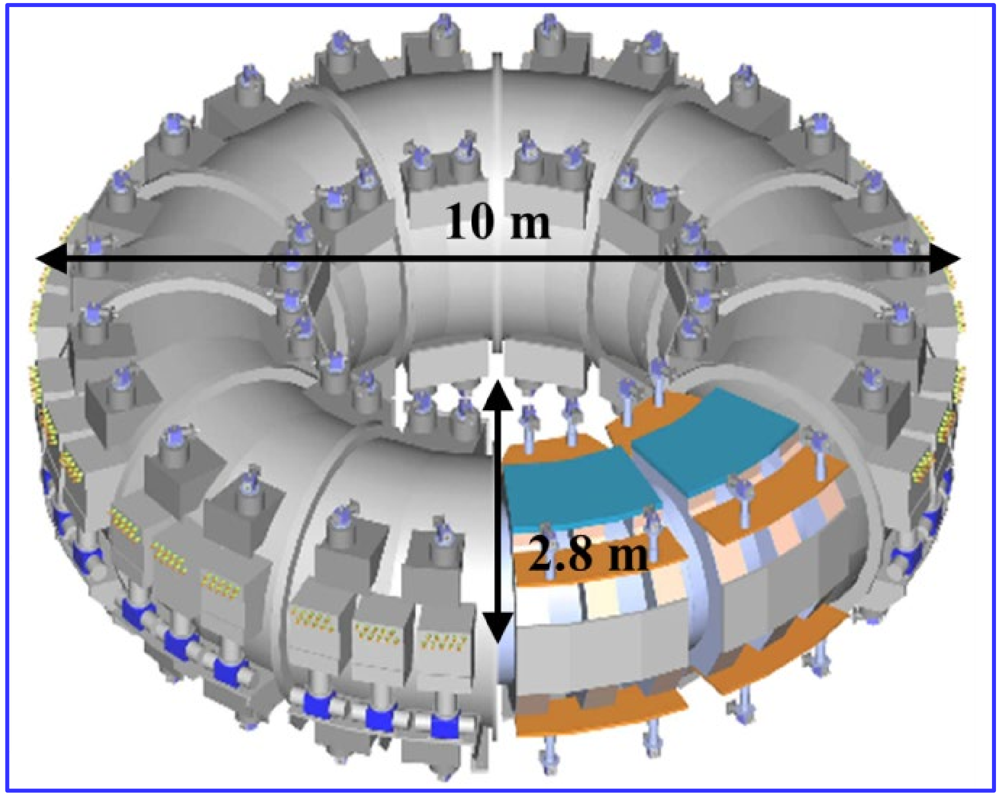

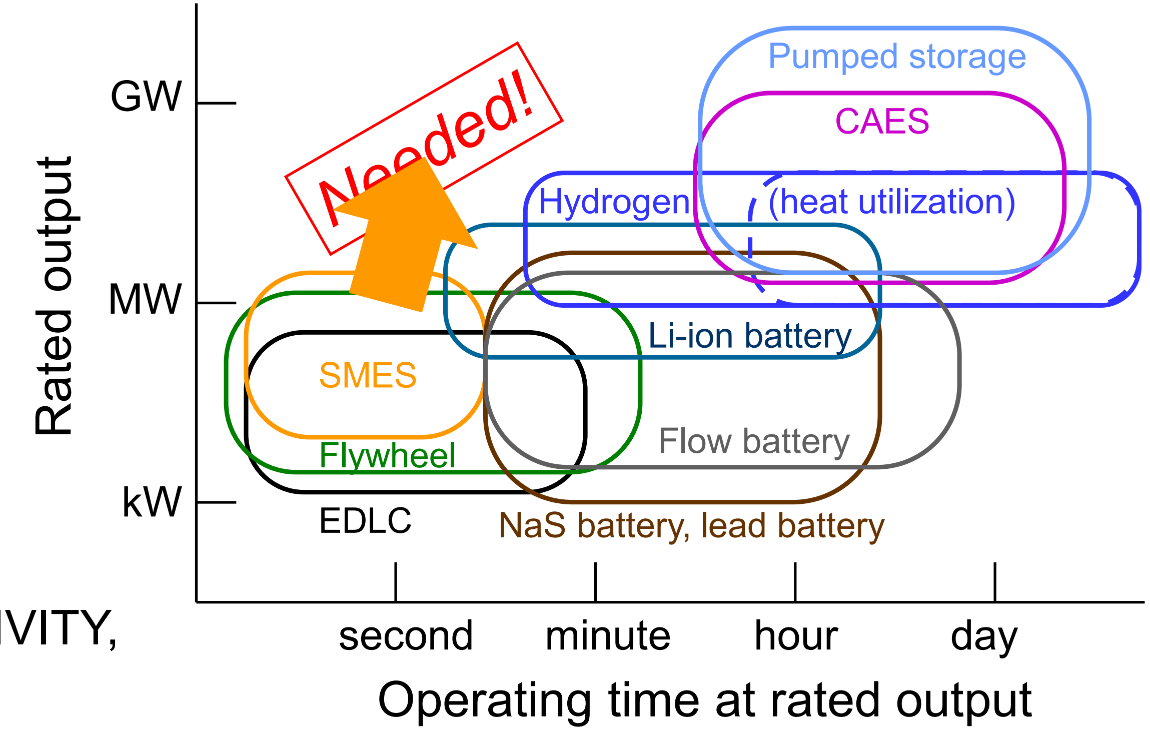

K. Shikimachi, et al.,
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 19, NO. 3, JUNE 2009

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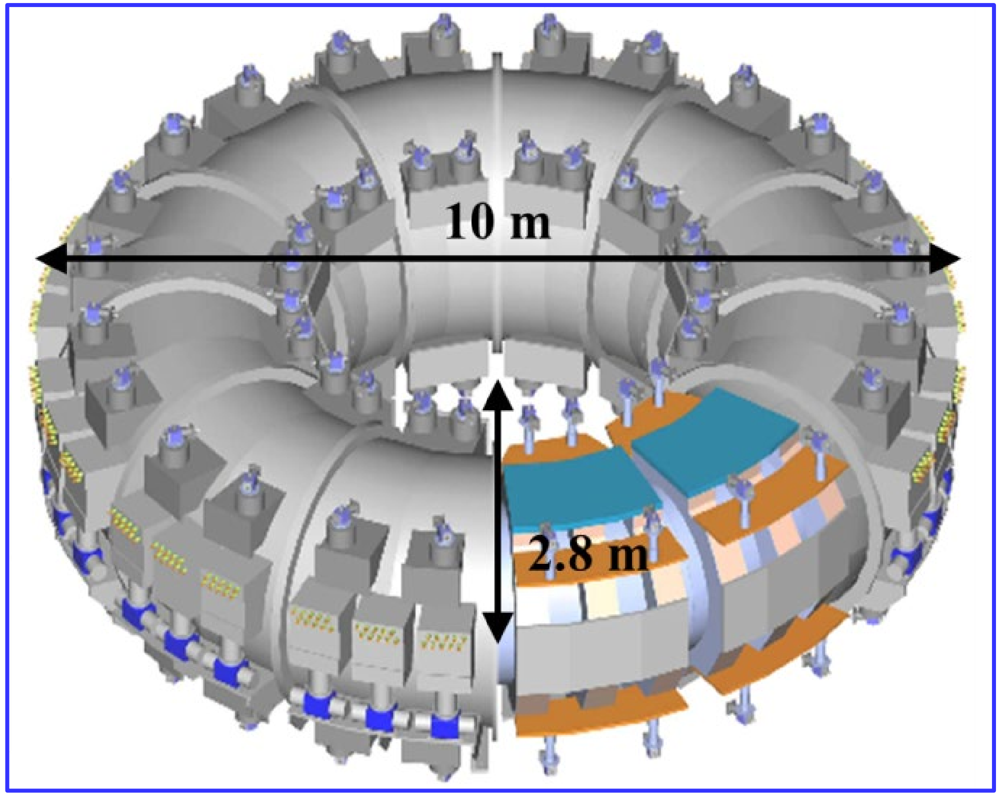

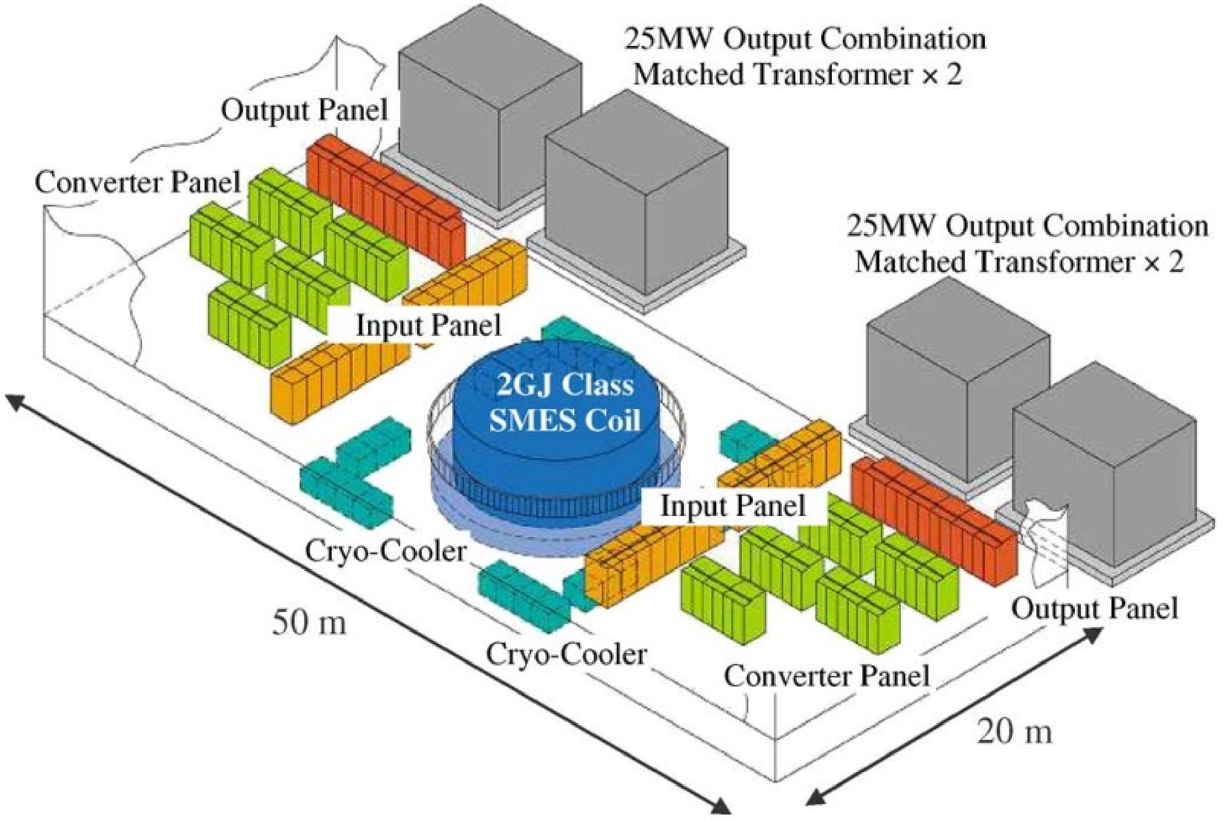

Fig. 7. Overview of the 100 MVA/2 GJ class YBCO SMES system for load fluctuation compensation.

K. Shikimachi, et al.,
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 19, NO. 3, JUNE 2009

Limitation to Larger Scale

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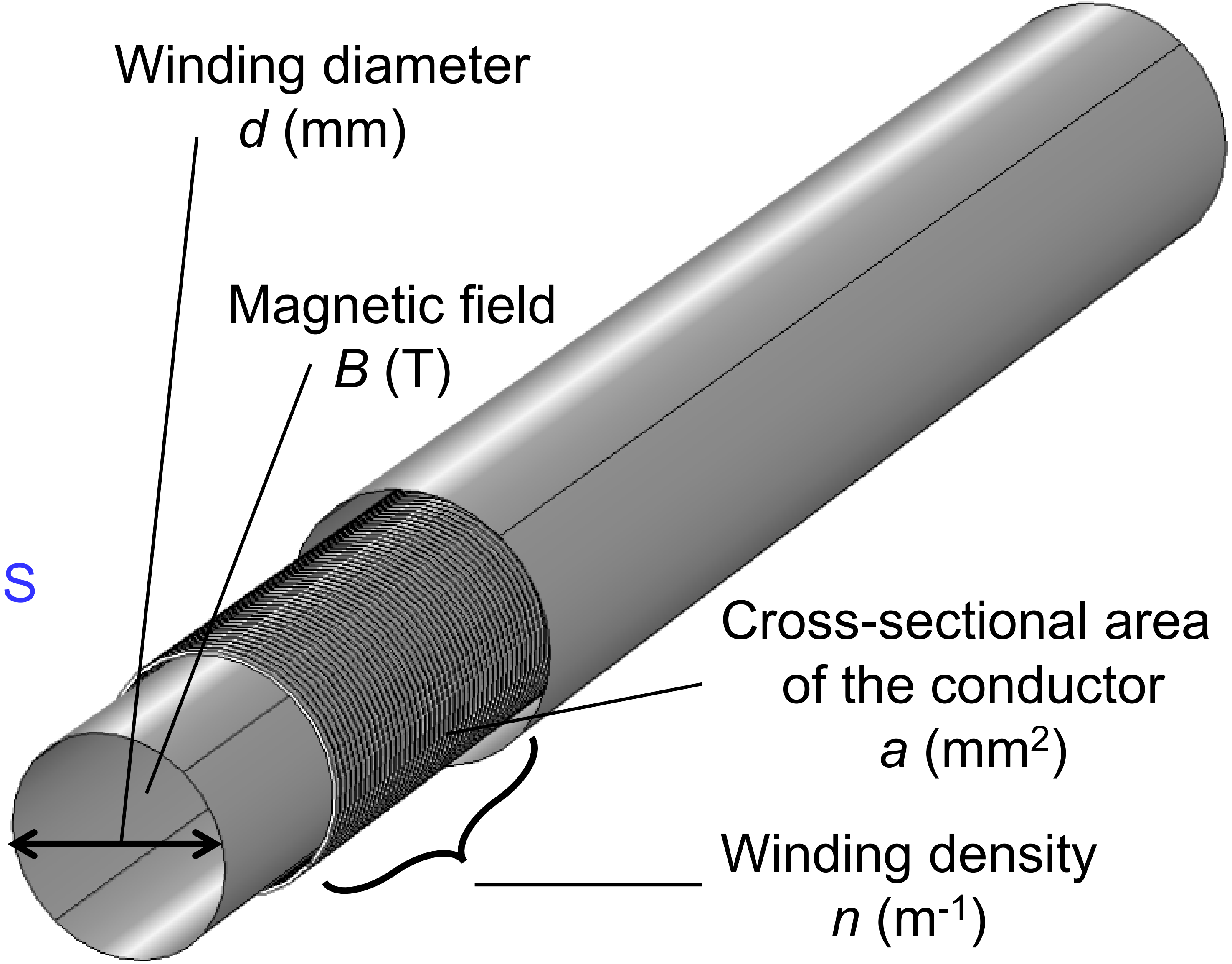
Superconducting Magnetic Energy Storage (SMES) Cable

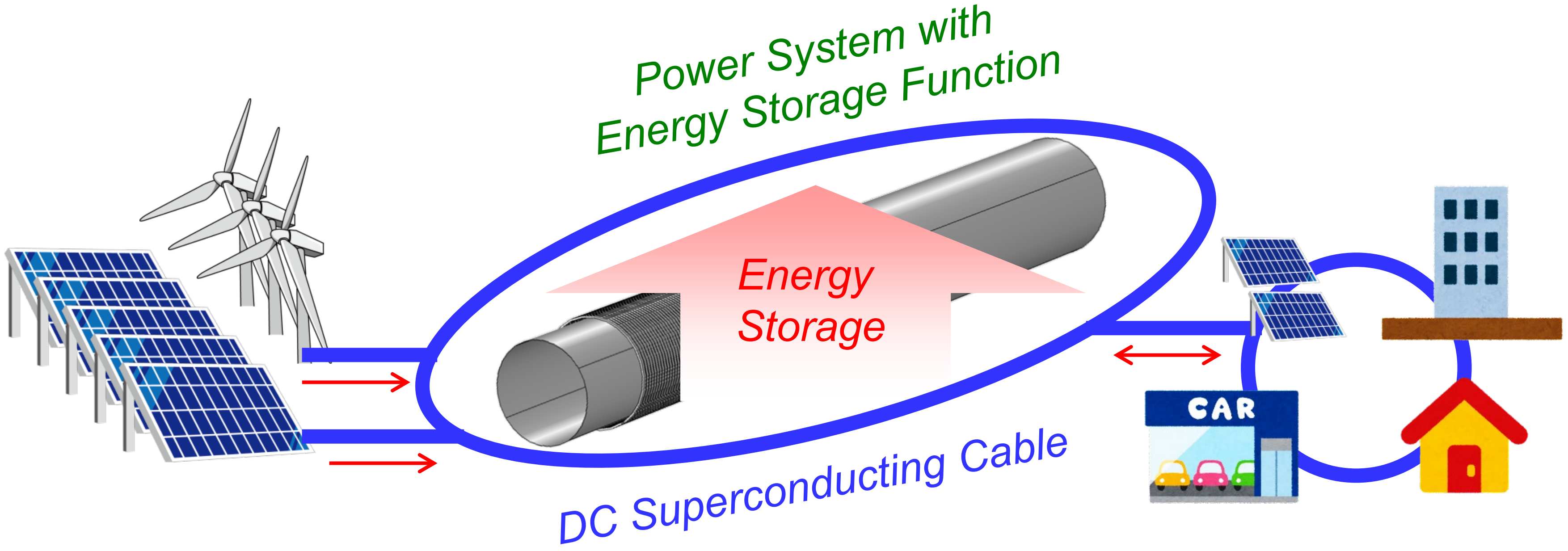
Magnetic energy storage
by large inductance
and large current:
$W = \frac{1}{2} L I^2$

Overcome the disadvantage of low energy density of SMES by using large volume of the superconducting cable



Proposal

Power System with Energy Storage Function by **DC Superconducting Cable** for Power Fluctuation Compensation of Renewable Energies



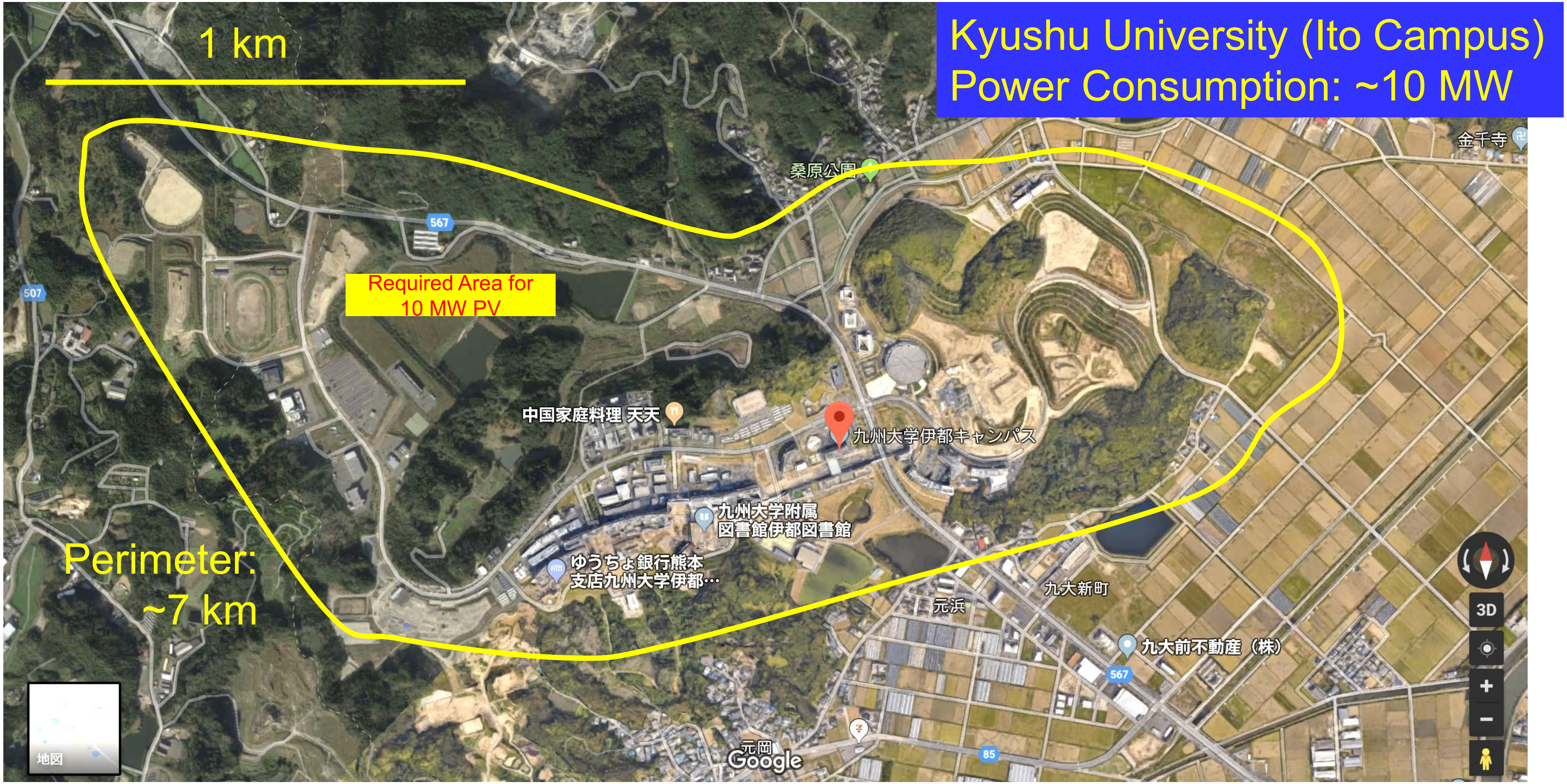
Advantages:

(i) high-speed & high-power & highly-efficient operation

(ii) no additional space for energy storage (iii) scalability

(iv) DC operation suitable for superconducting cable and for recent loads …

Typical Scale of a Micro Grid: ~10 MW, ~10 km

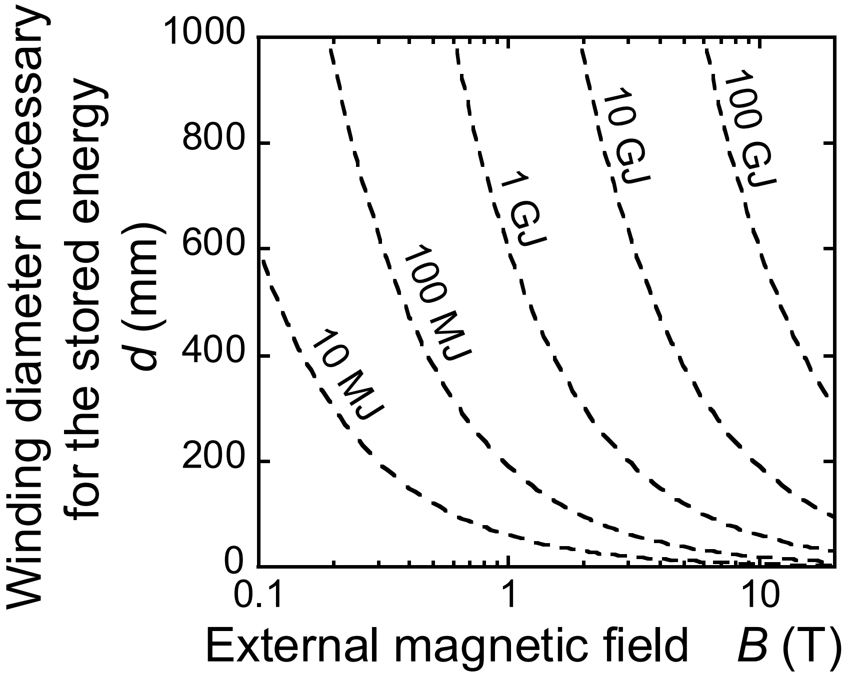


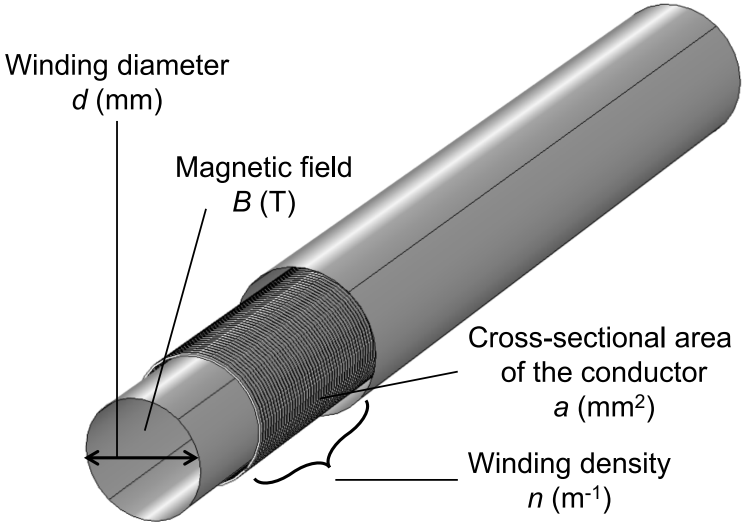
Stored Energy for 10-km-long Cable

Stored Energy:

$$W = \int_V \frac{1}{2}\frac{B^2}{\mu_0} dV = \left(\frac{1}{2}\frac{B^2}{\mu_0}\right)\left(\pi\left(\frac{d}{2}\right)^2 l\right)$$

energy density — volume





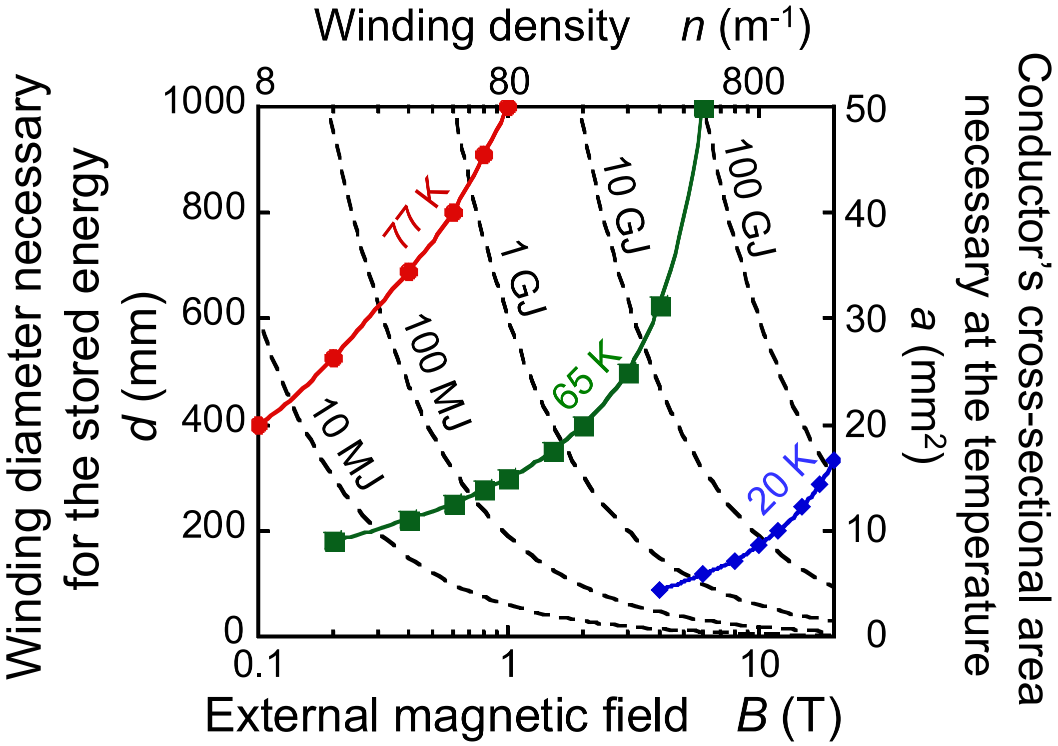
Requirement of 10 kA Conductor

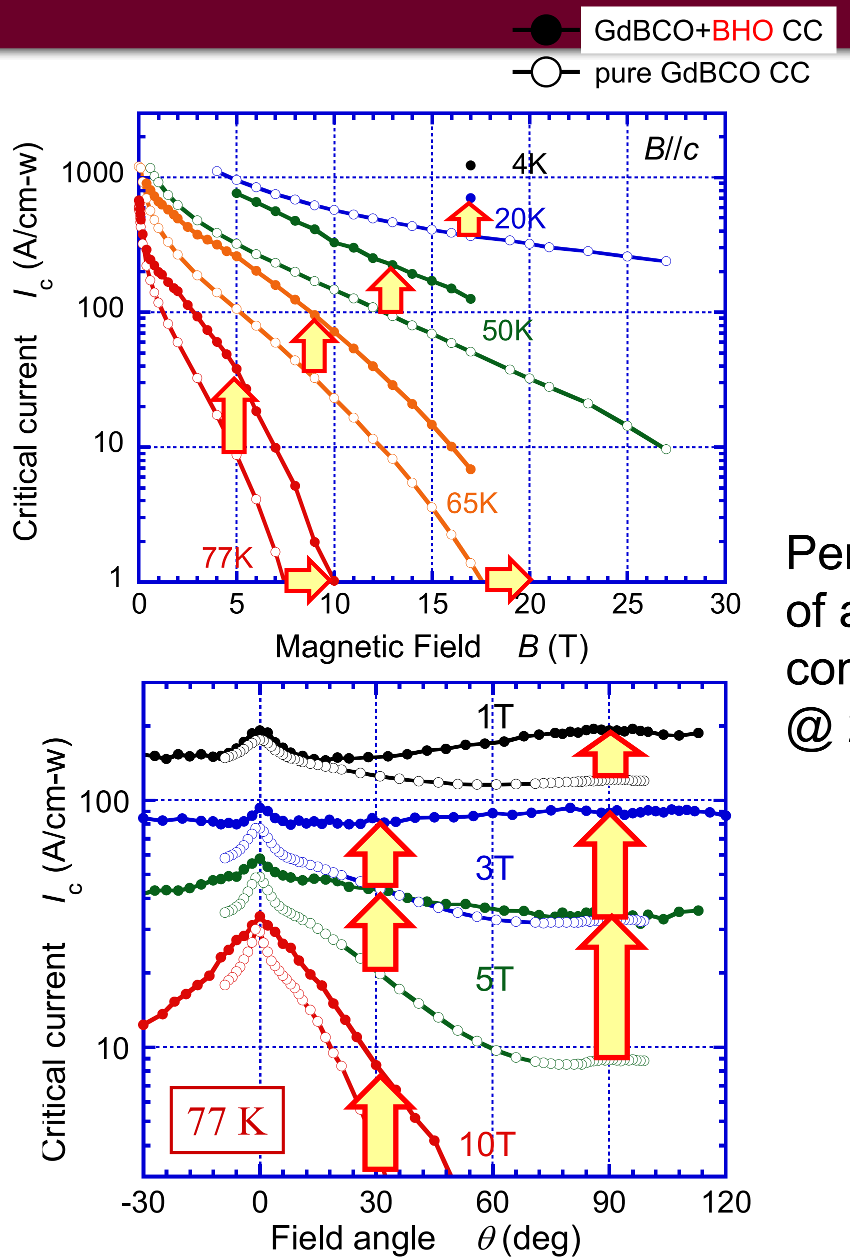
Power capacity of the micro-grid:

10 MW = 1 kV x 10 kA

Cross-section of 10-kA conductor:

a = 10 kA / J_e





Performance of a coated conductor @ 2012

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Design Example for Coated Conductor @ 2012

GdBCO BHO CC @ 2012 by Tobita et al. 100-um-thick substrate

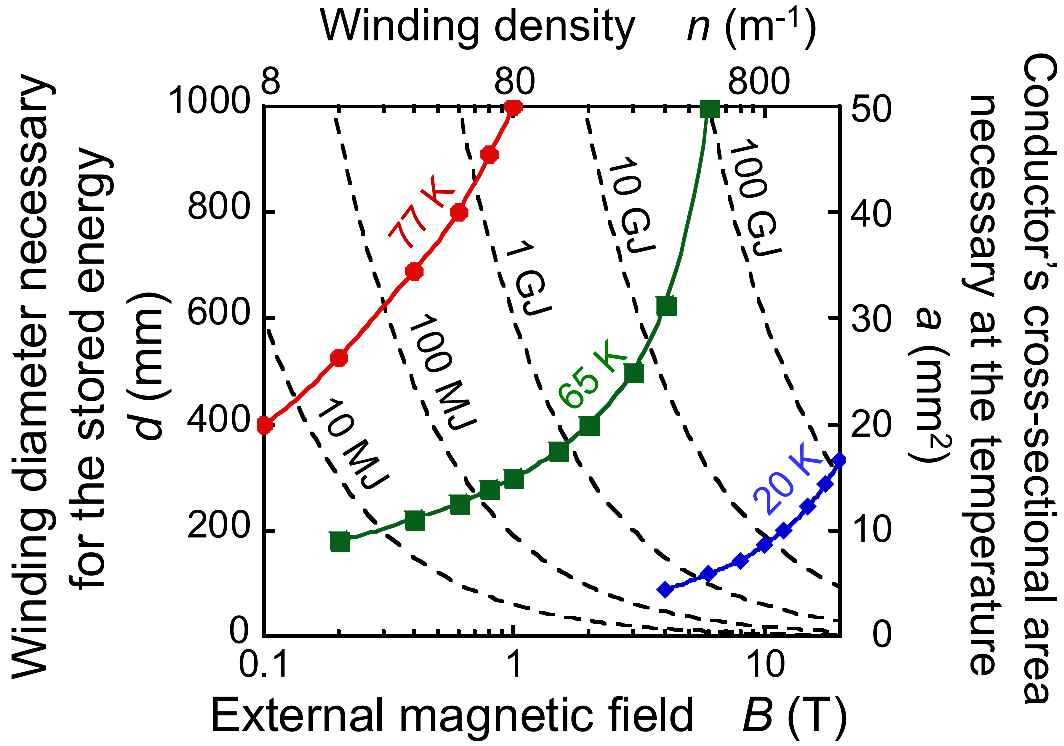
ϕ200 mm, 0.3 T @ 65 K → 10 MJ

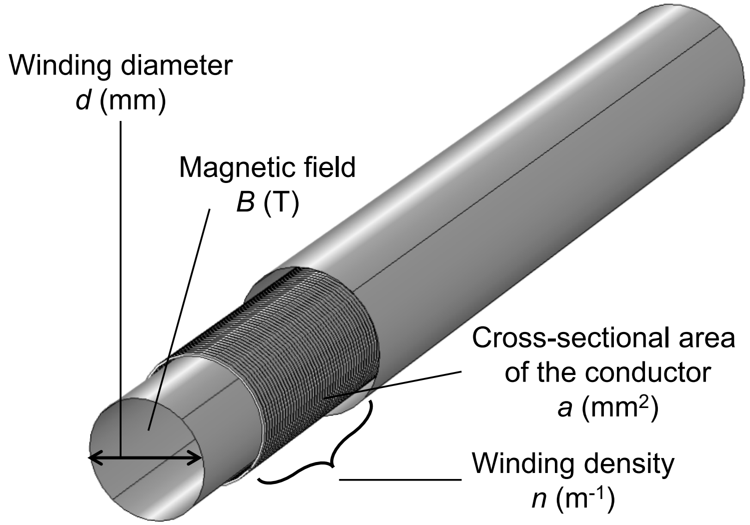
ϕ120 mm, 5 T @ 20 K → 1 GJ

Liquid hydrogen

1 s: Response compensation
> for batteries and fuel cells

100 s: Response compensation
> for **power generator without standby**
> for **heat utilization from fuel cells**





Design Example for Recent Thinner Coated Conductor

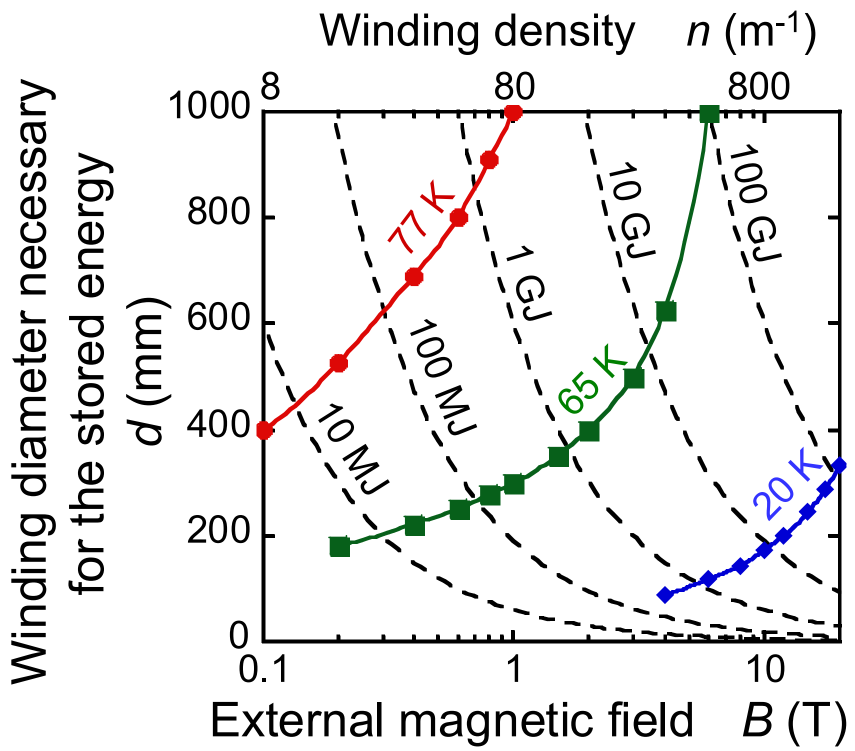
Coated Conductor @ 2012 — Recent CC with thinner substrate: 3x J_e

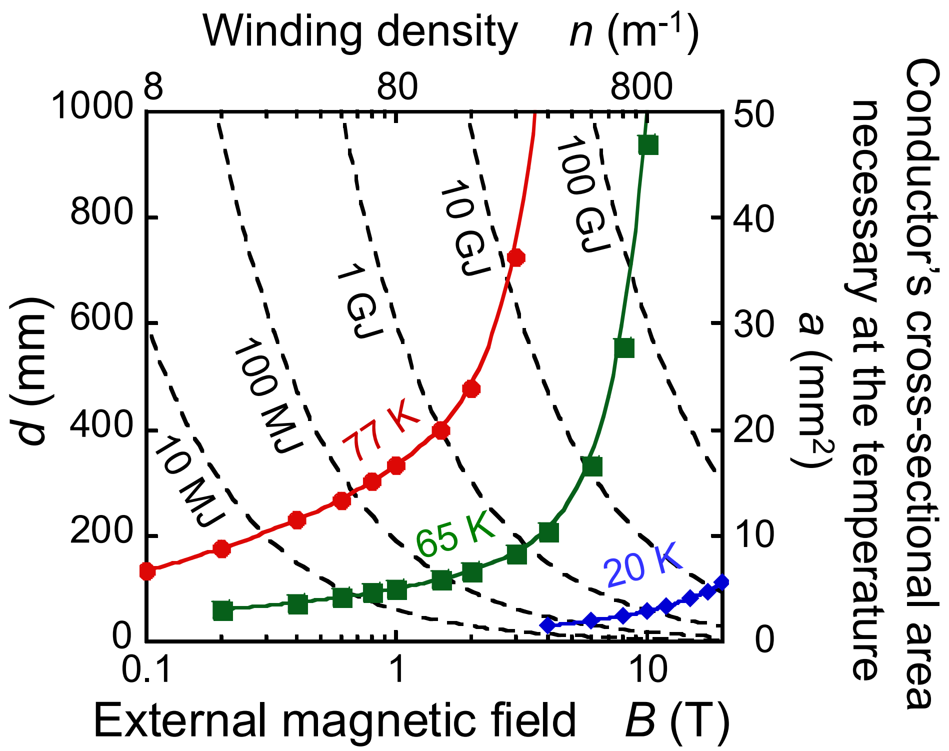
ϕ200 mm, 0.3 T @ 65 K → 10 MJ ← ϕ200 mm, 0.3 T @ 77 K

ϕ120 mm, 5 T @ 20 K → 1 GJ ← ϕ200 mm, 3.5 T @ 65 K

Liquid hydrogen

Potential even for **liquid nitrogen** operation





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Design Examples of SMES Cables

Stored energy *W*	Magnetic field *B*	Winding diameter *d*	Turns @1m *n*	Conductor length @1m	Inductance @1m	Cross-sectional area of the conductor (with recent thin CC) *a*	Functions
10 MJ	0.5 T	120 mm	40	15 m	20 uH	4 mm^2 @ 65 K 13 mm^2 @ 77 K	Response compensation for storage batteries and fuel cells (orders of seconds)
	0.3 T	200 mm	24			3 mm^2 @ 65 K 11 mm^2 @ 77 K	
40 MJ	1.15 T	105 mm	91	30 m	80 uH	5 mm^2 @ 65 K	
1 GJ	5 T	120 mm	400	150 m	2 mH	5 mm^2 @ 20 K (by stress constraints) 13 mm^2 @ 65 K	Response compensation for gas turbine including shutdown and for thermally efficient use of fuel cells (orders of minutes)
	3.5 T	200 mm	240			6 mm^2 @ 20 K (by stress constraints) 7 mm^2 @ 65 K	
100 GJ	20 T	300 mm	1600	1.5 km	0.2 H	50 mm^2 @ 20 K (by stress constraints)	Daily load leveling (orders of hours)
	8.5 T	700 mm	680			50 mm^2 @ 20 K (by stress constraints) 50 mm^2 @ 65 K (by stress constraints)	

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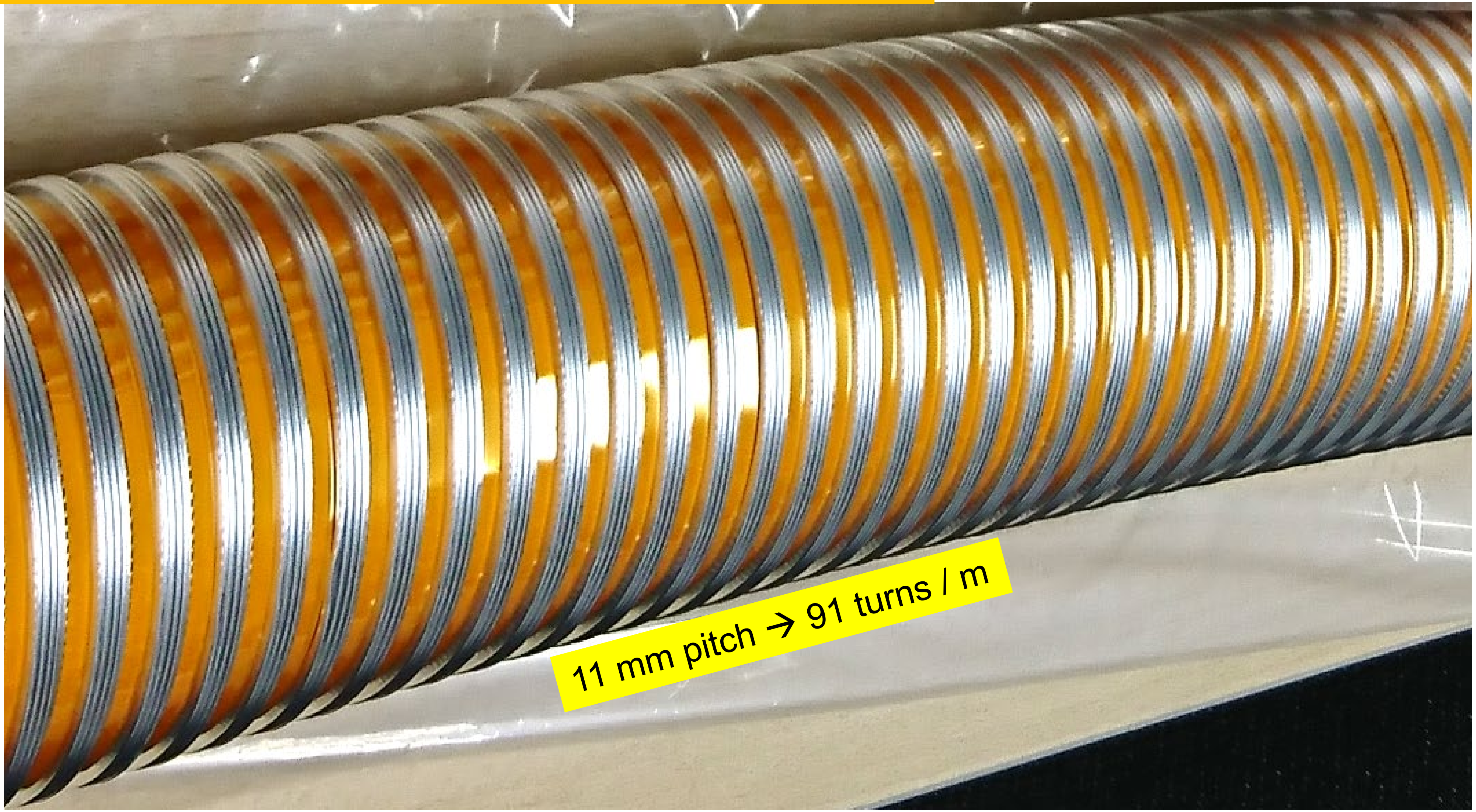
Small Model Cable for 40 MJ SMES Cable

High temperature superconducting tape: REBCO coated conductor



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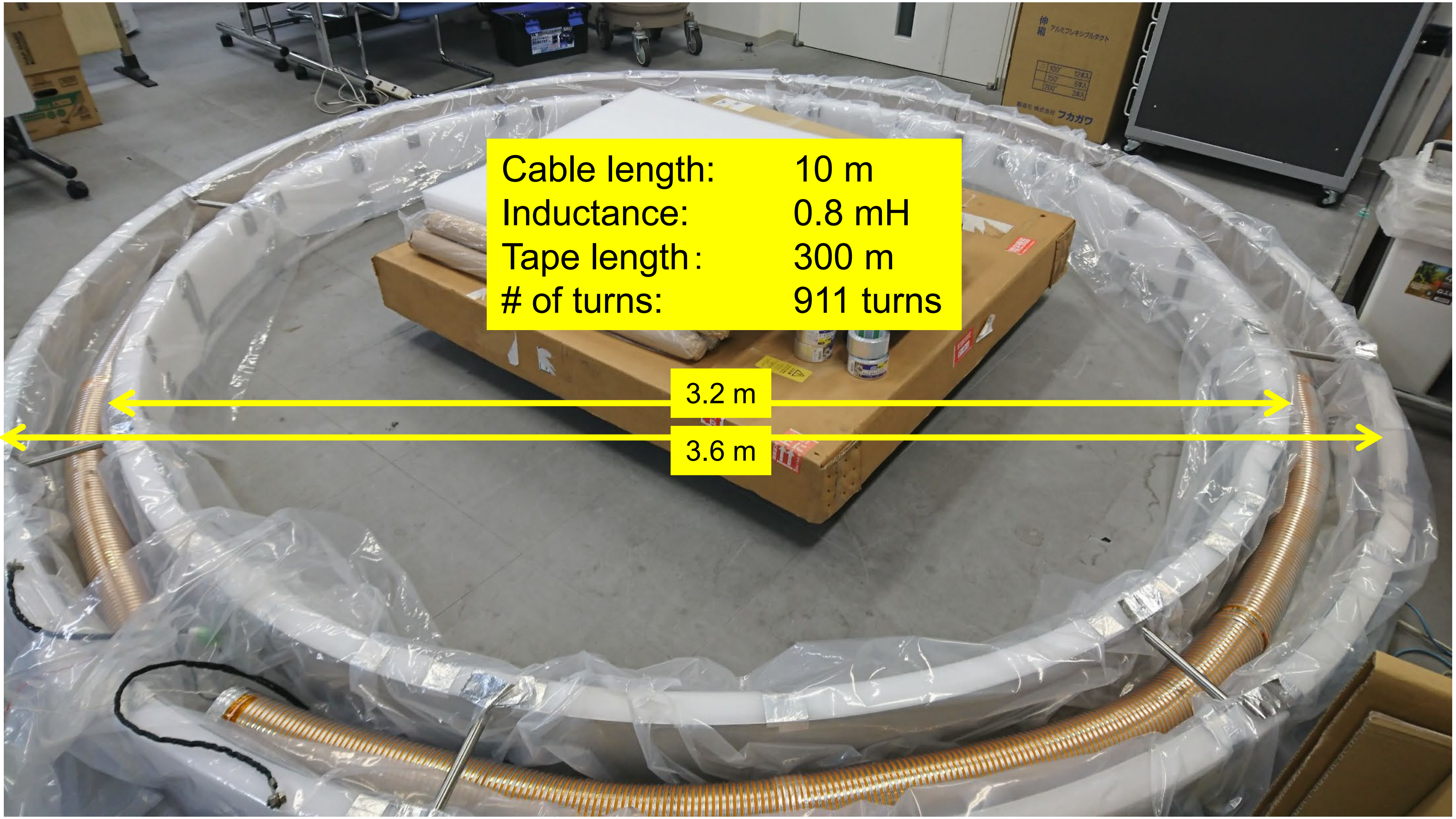

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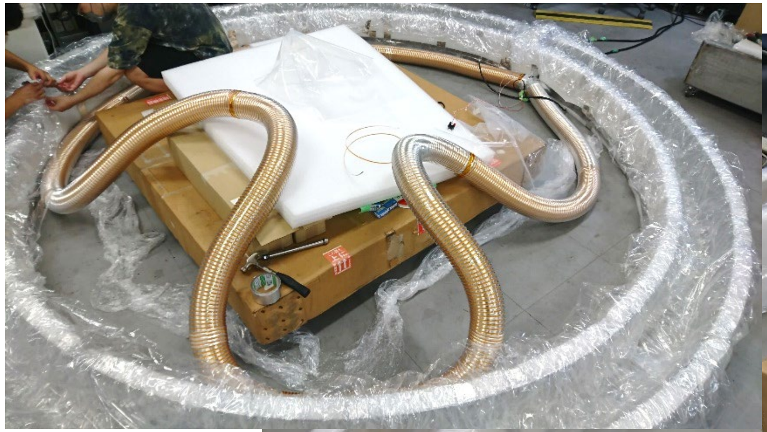
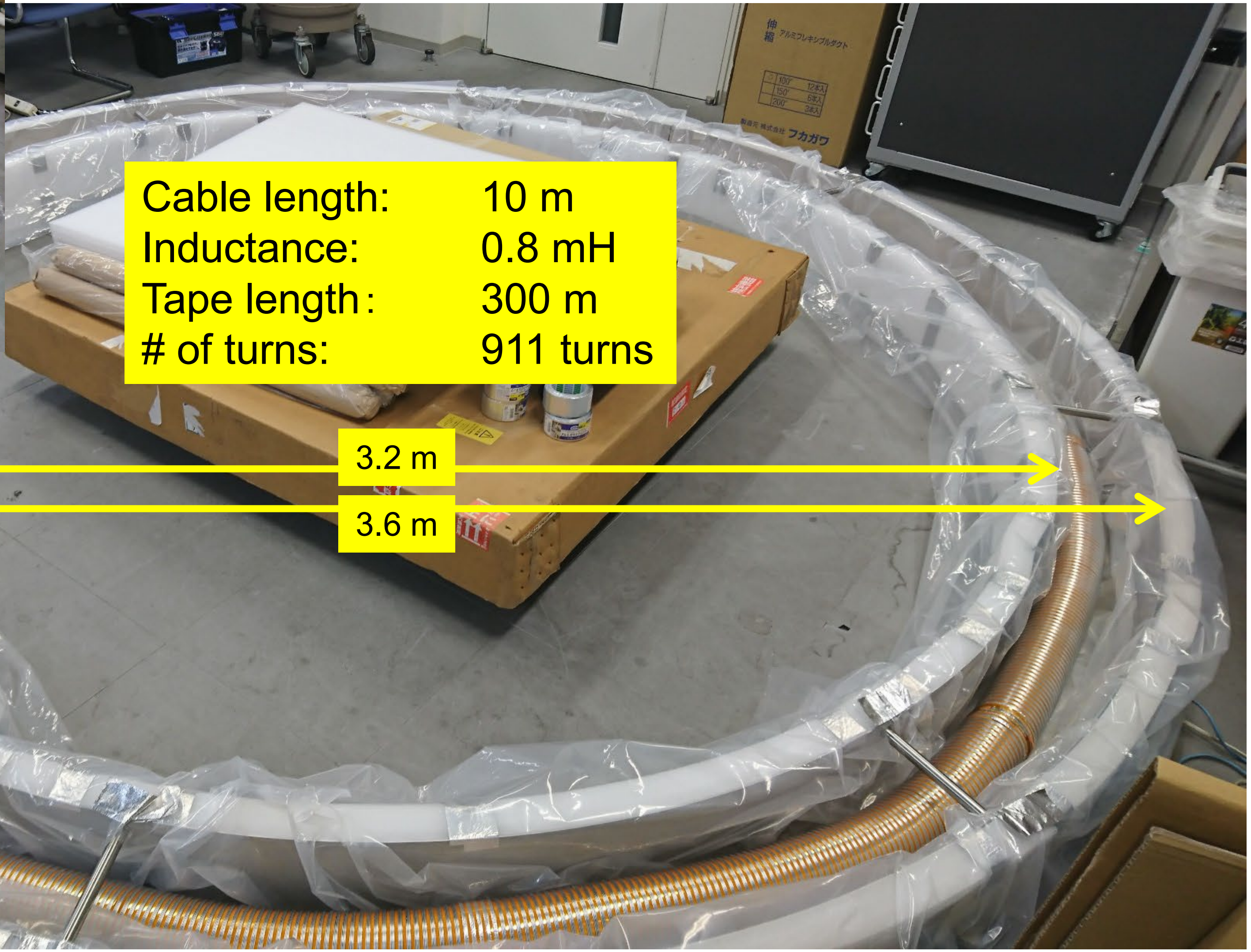


Bendable



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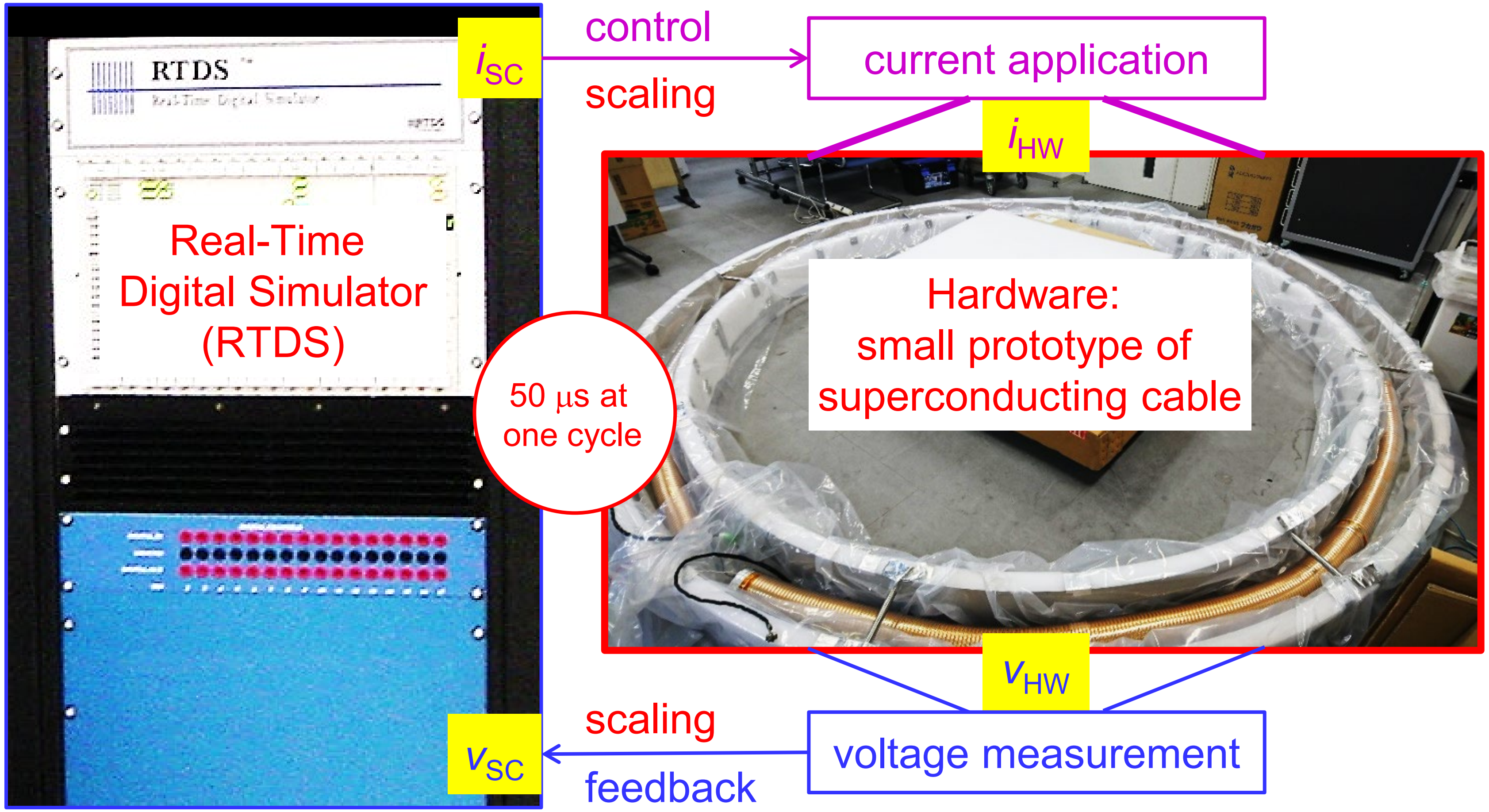
Hardware in the loop Simulation (HILS) for 40-MJ SMES Cable



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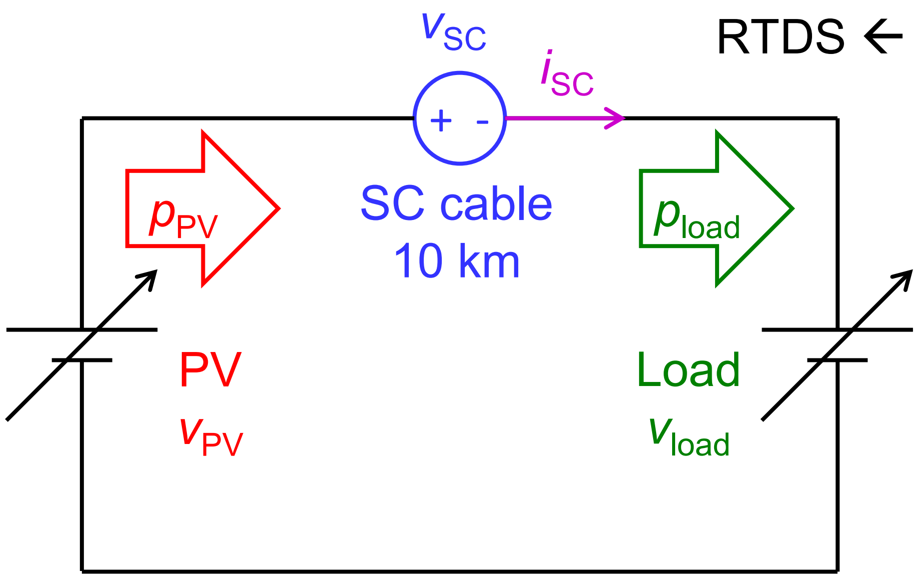
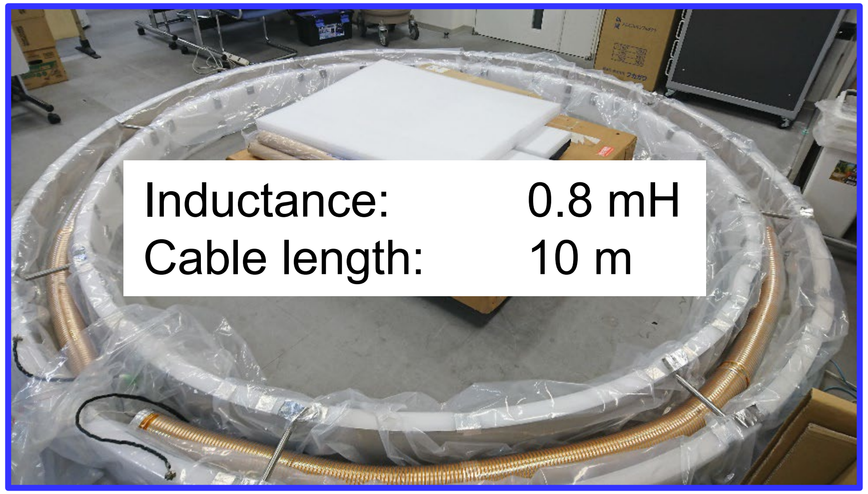
Scaling in Hardware-in-the-loop Simulation (HILS)

RTDS ← → Hardware





$$v_{SC} = L_{SC}\frac{di_{SC}}{dt} + R_{SC}i_{SC} \qquad v_{HW} = L_{HW}\frac{di_{HW}}{dt'} + R_{HW}i_{HW}$$

$$e(j) = L_{1m}\frac{di_{SC}}{dt} + \rho(j)j \qquad e(j) = L_{1m}\frac{di_{HW}}{dt'} + \rho(j)j$$

				Scaling factor
Current (rated):	i_{SC} = 10 kA	→	i_{HW} = 100 A	1/100
Time:	t	→	t'	1/100
Voltage (cable length):	v_{SC} (10 km)	←	v_{HW} (10 m)	1000
Time:	t	←	t'	100

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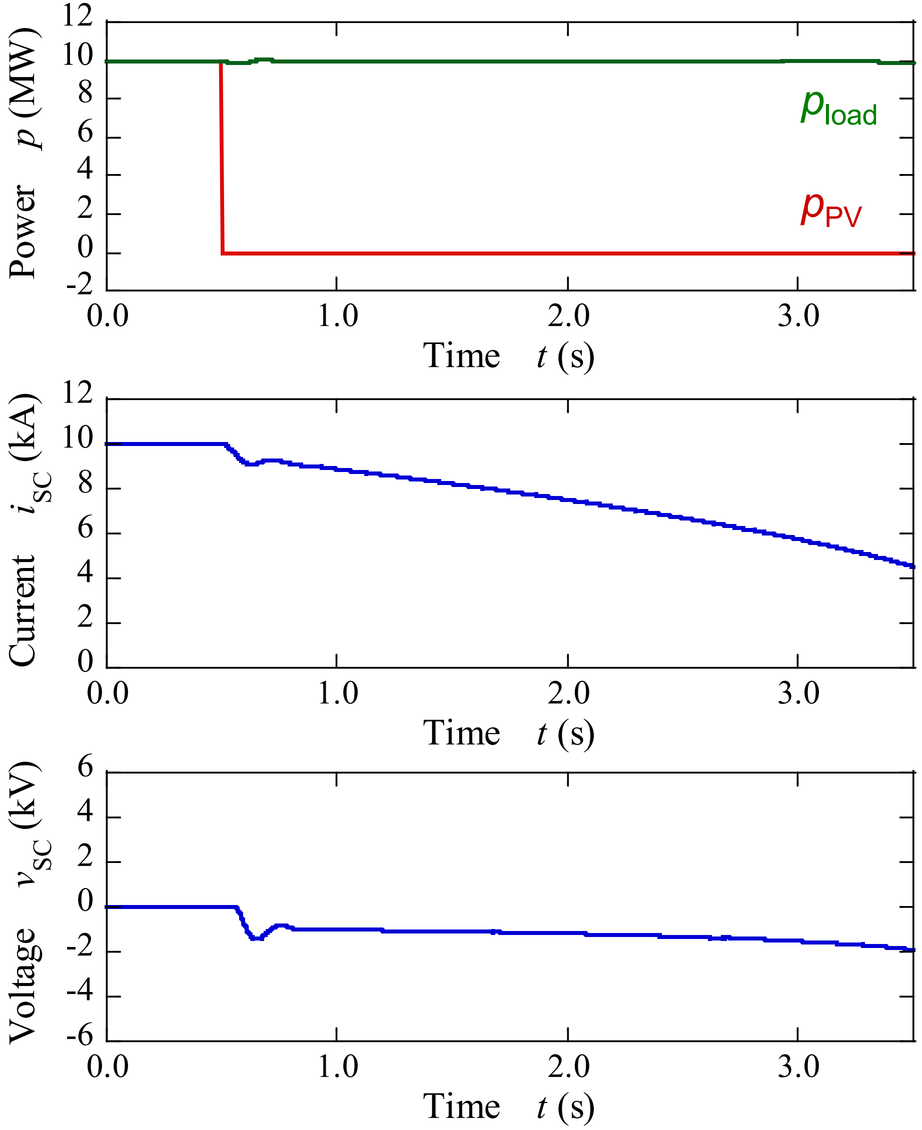
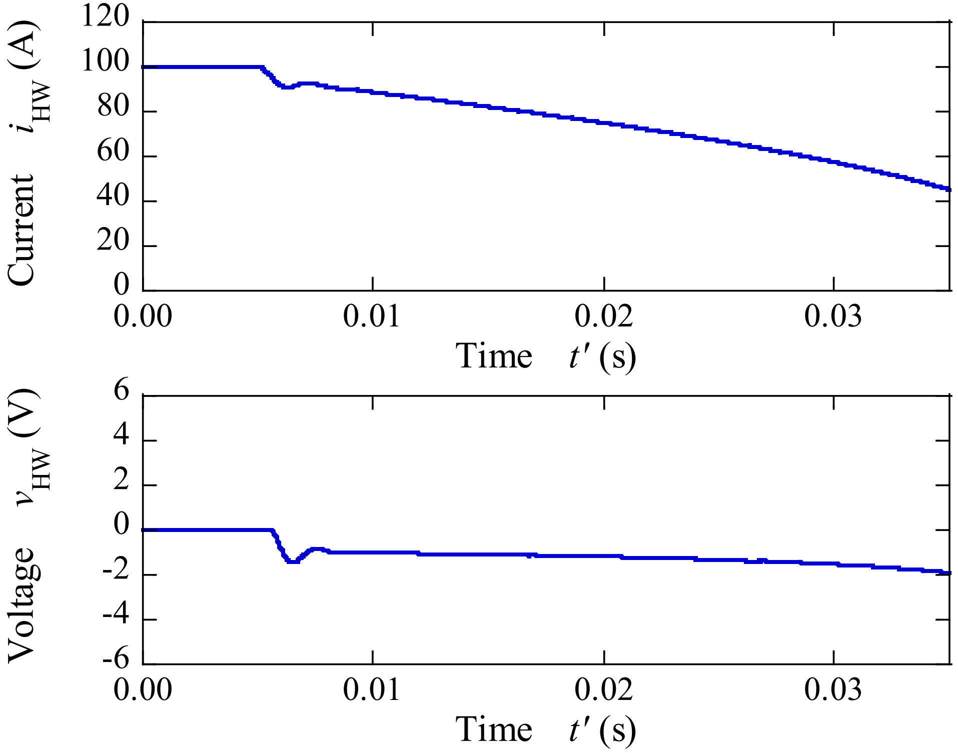
Results obtained by HILS (Discharge)

Real Time Digital Simulator: RTDS ← | → Hardware



ultimate output fluctuation compensation function (instantaneous compensation up to the rated power)



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Results obtained by HILS (Charge)

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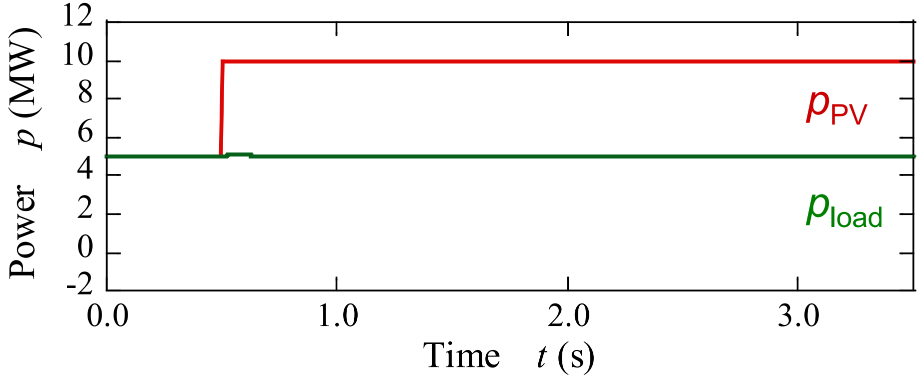
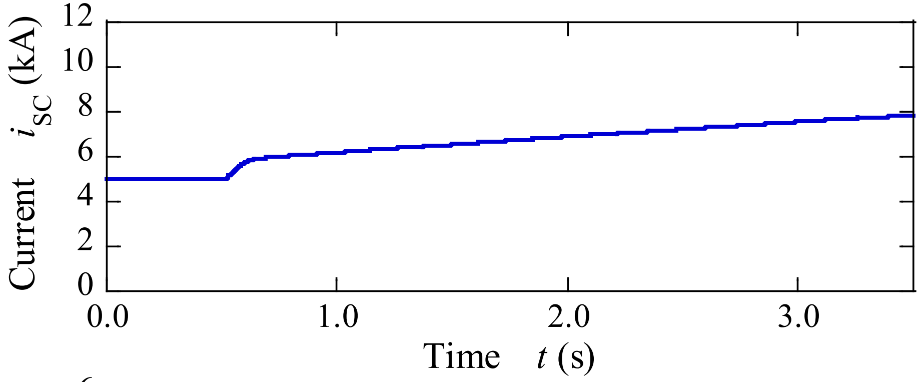
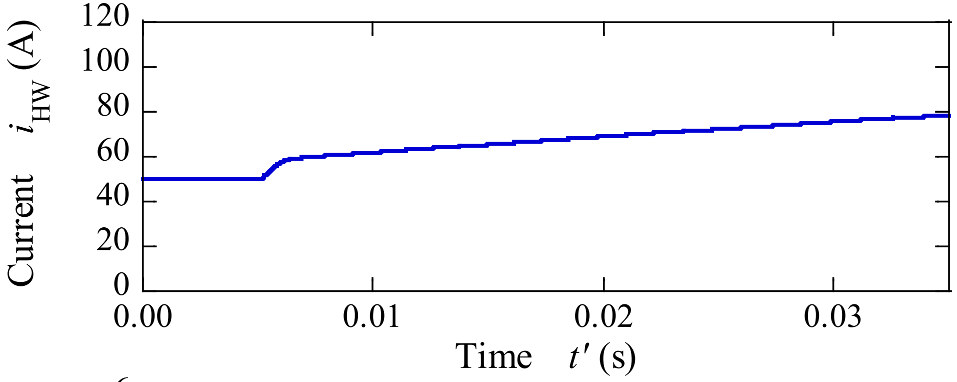
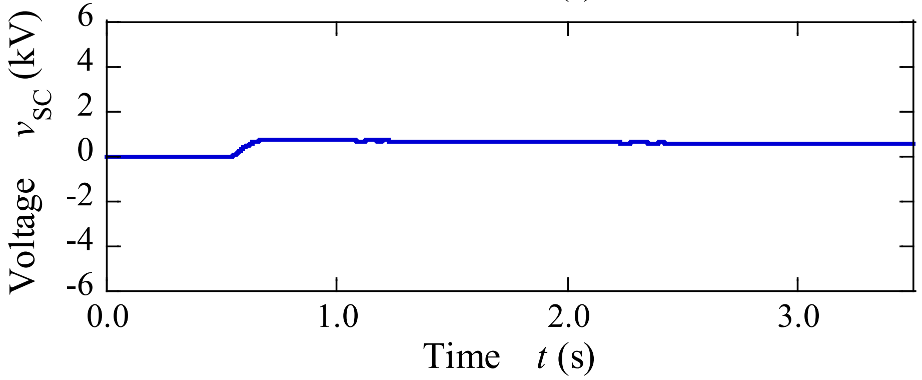
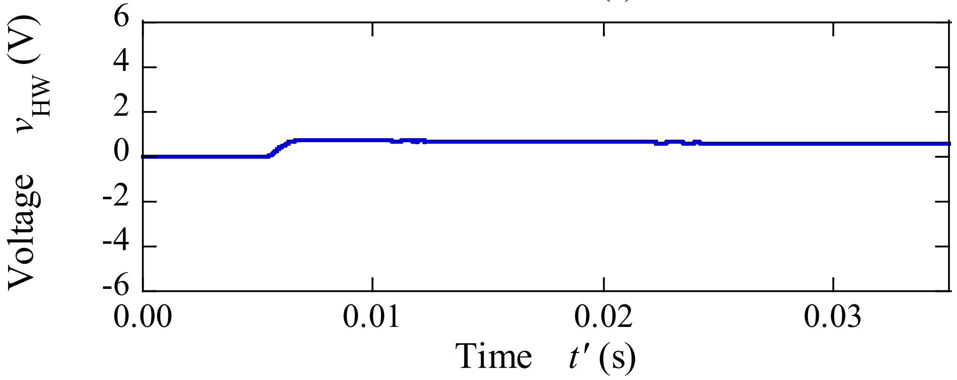


ultimate output fluctuation compensation function (instantaneous compensation)









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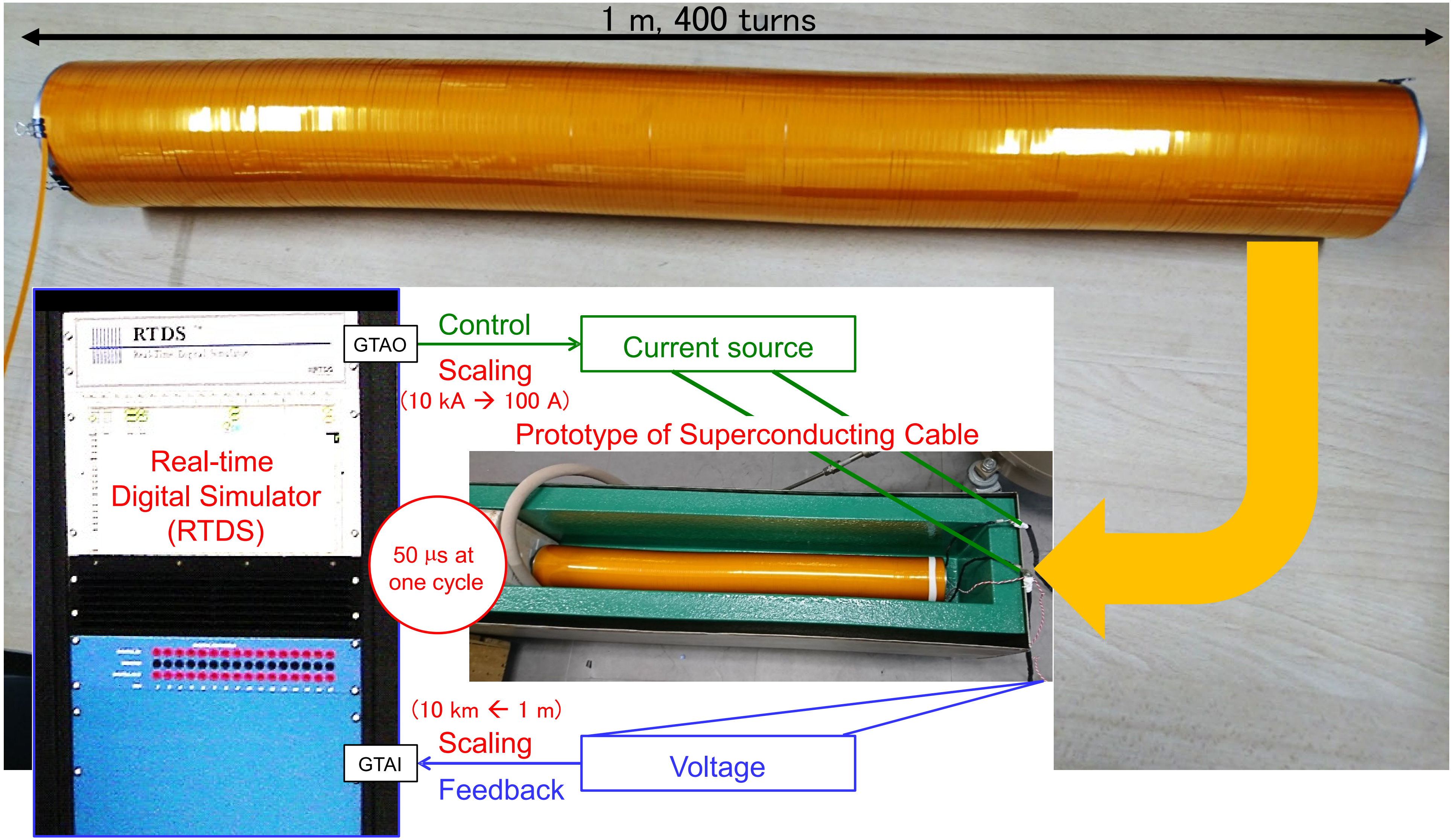
Hardware in the loop Simulation (HILS) for 1-GJ SMES Cable



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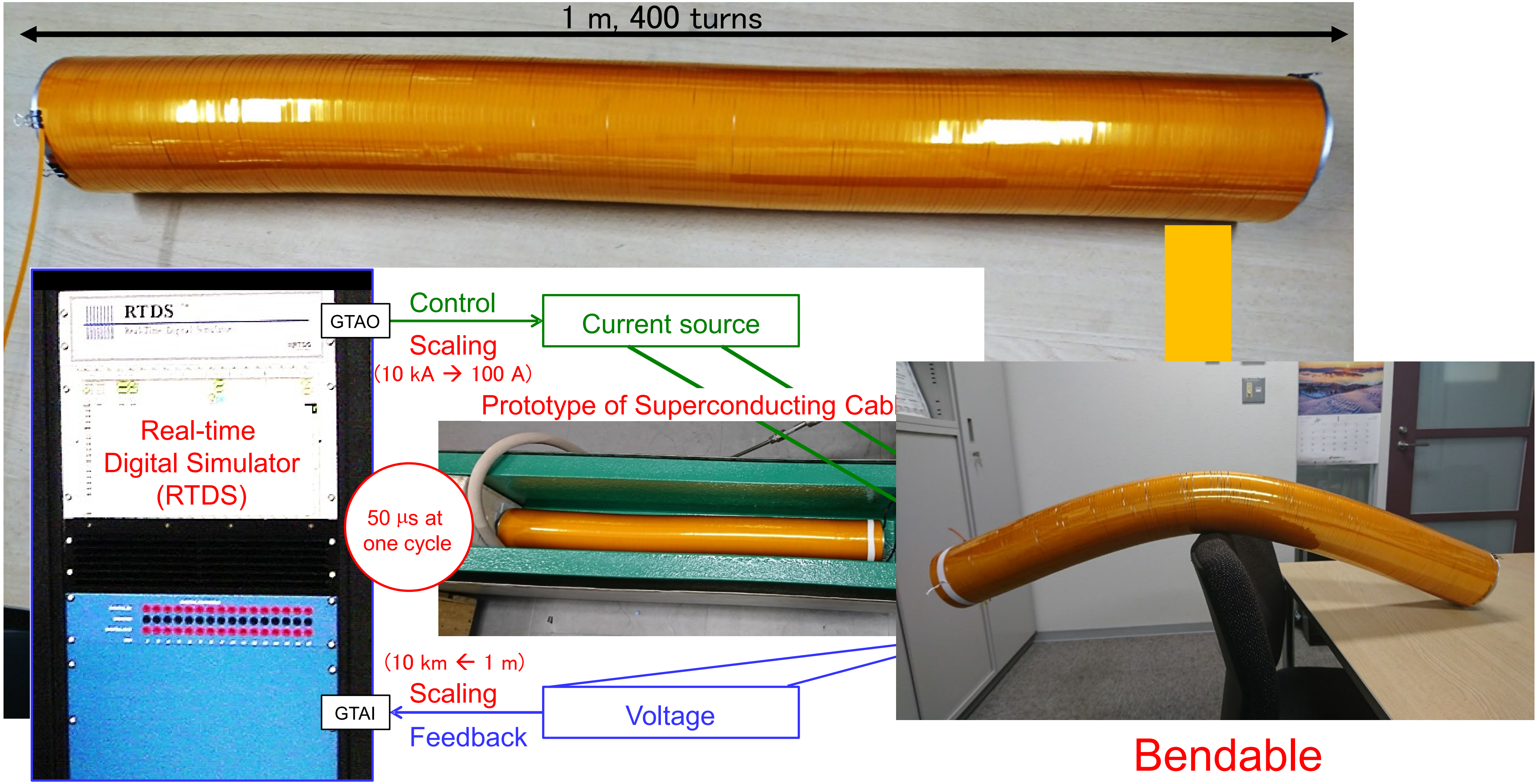
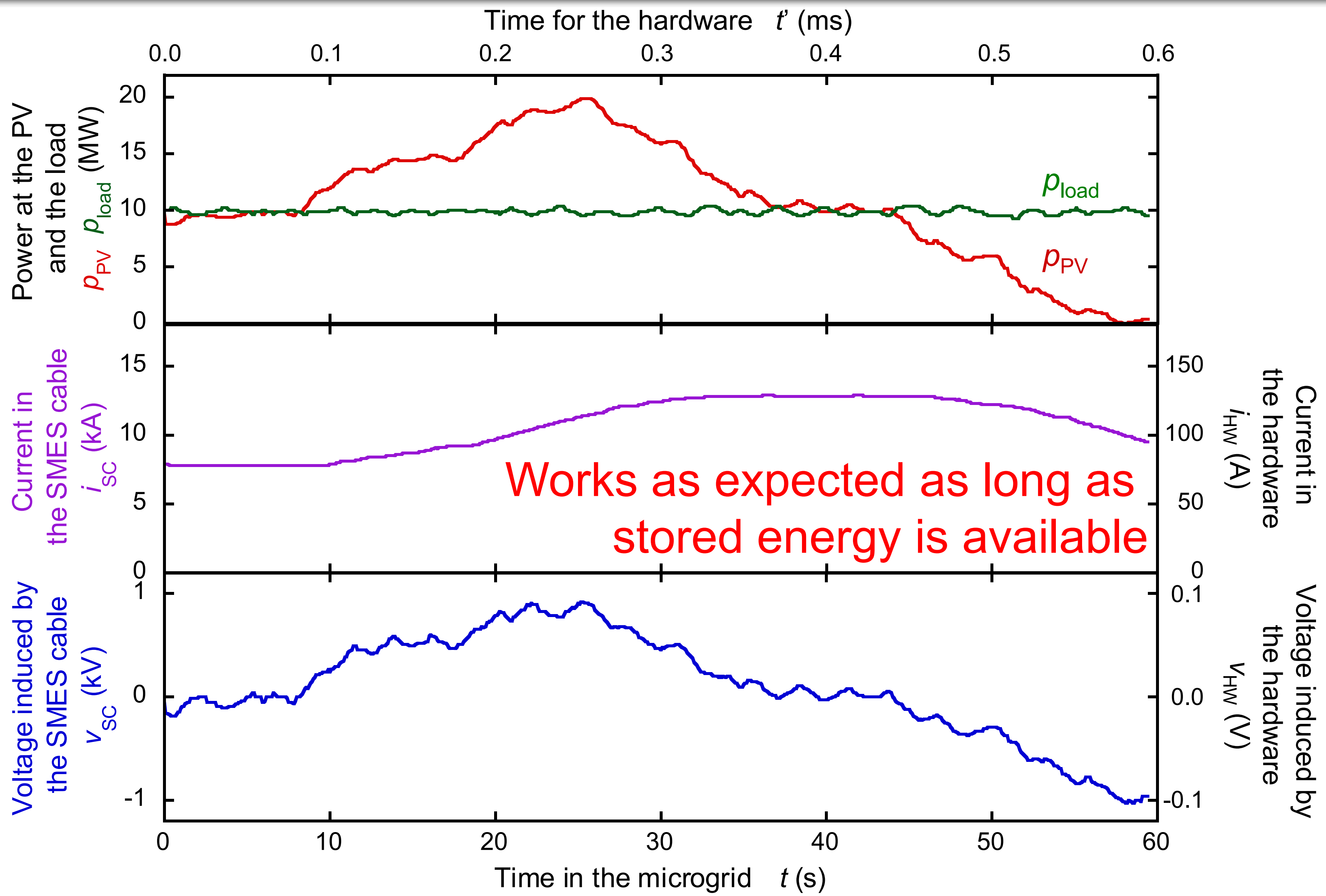
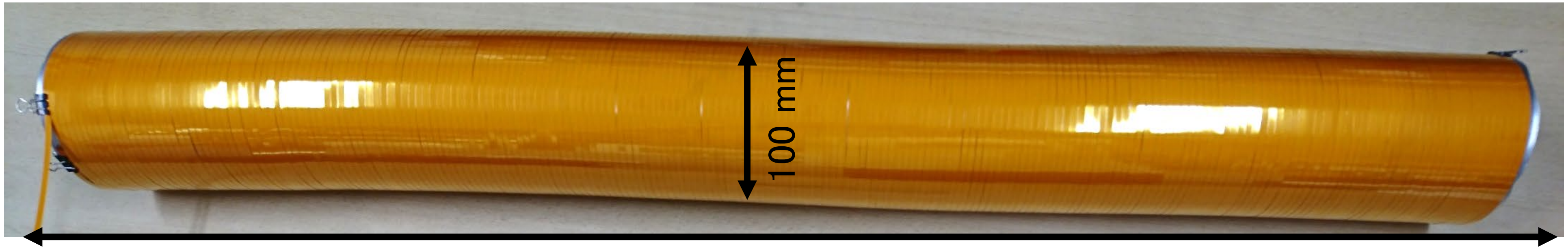


Results obtained by HILS (Charge-Discharge)



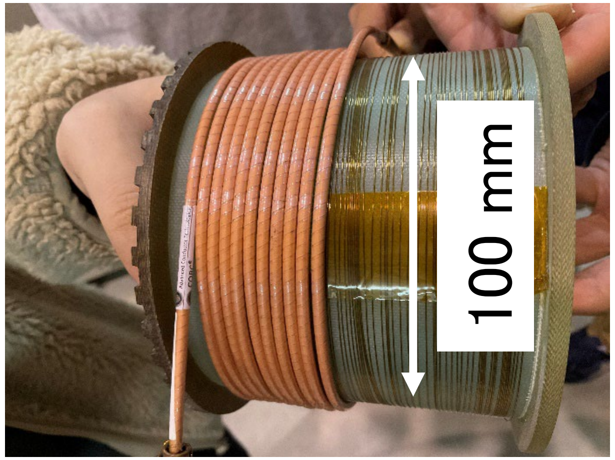
Winding Test with High-current Conductor

Small Model Cable by Single Tape
(RE-123 CC, cross-section: ~0.6 mm^2 (4 mm x 0.15 mm))



1 m, 400 turns

Winding test with high-current conductor
(CORC®, cross-section: 7.74 mm^2 (diameter: 3.14 mm))

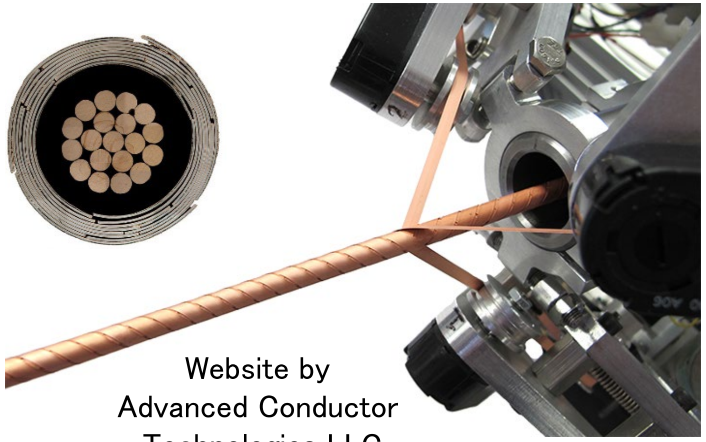


Specification:

Bundle of 12 tapes
(2 mm wide, 30 um thick)

Nominal I_c : 670 A @ 77K
Expected I_c : 500-600 A

(~10 kA @ 20 K)



Website by
Advanced Conductor
Technologies LLC

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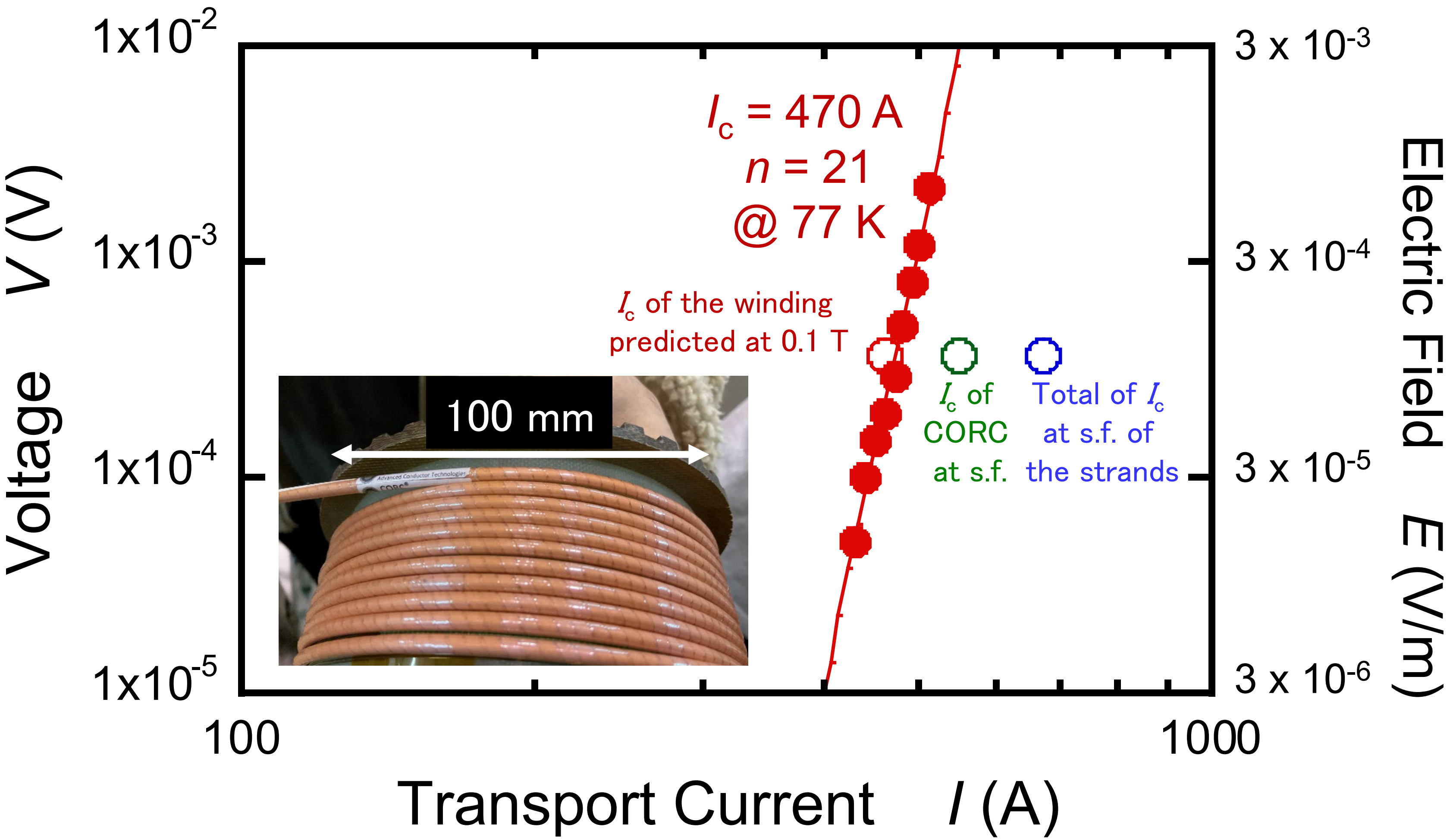

Winding with high-current conductors will be applicable

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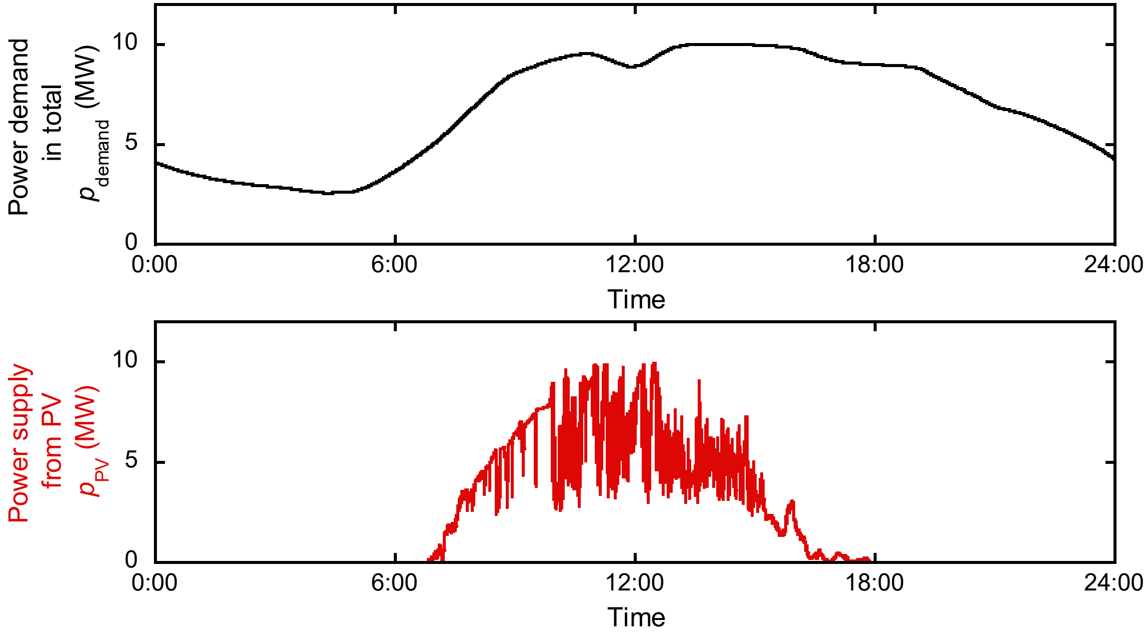
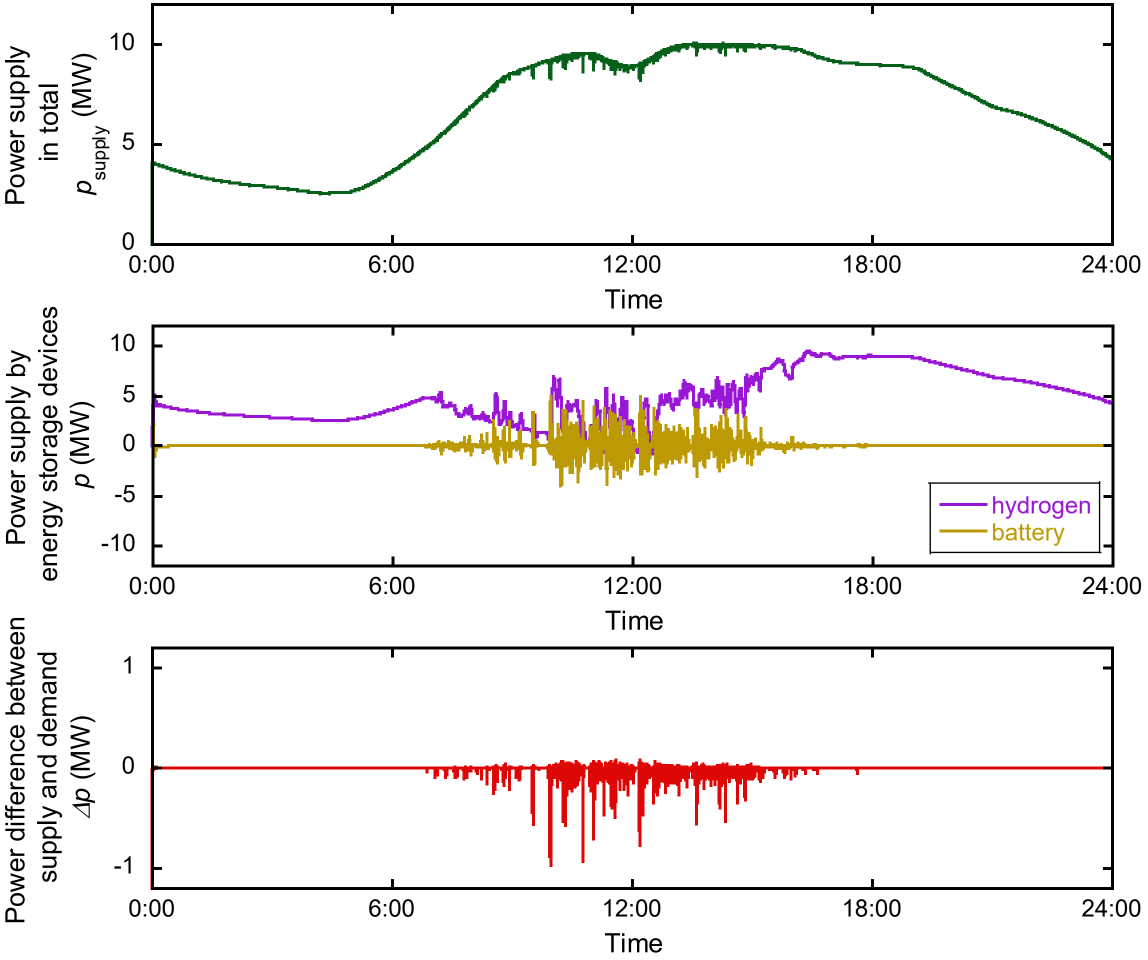
Effect of SMES Cable on Microgrid (without SMES Cable)

Supposed profiles of demand and output power from PV



Without SMES Cable

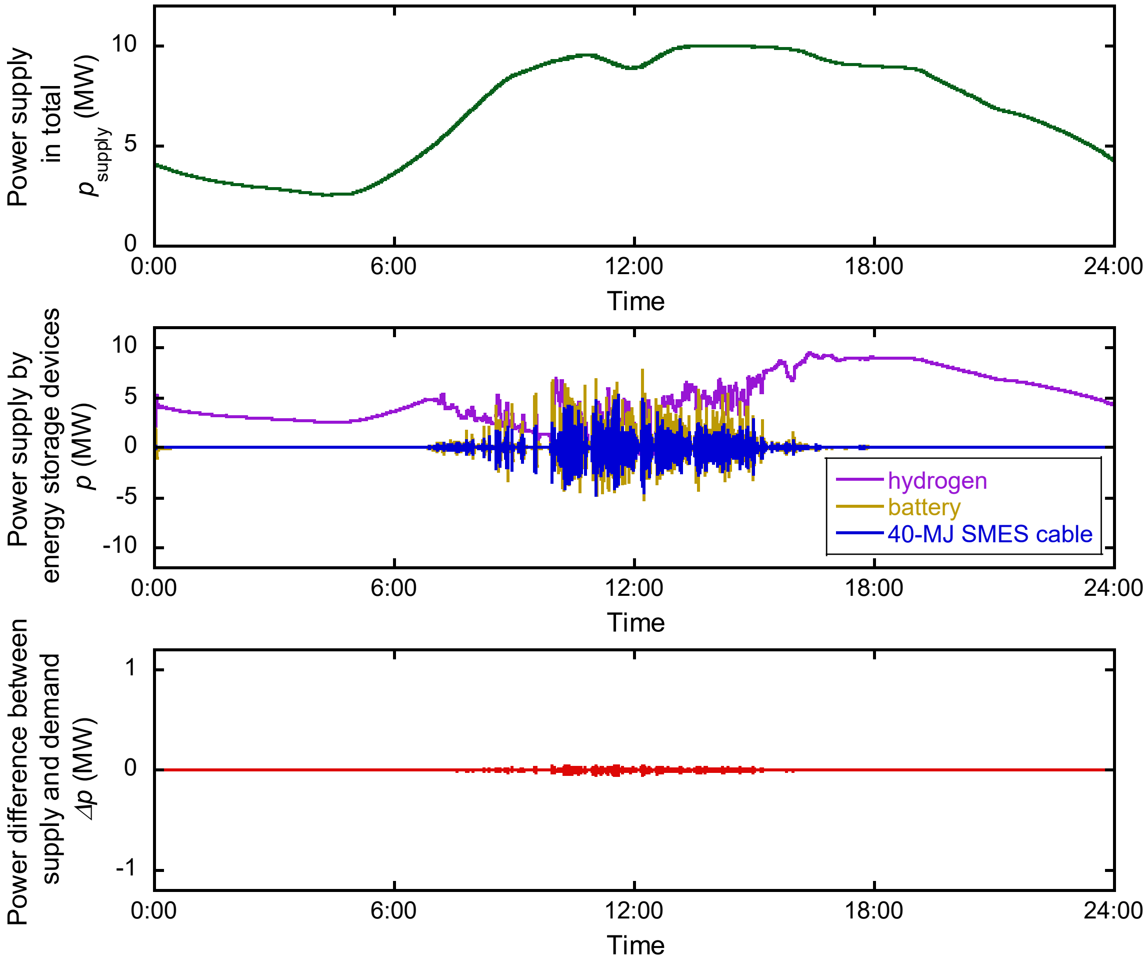


Difficult to compensate for
output power fluctuation of PV in real time

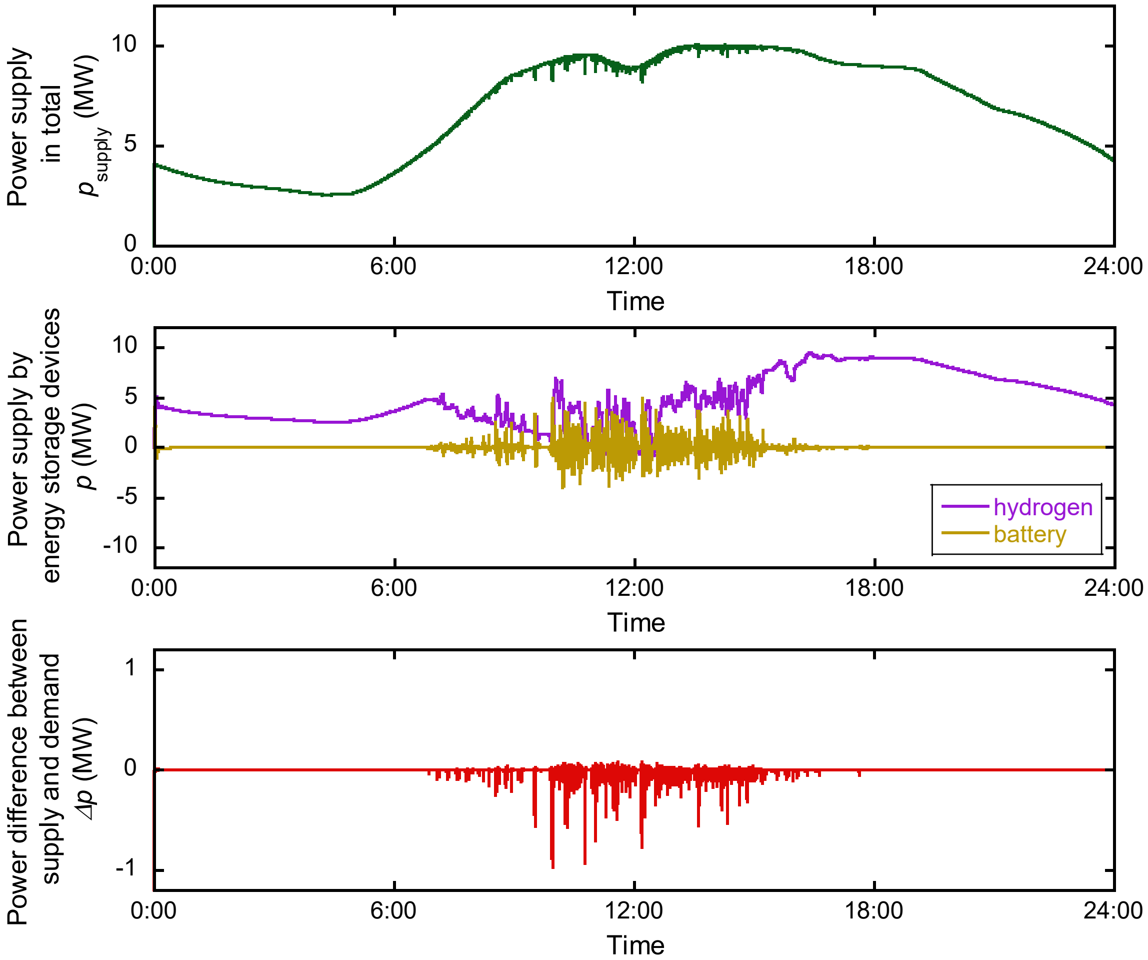
→ Need to convert energy into hydrogen in advance,
and efficiency until it is converted back into electrical energy is an issue.

Effect of SMES Cable on Microgrid (with 40-MJ SMES Cable)

With 40-MJ SMES Cable



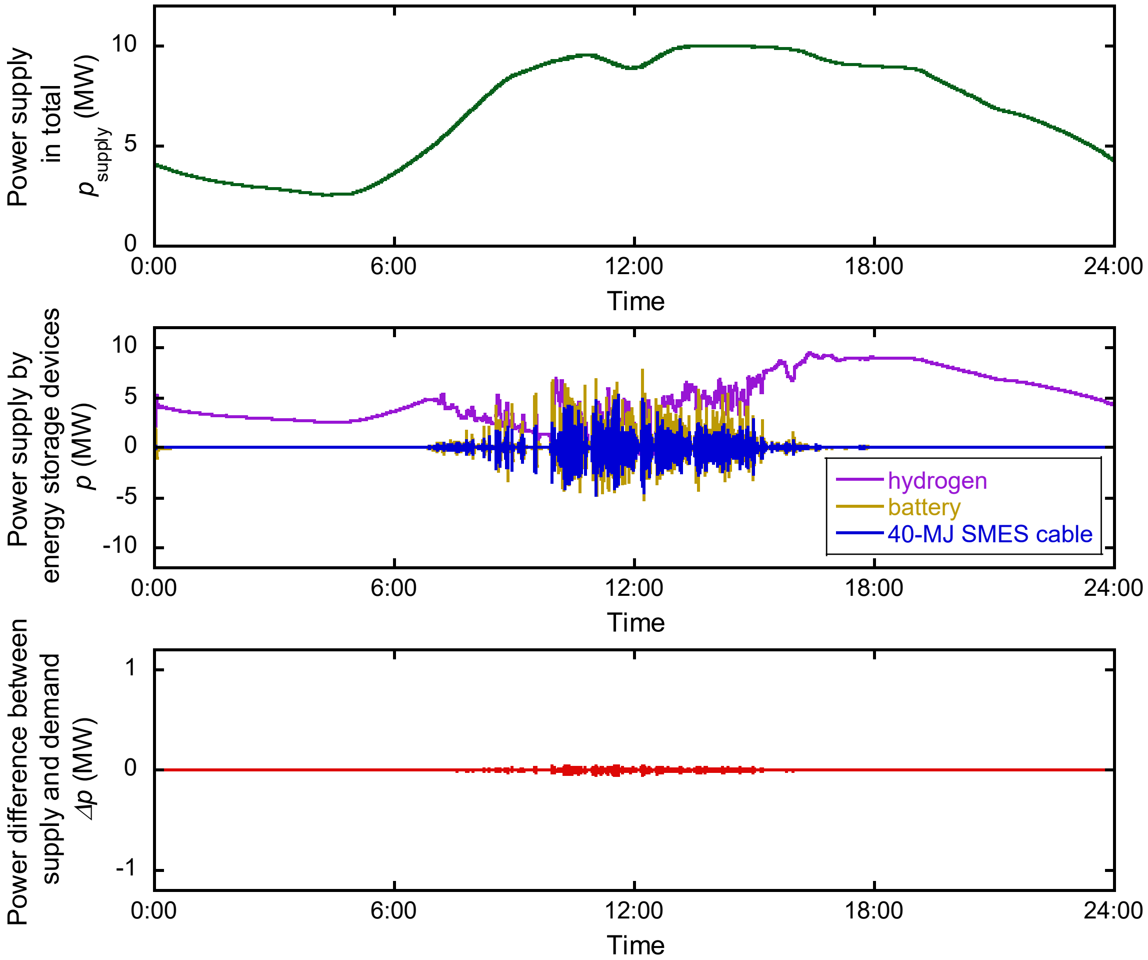
Without SMES Cable

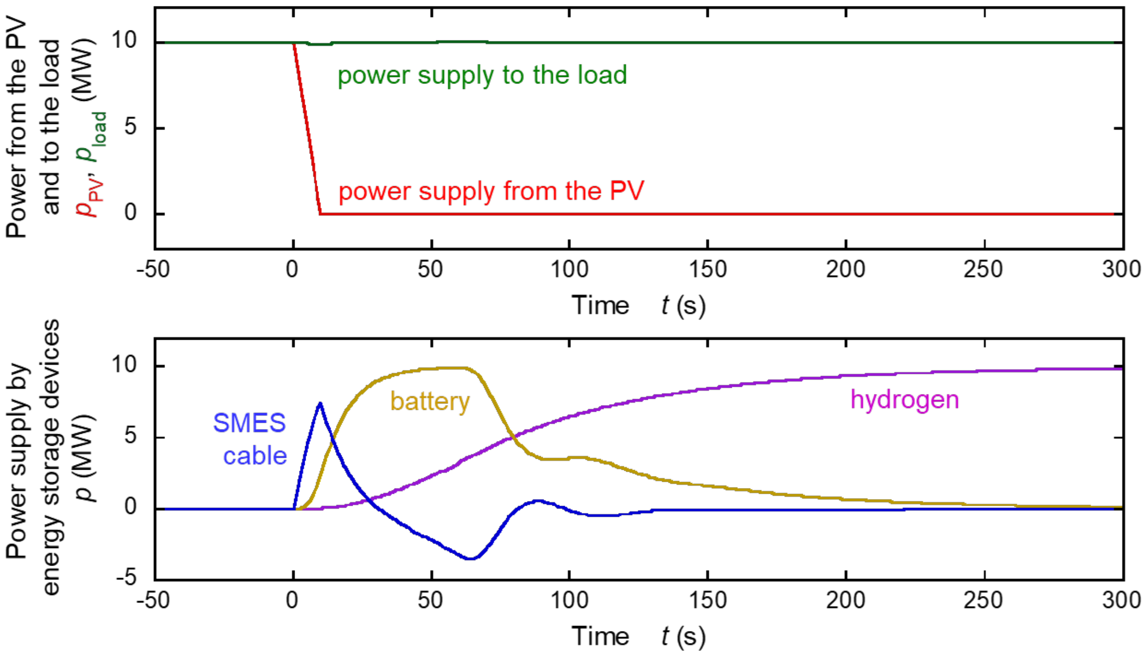


The introduction of the SMES cable will eliminate the problem of instantaneous mismatch between supply and demand.

Effect of SMES Cable on Microgrid (with 40-MJ SMES Cable)

With 40-MJ SMES Cable





The introduction of the SMES cable will eliminate the problem of instantaneous mismatch between supply and demand.

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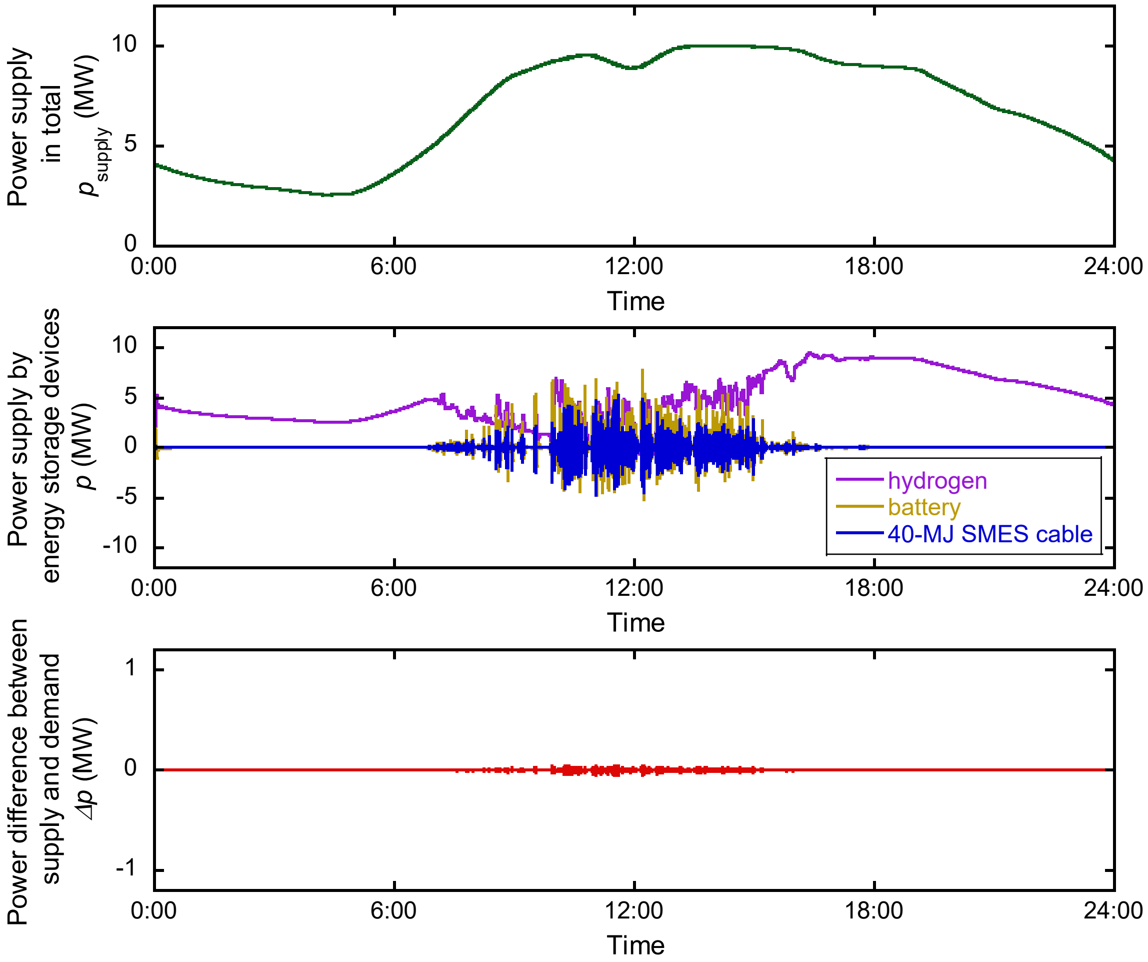
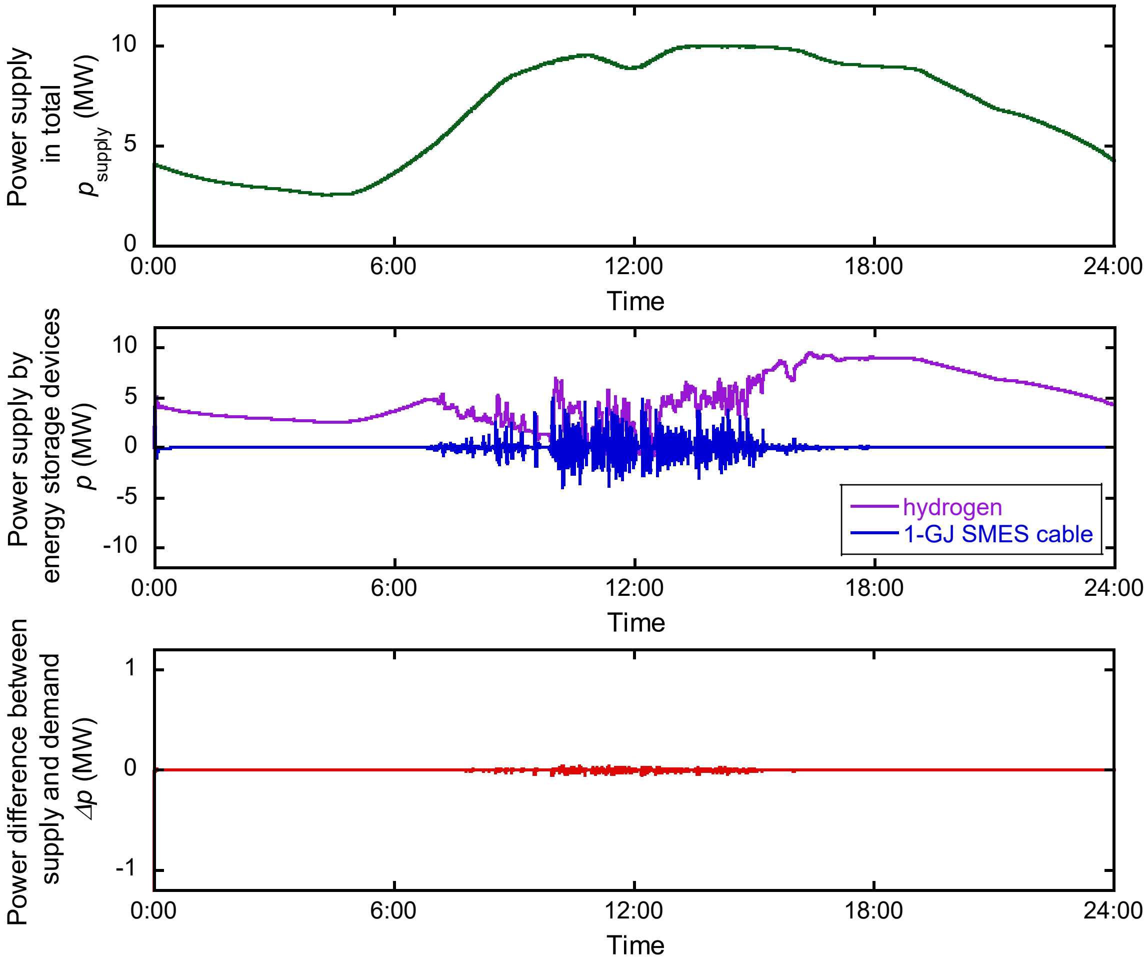
Effect of SMES Cable on Microgrid (with 1-GJ SMES Cable)

With 40-MJ SMES Cable



With 1-GJ SMES Cable



In addition,
storage batteries may no longer be needed.

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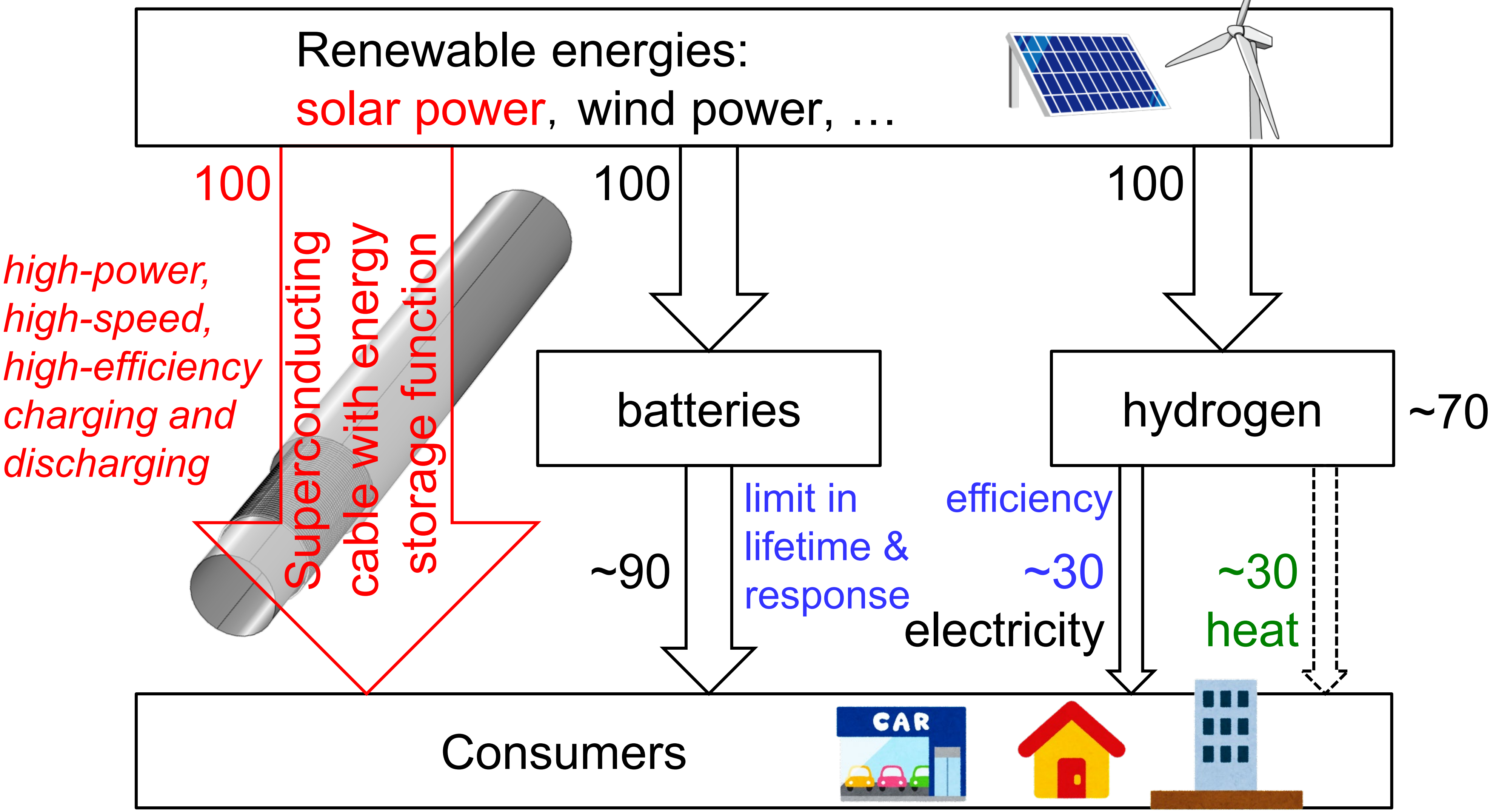
Summary

Solves the problem of fluctuating renewable energy output and further maximizes energy utilization
Almost zero additional losses for energy storage because it also transports electricity!



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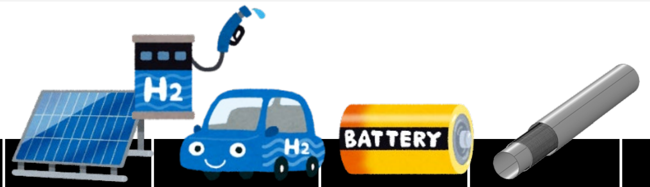
Energy Use Efficiency and The Corresponding Cost Impact

“Byen” means billion (Japanese) yen. The costs are estimated both from present unit cost of energy and from future one, and are listed above and below in each cell, respectively. The battery is assumed to be replaced twice every 30 years due to its lifetime.



Case	PV	hydrogen	battery	SMES cable	supply-demand balancing	energy utilization efficiency (cloudy day)	energy utilization efficiency (clear sometimes cloudy day)	energy utilization efficiency (clear day)	annual average efficiency	electricity directly suppled by PV for 30 years	electricity supply by hydrogen for 30 years	energy cost for 30 years: present, future	Allowable cost for installing SMES cable: present, future
Case O	10 MW	10 MW	-	-	NG	-	-	-	-	-	-	-	-
Case B	10 MW	10 MW	10 MW	-	NG	-	-	-	-	-	-	-	-
Case H	-	10 MW	-	-	OK	30%	30%	30%	30%	-	1.75 TWh	175 Byen, 53 Byen	-
Case SB	10 MW	10 MW	10 MW	60 MJ	OK	32%	37%	43%	38%	0.52 TWh	1.24 TWh	134 Byen, 42 Byen	38 Byen, 8 Byen
Case S	10 MW	10 MW	-	500 MJ	OK	32%	38%	43%	38%	0.52 TWh	1.23 TWh	133 Byen, 42 Byen	42 Byen, 11 Byen
Case S15	15 MW	10 MW	-	750 MJ	OK	34%	41%	46%	41%	0.68 TWh	1.07 TWh	121 Byen, 38 Byen	54 Byen, 15 Byen
Case S19	19 MW	10 MW	-	1 GJ	OK	35%	43%	48%	43%	0.77 TWh	0.98 TWh	113 Byen, 37 Byen	62 Byen, 16 Byen
Case SB19	19 MW	10 MW	10 MW	120 MJ	OK	35%	43%	48%	43%	0.77 TWh	0.99 TWh	114 Byen, 37 Byen	58 Byen, 13 Byen

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Stored energy:	60 MJ
Magnetic field:	1.5 T
Cable diameter:	100 mm
Turn number per unit length:	120 turns
Length of conductor per unit length:	37.7 m/m
Bundle of 4-mm-wide CC	38 tapes / 10 kA at 65 K
Total amount of 4-mm-wide CC	14326 km / 10 km cable

Permissible price of 4-mm-wide CC

~20 USD / m (2652 yen / m)
for present of green hydrogen

~4 USD / m (558 yen / m)
for future cost of green hydrogen

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Conclusion

Thank you very much for your kind attention!

A novel power system with energy storage function by superconducting cable was proposed, designed, and demonstrated

Advantages:

(i) high-speed & high-power operation

(ii) no additional space for energy storage

(iii) scalability

(iv) DC operation suitable for superconducting cable and for recent loads

(v) overcoming the disadvantage of small energy capacity of SMES

This technology will offer high-power and high-speed power compensation necessary for future large-scale utilization of renewable energies especially for PV power generation.

This work was mainly supported by
NEDO Feasibility Study Program (Uncharted Territory Challenge 2050)
with one of the largest budget for young researcher: ~100 million (Japanese) yen.

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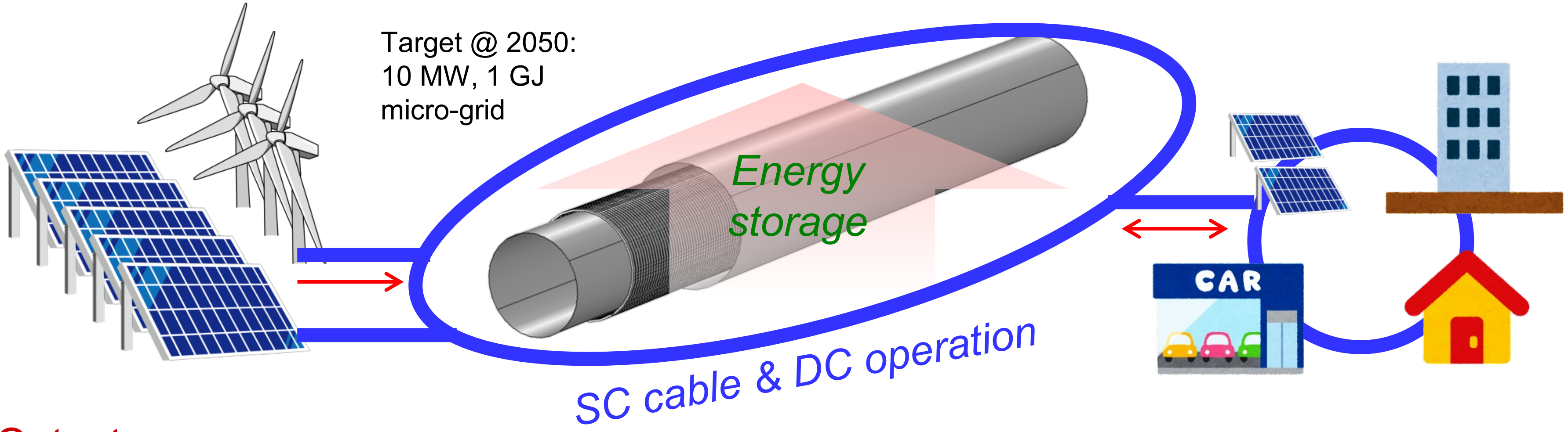
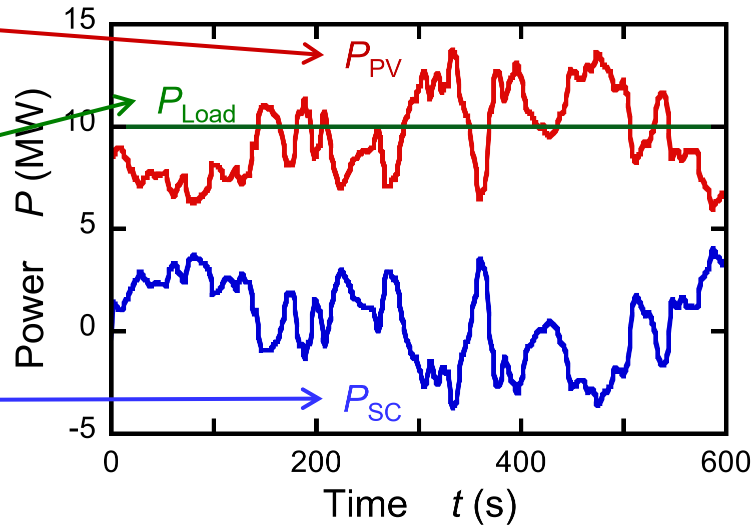
Summary

Newly proposed special superconducting cables and their innovative operation will give the power grid energy storage, charge and discharge functions

→ A decisive factor for the mass introduction of renewable energy!



Output power fluctuation from **renewable energies** **compensated** by **superconducting cable with fast & large-power charge-discharge operation** without any batteries



Game-changing technology for
Large-scale Utilization of Renewable Energies