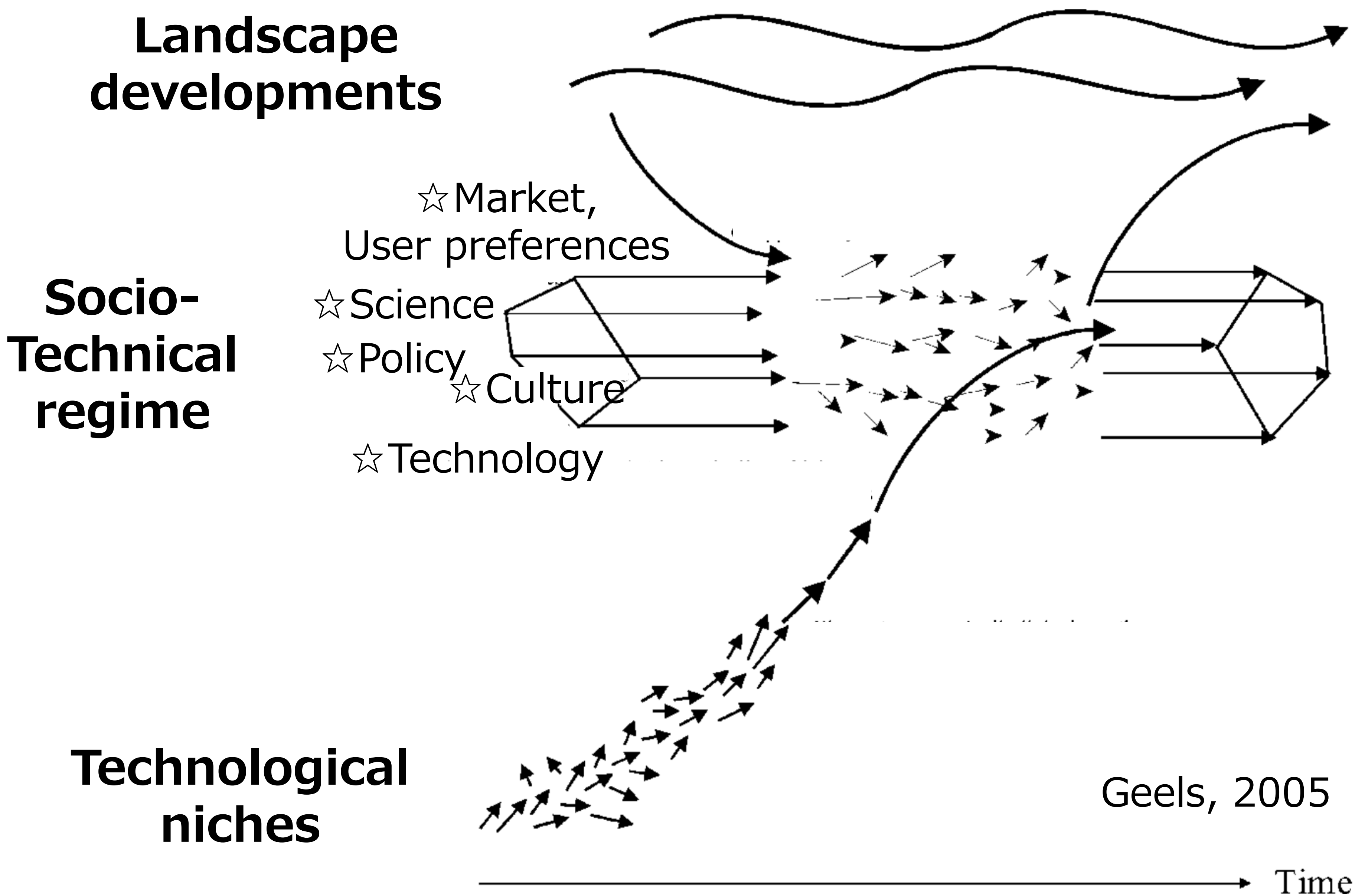
The 8th FC International Meeting 2020
2020.2.25

Toward Economically Rational Hydrogen Production from Solar Energy:
From Battery versus Hydrogen to Battery × Hydrogen

Michihisa KOYAMA

2019-Present	COO & Co-founder, X-Scientia Co. Ltd.
2018-Present	Professor, Shinshu University
2016-Present	Unit Director (Visiting Researcher) National Institute for Materials Science
2016-Present	Visiting Professor, Hiroshima University
2008-2018	Professor, Kyushu University
2003-2008	Assistant Professor, Tohoku University
2002-2003	Postdoctoral Fellow, The University of Tokyo
2002	Ph.D.(Eng.), The University of Tokyo

Landscape, Regime & Niche Techs



ESG Investment

https://theinvestoragenda.org/wp-content/uploads/2019/12/191201-GISGCC-FINAL-for-COP25.pdf

Global Investor Statement to Governments on Climate Change

GLOBAL INVESTOR STATEMENT TO GOVERNMENTS ON CLIMATE CHANGE

This statement is signed by 631 investors representing over USD $37 trillion in assets.

As institutional investors with millions of beneficiaries around the world, we reiterate our full support for the Paris Agreement [link] and strongly urge all governments to implement the actions that are needed to achieve the goals of the Agreement, with the utmost urgency.

Investors are taking action on climate change. The global shift to clean energy is underway, but much more needs to be done by governments to accelerate the low carbon transition and to improve the resilience of our economy, society and the financial system to climate risks. Investors continue to make significant investments into the low carbon transition across a range of asset classes. Investors are also increasingly incorporating climate change scenarios and climate risk management strategies into their investment processes and engaging with high-emitting companies. To build on this momentum and maintain investor confidence to further shift investment portfolios, it is vital that policy makers are firmly committed to achieving the goals of the Paris Agreement.

Sustainable Finance

EU Taxonomy : Classification Frame

Six environmental objectives

(1) climate change mitigation
(2) climate change adaptation
(3) sustainable use and protection of water & marine resources
(4) transition to a circular economy, waste prevention and recycling
(5) pollution prevention and control
(6) protection of healthy ecosystems

Technical Screening Criteria

-Substantial contribution to at least one environmental objective
-Doing no significant harm to the other environmental objectives (DNSH)

【Nuclear power plant】
excluded from DNSH point of views

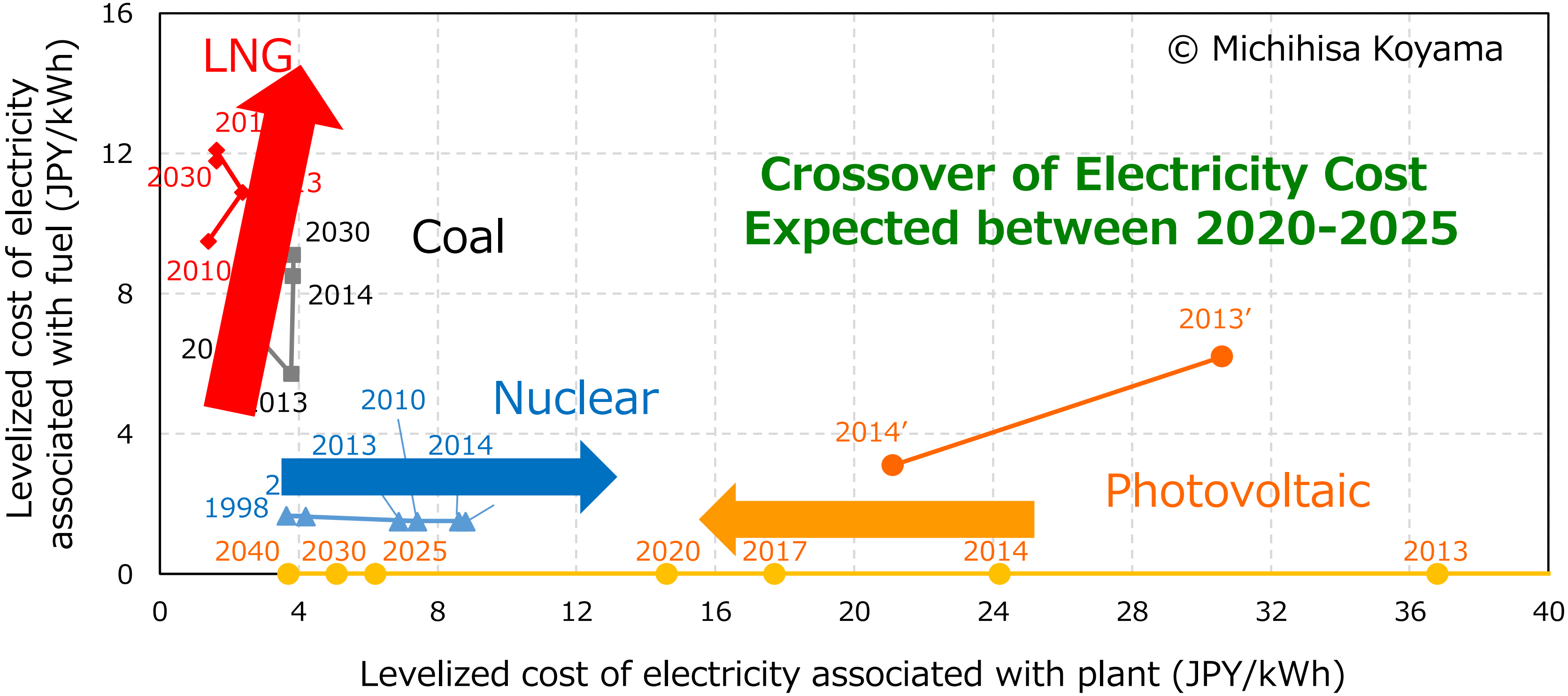
【Gas thermal power plant】
without CCS: excluded
with CCS: emissions from total supply chain should be measured (not estimated)

【Coal power plant with CCS】
excluded

【CCS】
CCS itself is included

Landscape – Changing Cost in Japan

Cost of PV Electricity is expensive in Japan !?



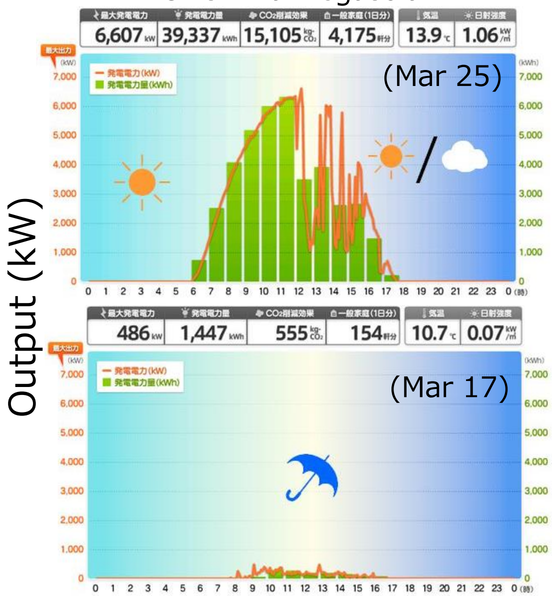
M. Koyama, Chapter 16. Toward Economically Rational Hydrogen Production from Solar Energy: From Battery versus Hydrogen to Battery × Hydrogen, in Nanostructured Materials for Next-Generation Energy Storage and Conversion: Photovoltaic and Solar Energy, T. A. Atesin, S. Bashir, J. Liu Eds., Springer, 2019, pp. 457-470.

Necessity of Energy Storage

Low operation ratio : ～12%

From TEPCO Web Page

Ukishima Megasolar

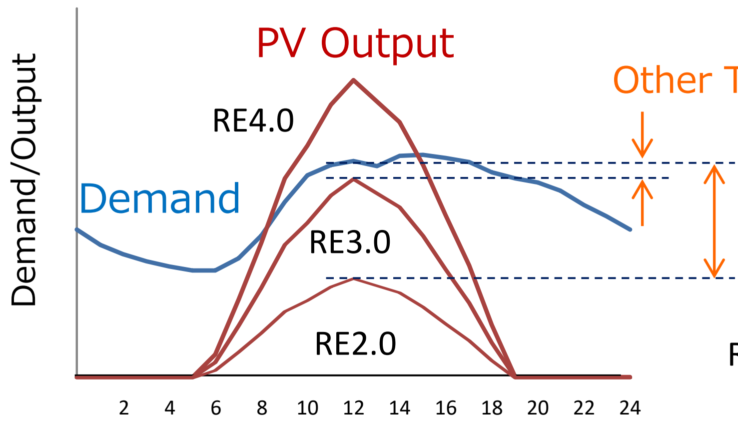


Time

Cf. Wind : ～22%

Small Hydro : ～70%

Geothermal : ～80%



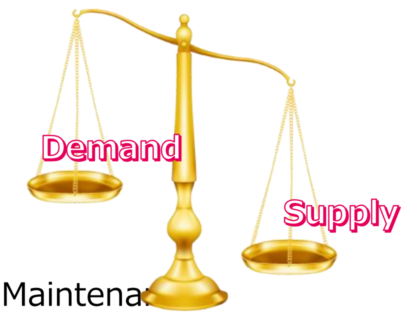
RE: Renewable Energy

Demand < Supply

Frequency ↑

Demand > Supply

Frequency ↓



Electricity Business Act

Article 44, Clause 2

Commitment for Frequency Maintena[nce]

±0.2Hz (±0.3Hz in Hokkaido)

Output fluctuation of PV･･･

⇒Adjusted by Thermal/Pumped hydro plants etc.

Landscape, Regime & Niche Techs

Landscape developments

Socio-Technical regime

☆Market, User preferences

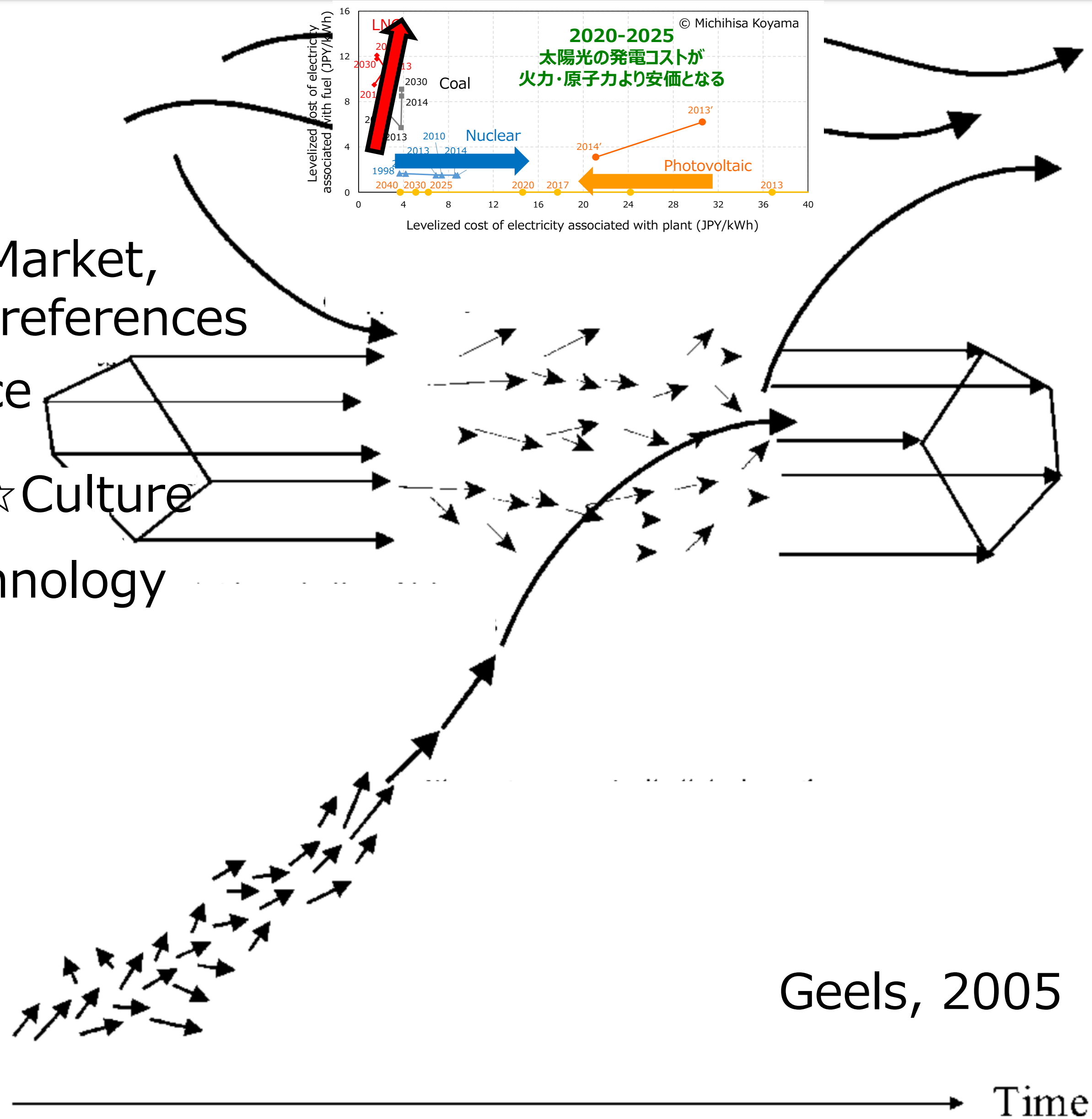
☆Science

☆Policy

☆Culture

☆Technology

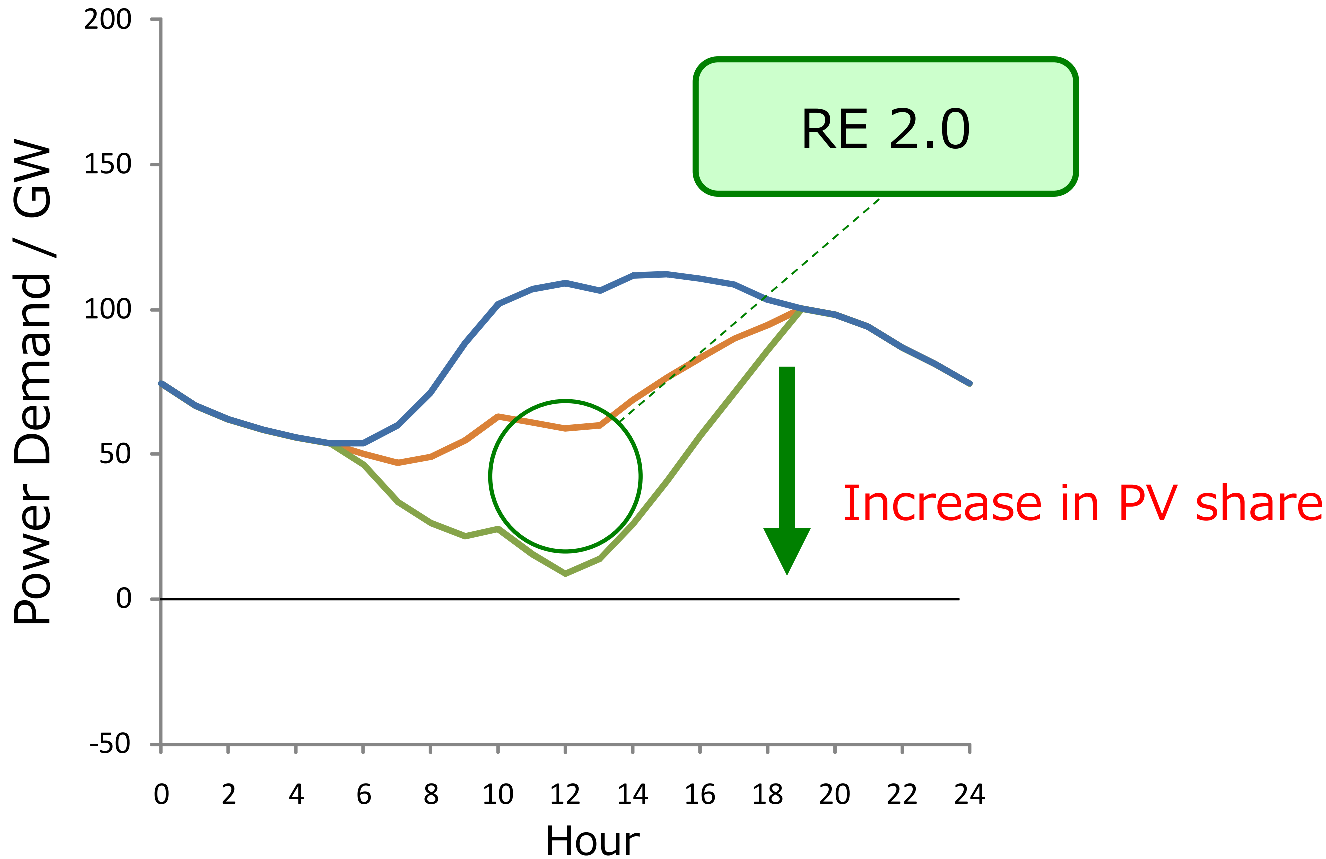
Technological niches



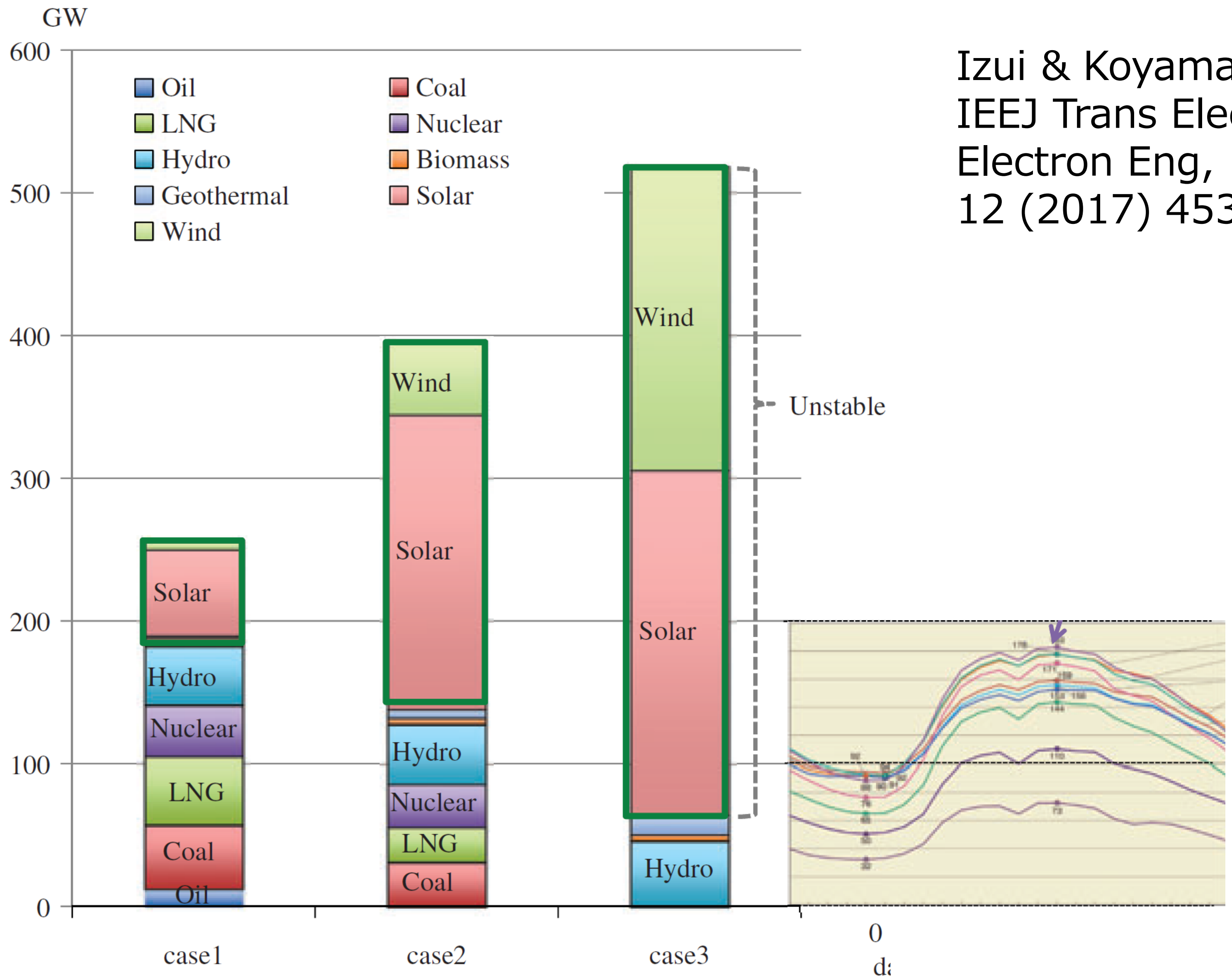
Geels, 2005

Power Grid with Renewable ?

Supply-Demand Gap with Massive Renewable Contribution



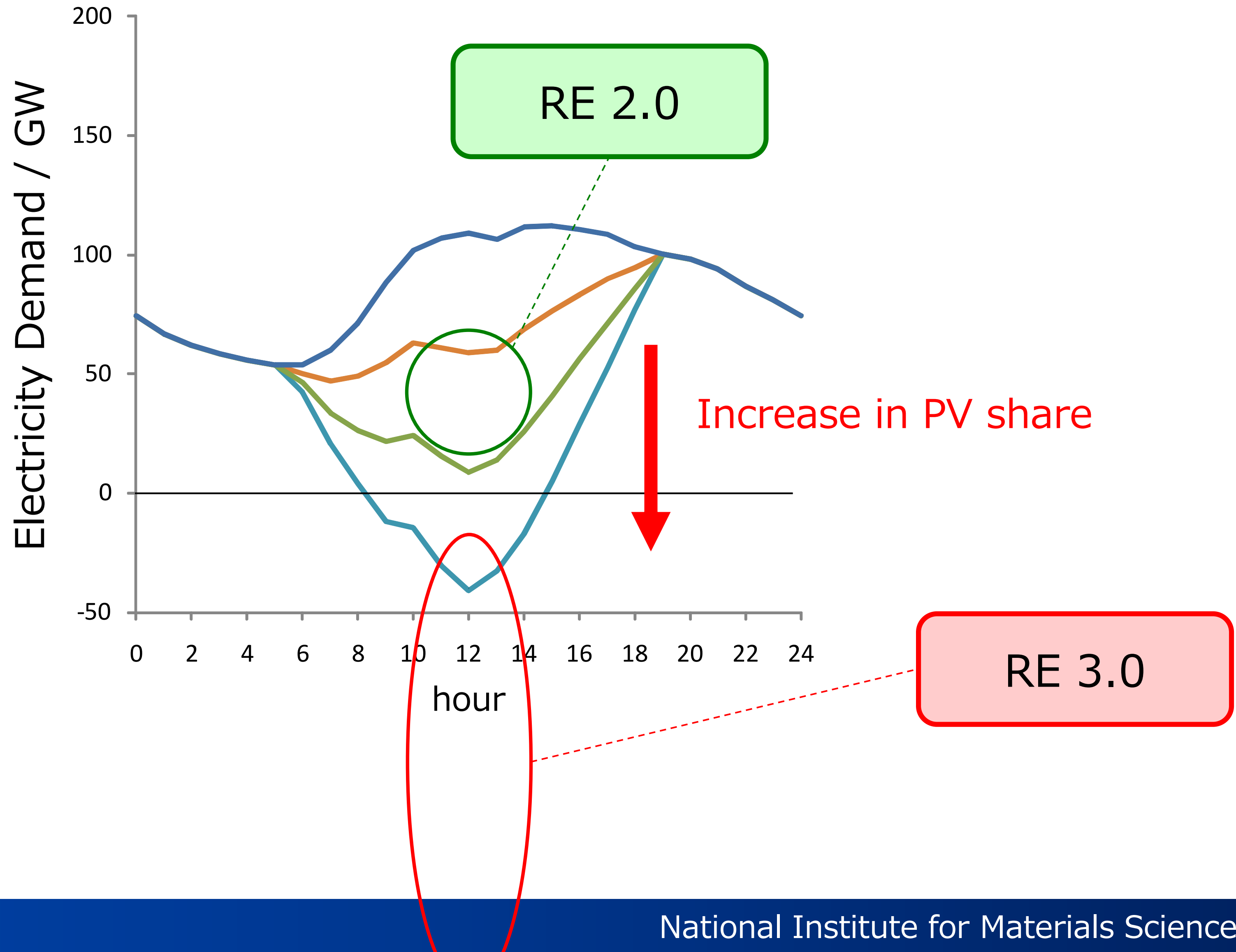
Power Grid with RE100 ?



Izui & Koyama, IEEJ Trans Electr Electron Eng, 12 (2017) 453.

Power Grid with RE100% ?

Supply-Demand Gap with Massive Renewable Contribution



H_2 Production from PV

$$\underset{(LCOH)}{Levelized\ Cost\ of\ Hydrogen} = \frac{Capital\ Cost + Operation\ Cost + Maintenance\ Cost}{Amont\ of\ Hydrogen\ Produced}$$

Capital Cost ≒ Capacity×Unit Cost/Depreciation Period
Operation Cost ≒ （Electricity & Water Unit Cost）×Capacity×Operation Time
Maintenance Cost ≒ Capacity×Unit Cost×Maintenance Ratio
Amount of Hydrogen ≒ Capacity×Operation Time×Efficiency

$$LCOH = \frac{Unit\ Cost/(Depreciation\ Period)}{Operation\ Time \times Efficiency} + e^{-}\ \&\ H_2O\ Cost + \frac{Unit\ Cost \times Maintenance\ Ratio}{Operation\ Time \times Efficiency}$$

Assuming 5kWh/Nm^3-H_2

20 JPY/kWh ⇒ 100 JPY/Nm^3-H_2
13 JPY/kWh ⇒ 65 JPY/Nm^3-H_2
7 JPY/kWh ⇒ 35 JPY/Nm^3-H_2
3 JPY/kWh ⇒ 15 JPY/Nm^3-H_2

H_2 Production from PV

$$\text{Levelized Cost of Hydrogen (LCOH)} = \frac{\text{Capital Cost} + \text{Operation Cost} + \text{Maintenance Cost}}{\text{Amont of Hydrogen Produced}}$$

Capital Cost ≒ Capacity×Unit Cost/Depreciation Period
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Amount of Hydrogen ≒ Capacity×Operation Time×Efficiency

$$LCOH = \frac{\text{Unit Cost}/(\text{Depreciation Period})}{\text{Operation Time} \times \text{Efficiency}} + e^{-}\ \&\ H_2O\ \text{Cost} + \frac{\text{Unit Cost} \times \text{Maintenance Ratio}}{\text{Operation Time} \times \text{Efficiency}}$$

Assuming
electrolyzer Cost 100,000 JPY/kW Depreciation 10 yr 5kWh/Nm^3-H_2

1．Unpurchased surplus power of 400 hrs/yr
(Capacity ratio = 400/(24×365) ≒ 4.6%)
⇒125 JPY / Nm^3-H_2 （**Free electricity ≠ Cheap H_2**）
※Total H2 Price @ Refueling Station ≈ 90 JPY/Nm^3-H_2

2．Capacity ratio of 12% ⇒ 48 JPY / Nm^3-H_2

From EU : Hybridized Power to Gas

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 42 (2017) 13554–13567

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journal homepage: www.elsevier.com/locate/he

Hybridization strategies of power-to-gas systems and battery storage using renewable energy

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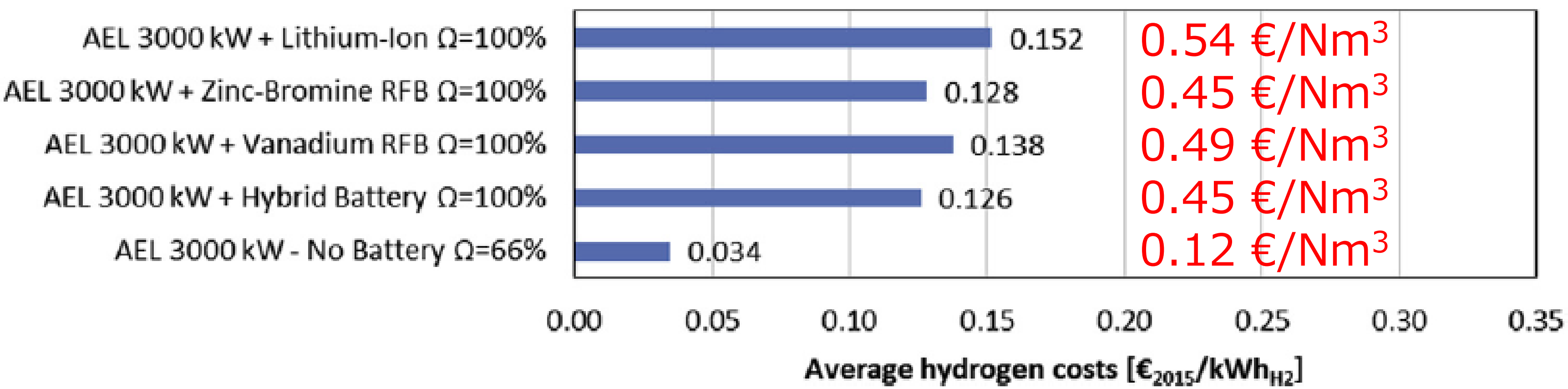


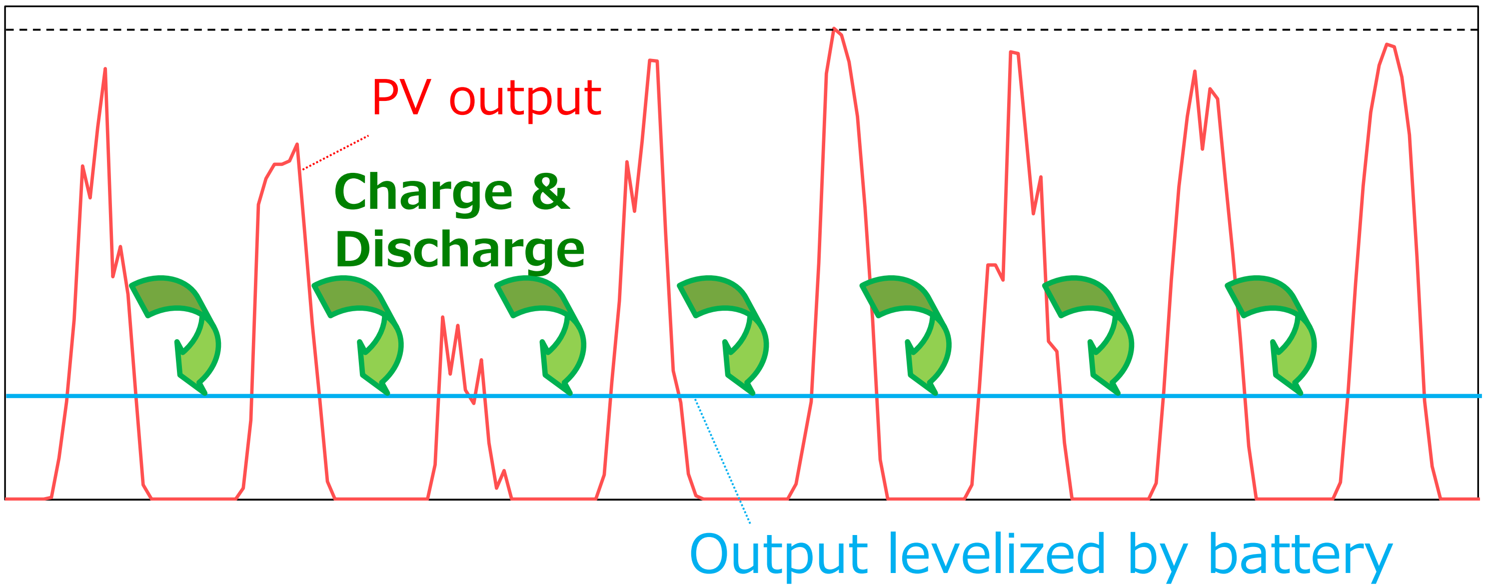
Fig. 10 – Average hydrogen costs for a 3000 kW$_{el}$ electrolyser system with data for 2030.

An Extreme of Battery Cost = 0

No effective solution to lower H2 Production cost from PV?
⇒Considering extremes to explore golden mean

Extreme 1: Electricity cost = 0 ⇒ No solution found so far
Extreme 2: Battery cost = 0 ⇒ ???

Battery Cost = 0 JPY/kWh & Efficiency = 100%
⇒Installation of infinite capacity battery!!

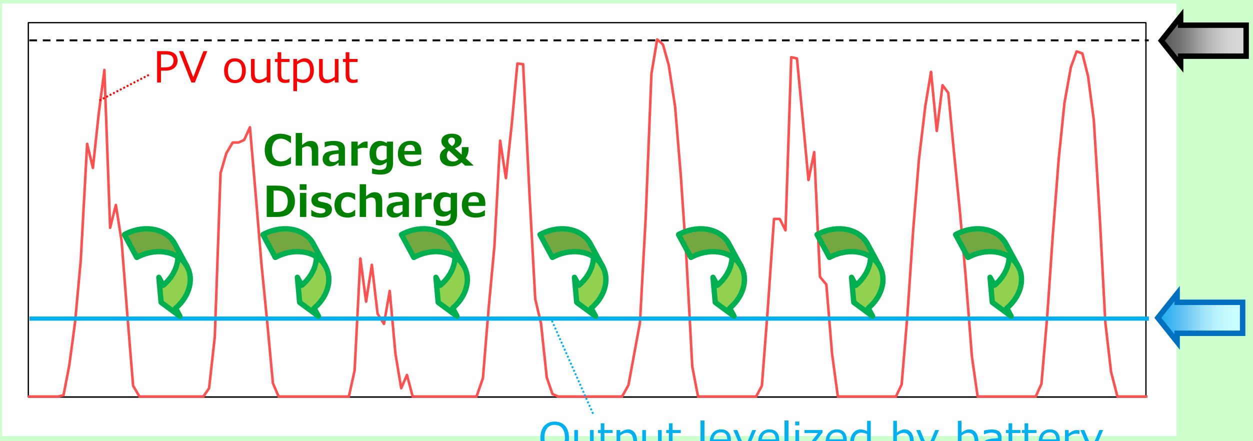


Integrated PV・Battery・Electrolyzer

$$LCOH = \frac{Unit\ Cost/(Depreciation\ Period)}{Operation\ Time \times Efficiency} + e^- \ \& \ H_2O\ Cost + \frac{Unit\ Cost \times Maintenance\ Ratio}{Operation\ Time \times Efficiency}$$

Battery Cost = 0 JPY/kWh & Efficiency = 100%

⇒Installation of infinite capacity battery!!



Benefit 1 : Capacity ratio⇒100%

Benefit 2 : Reduction of electrolyzer capacity⇒1/7～1/8

(When PV capacity ratio = 12～14%)

In real operation condition

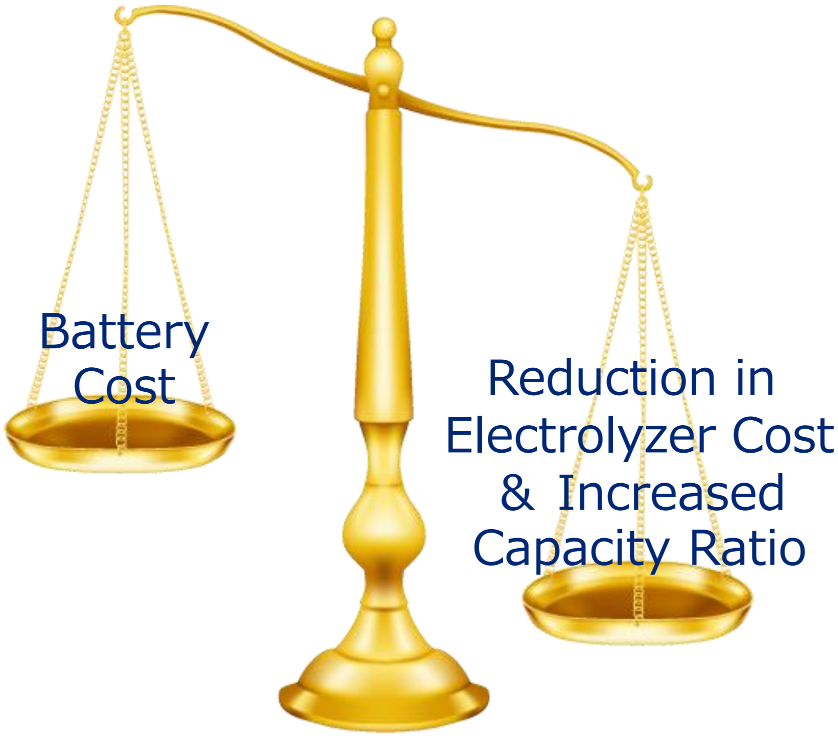
PV 1. ⇒ electrolyzer

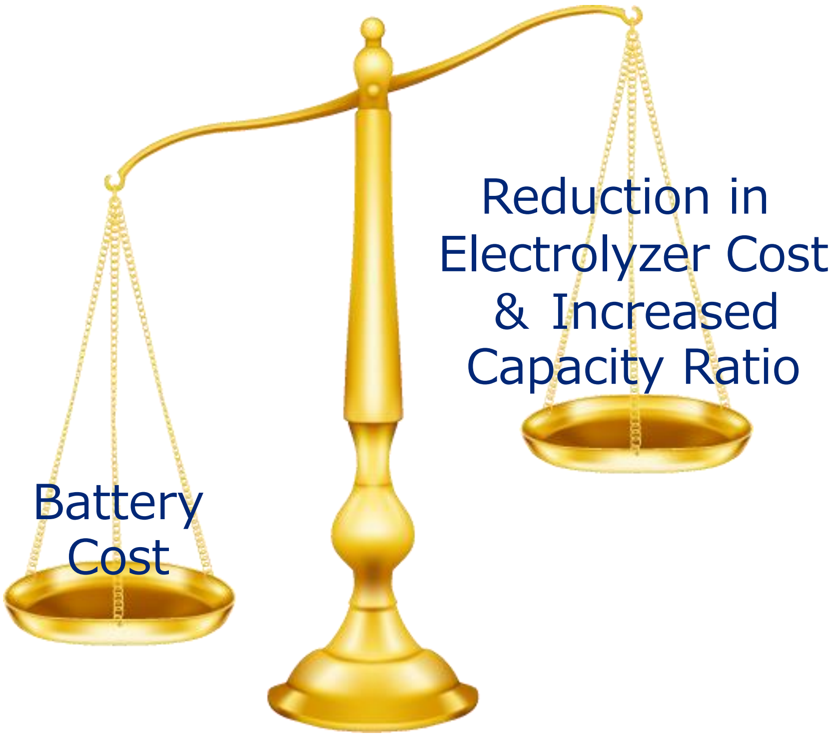
2. ⇒ battery ⇒ electrolyzer (charge/discharge loss)

3. ⇒ cut off

Need to identify condition additional cost of battery

Essential Problem to Tackle

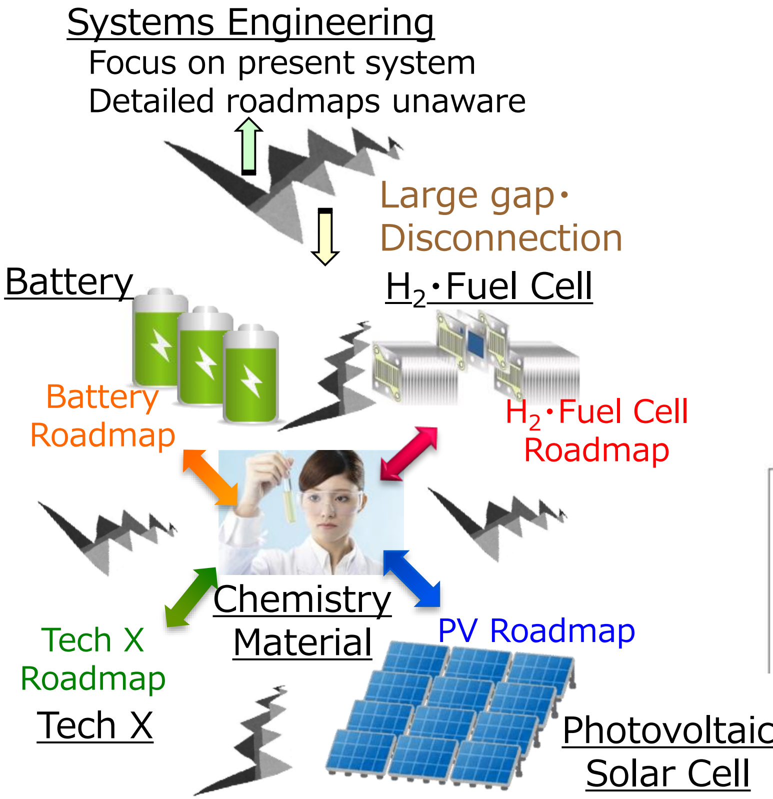




Economically Rational Renewable H_2

Conventional : Limited communication between disciplines

Collaboration : Share Common Vision for Deep Decarbonization
⇒Proposed Economically Rational H_2 Production System



Experts with Different Disciplines

再生可能エネルギーによる安価な水素製造に必要な技術レベルを試算

～蓄電池援用の妥当性を初めて提示、再エネの主力電源化にむけた開発指針として期待～

配布日時：平成30年12月13日14時
解禁日時：平成30年12月13日21時
国立研究開発法人　物質・材料研究機構（NIMS）
国立大学法人東京大学
国立大学法人広島大学

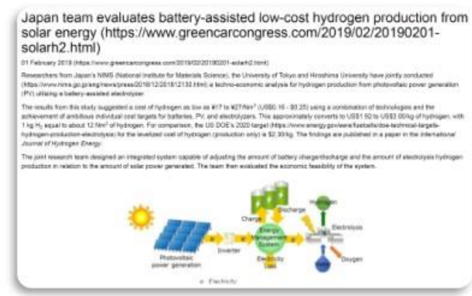
概要

1．NIMSは東京大学、広島大学と共同で、太陽光発電と蓄電池を組み合わせた水素製造システムの技術経済性評価を実施し、国際的に価格競争力を持った安価な水素製造に必要な技術レベルを明らかにしました。本成果は、再生可能エネルギーの主力電源化に向けた技術開発の重要な指針となります。

2．2014年9月の再生可能エネルギーの新規申し込み保留問題や、2018年10月に九州電力管内で実施された太陽光発電の出力制御など、再生 … ています。その対策として、再生可能 … to Gas）システム」や、余剰電力を蓄 … んどはコスト高につながると結論され … 化を目指すための技術開発の方向性が …

Advances in Engineering

Eurekalert

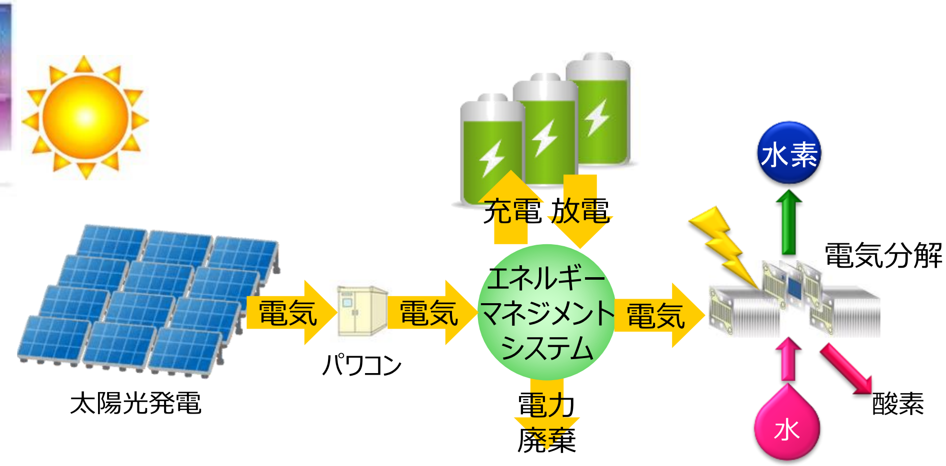


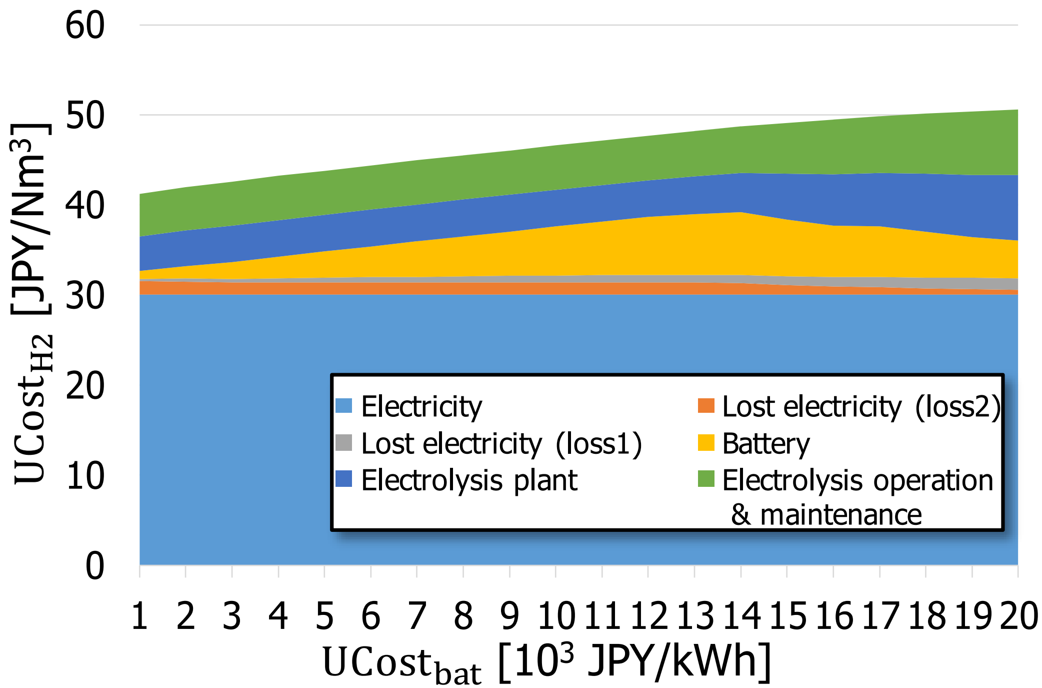
Battery-assisted Solar H_2 Production

ELSEVIER
International Journal of Hydrogen Energy
Volume 44, Issue 3, 15 January 2019, Pages 1451-1465

Battery-assisted low-cost hydrogen production from solar energy: Rational target setting for future technology systems

Yasunori Kikuchi [a, b, c], Takayuki Ichikawa [d], Masakazu Sugiyama [e], Michihisa Koyama [a, d, f]

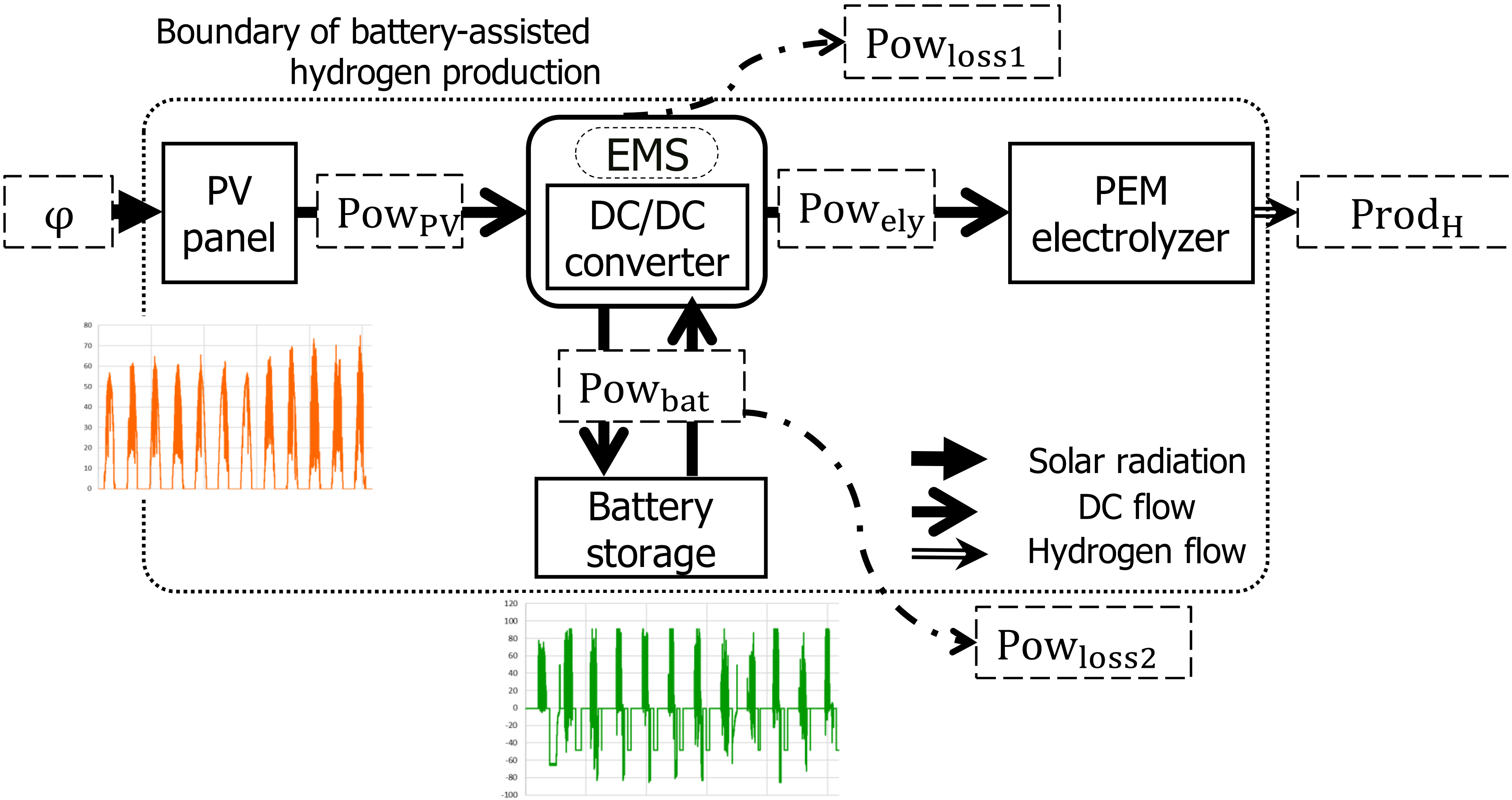




PV 7 JPY/kWh
Electrolyzer 50,000 JPY/kW

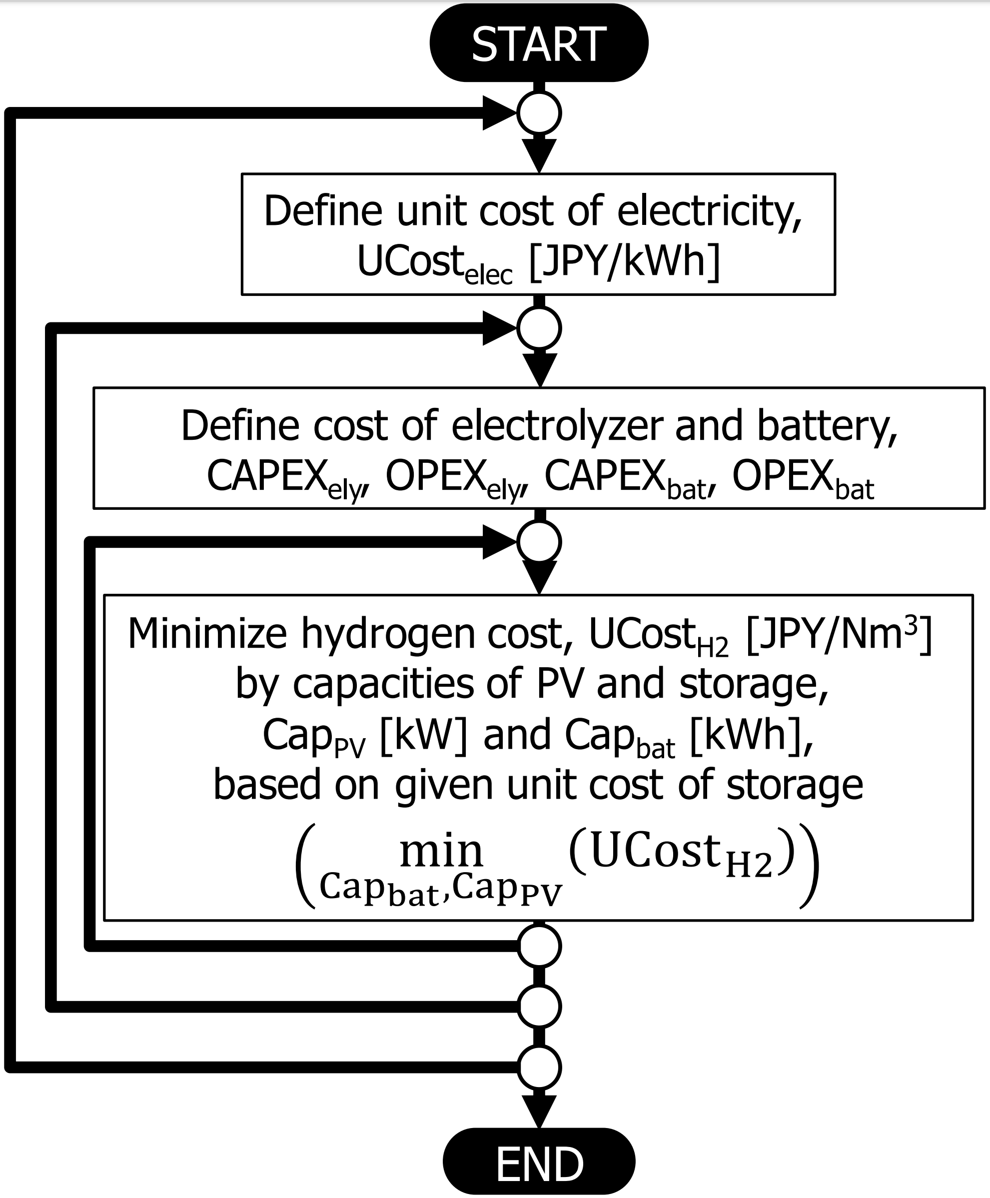
Boundary for System Evaluation

Kikuchi *et al.*, Int J H_2 Energy, **44** (2019) 1451



Algorithm for Optimization

Kikuchi *et al.*, Int J H_2 Energy, **44** (2019) 1451



Optimization

- Given Constants :
  - Unit Capital Cost
    - Electrolyzer, battery
  - Operation Cost
    - Electricity,
    - maintenance
- Design Variables :
  - Capacity
    - Electrolyzer,
    - Battery,
    - PV

Reference Costs : Electrolyzer

Published Roadmaps

Fuel Cells and Hydrogen Joint Undertaking、2014

1,860-2,320 EUR/kW @ 2014

250-1,270 EUR/kW @ 2030

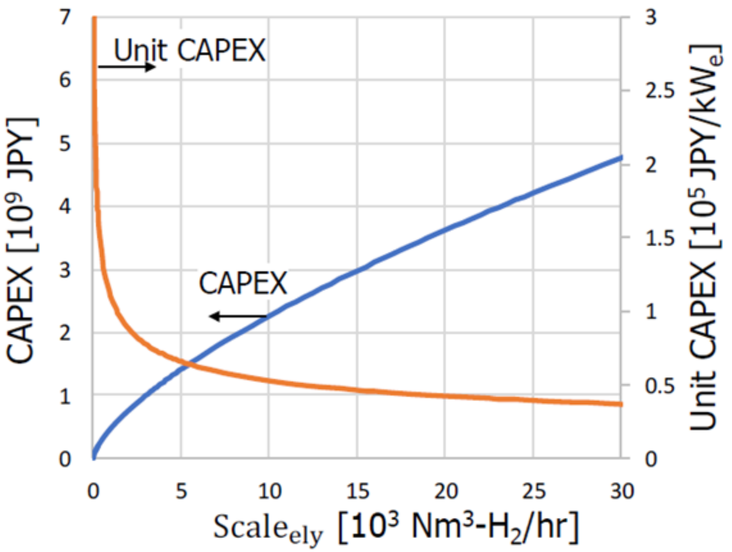
International Energy Agency,
Technology Roadmap:
Hydrogen and fuel cells, 2015

20,000-60,000 hr
(1,500-3,800 USD/kW)
@ 2015

80,000 hr (830 USD/kW)
@ 2030

CO_2 Free H_2 Working Group, 2017

50,000 JPY/kW
(385 EUR/kW or 455 USD/kW)



PEM Electrolyzer (WE-NET)

Settings : 30,000, 50,000, 100,000 JPY/kW（Discrete Values)

Reference Costs : PV

Published Roadmaps

NEDO PV Challenge

7~14 JPY/kWh

The SunShot Initiative's 2030 Goal & Renewable Power Generation Costs in 2017

3~5 JPY/kWh

(0.03 ~ 0.05 USD/kWh, 110 JPY/USD)

Recent Procurement Price

Renewable Energy Project Development Office, Saudi Arabia.(2017)

1.95 to 3.68 JPY/kWh

(6.70 to 12.63 Halalas/kWh, 0.291861 JPY/Halalas)

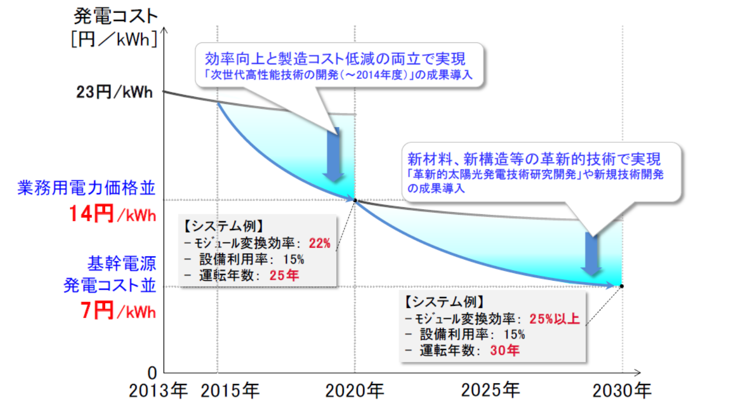


図 1-1 非住宅用システムの発電コスト目標と低減シナリオ

出典： NEDO 作成

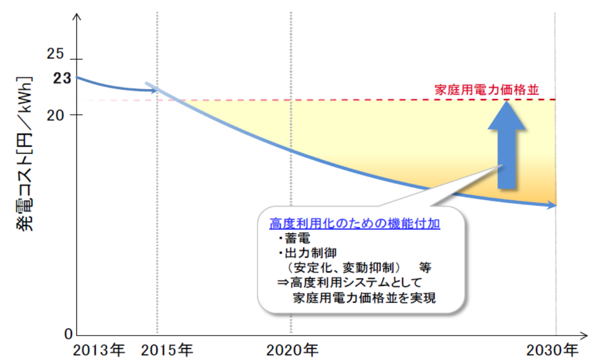


図 1-2 住宅用システムの発電コスト低減シナリオ

出典： NEDO 作成

Reference Values : 3, 5, 7 …JPY/kWh

Reference Costs : Battery

Published Roadmaps

NEDO Secondary Battery Roadmap, 2013

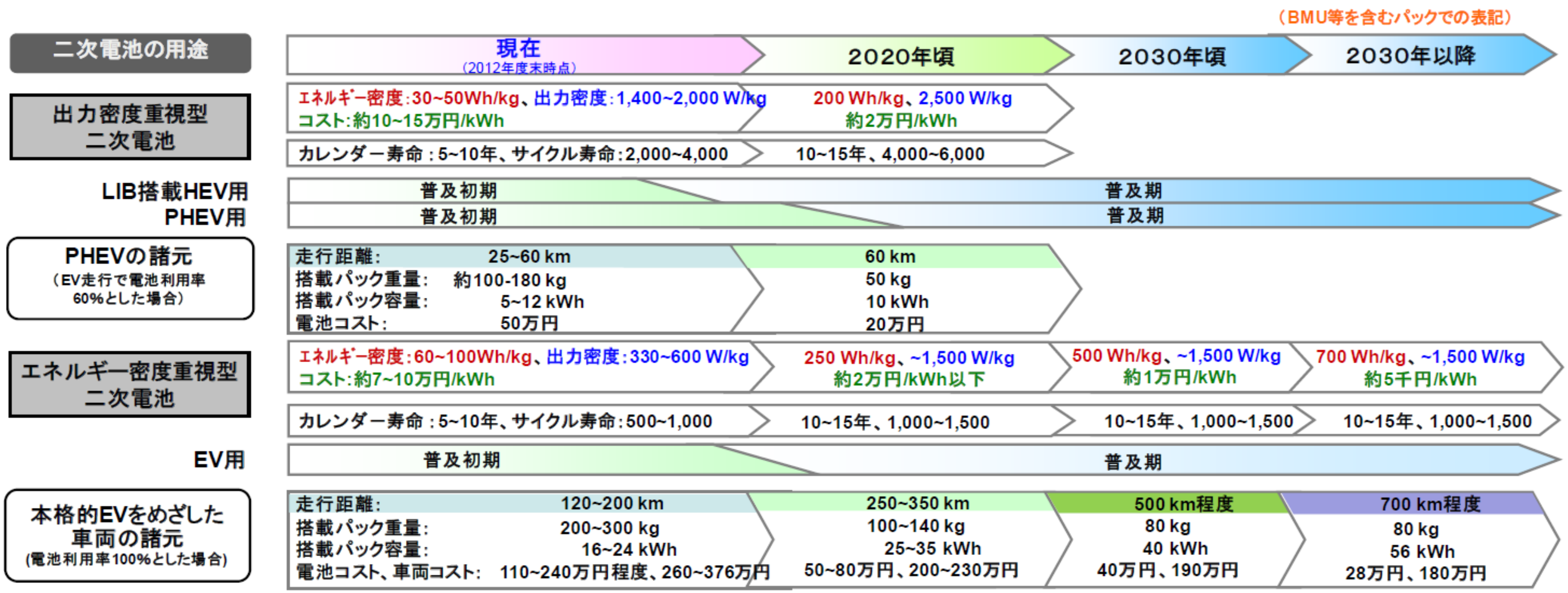
5000 JPY/kWh at 2030

Berckmans *et al.*, Energies, 2017

5500 JPY/kWh (50 USD/kWh) @ 2030

Ultimate Target of 5000 JPY/kWh assumed

（2） 自動車用二次電池ロードマップ



Objective Functions & Method

【Objective Function】

Hydrogen Production Cost (¥/Nm^3-H_2)

=(PV LCOE)x(PV Output)+(Capital Costs* + OPEX)

*Battery & Electrolyzer

$$\mathrm{UCost_{H2}} = \frac{\mathrm{UCost_{elec}} \cdot \int \mathrm{Pow_{PV}}(t)dt + \left(\mathrm{CAPEX_{ely}}/\mathrm{L_{ely}} + \mathrm{OPEX_{ely}}\right) + \left(\mathrm{CAPEX_{bat}}/\mathrm{L_{bat}} + \mathrm{OPEX_{bat}}\right)}{\mathrm{Prod_H}}$$

Major Technological Parameters Assumed

Battery : Depreciation = 20 y; Efficiency = 0.9; OPEX = 0;

Electrolyzer : Depreciation = 10 y;

Other parameters are from WE-NET report

【Optimization Method】

Non-linear Problem (Non-monotonic increase/decrease)

⇒Difficult to find rigorous solution

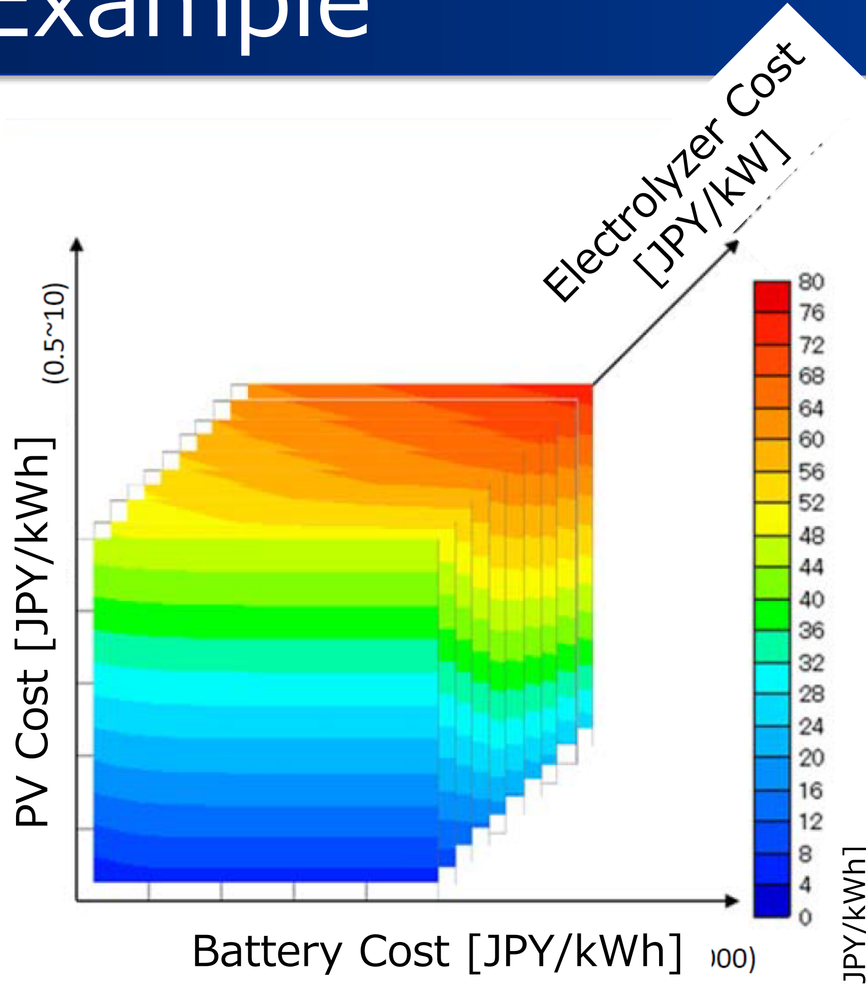
Golden ratio division method (Kiefer,1953)

Relative Error of 0.001 allowed

※Strategy to find neighborhood solution

Explore wide range of parameters space

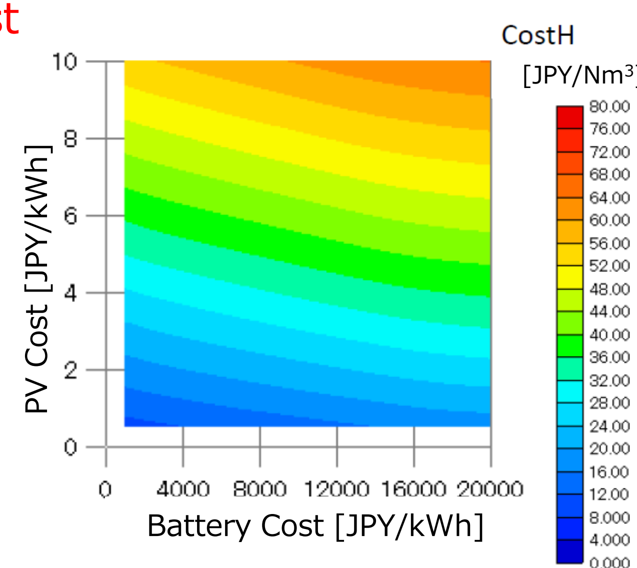
Example

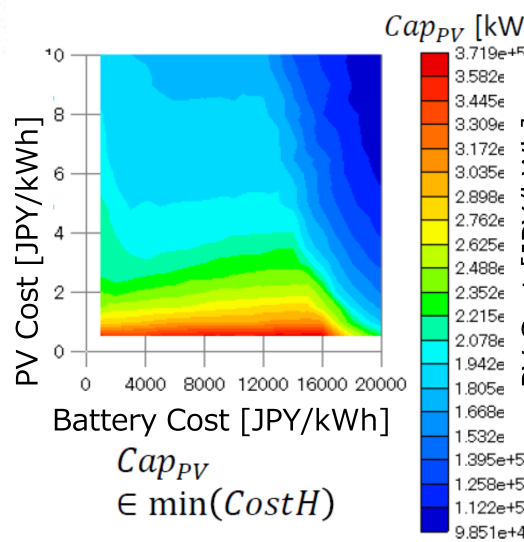


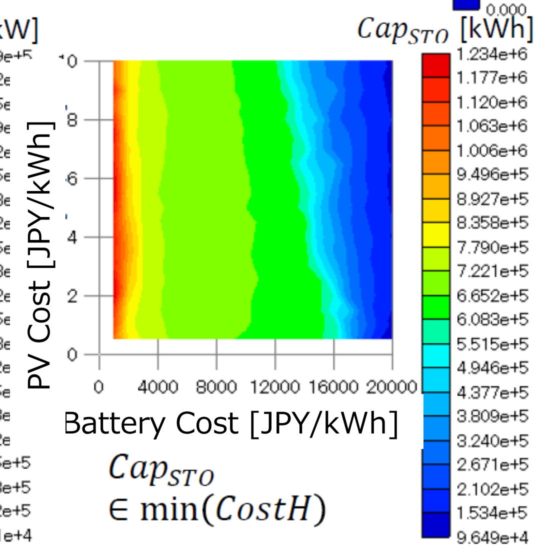
Electrolyzer Cost
5,000 JPY/kW

Production of
~1×10⁴ Nm³/h

No C-rate constraint



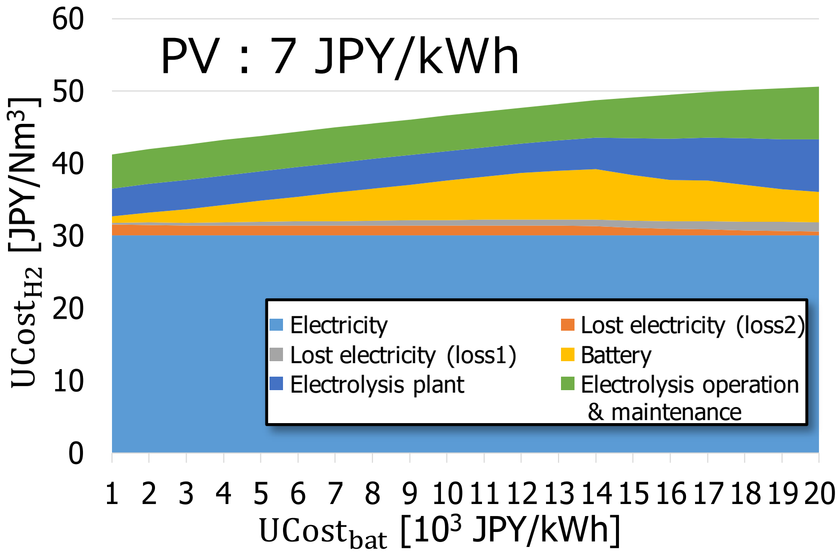


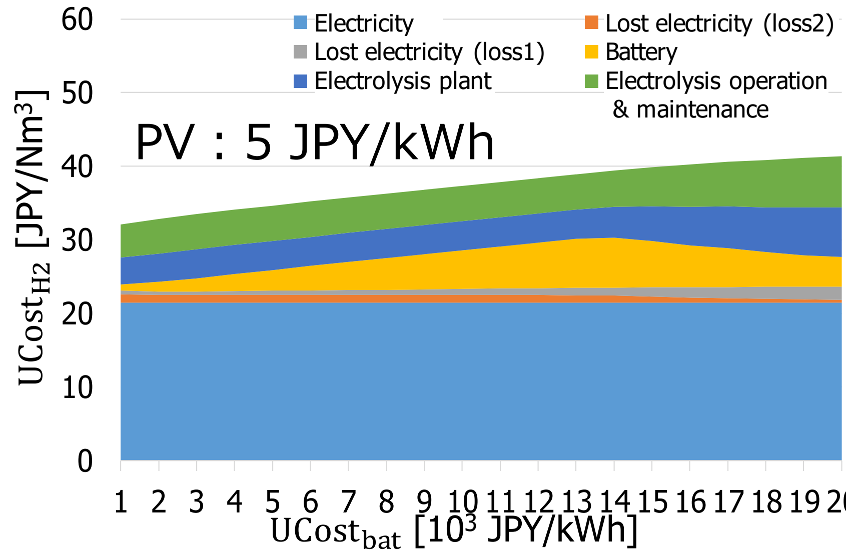


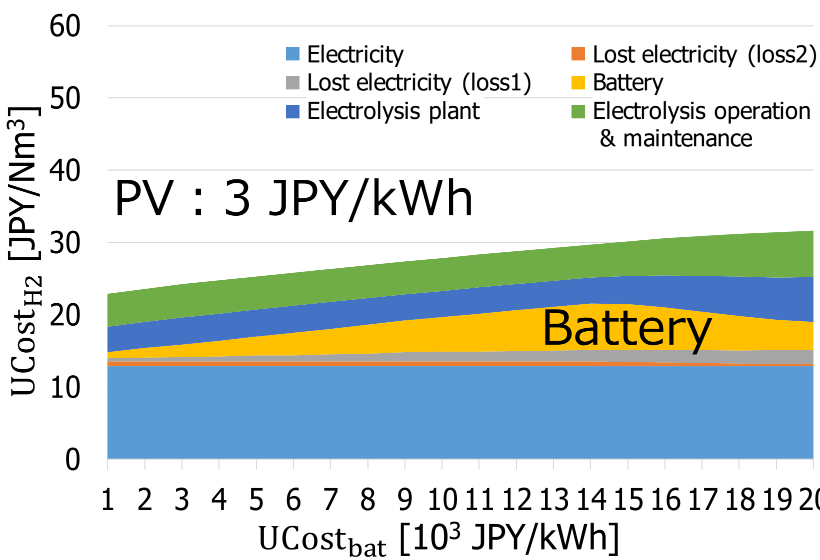
Kikuchi *et al.*, Int J H_2 Energy, **44** (2019) 1451

Cost Breakdown

Kikuchi *et al.*, Int J H_2 Energy, **44** (2019) 1451







Electrolyzer (CAPEX+OPEX))

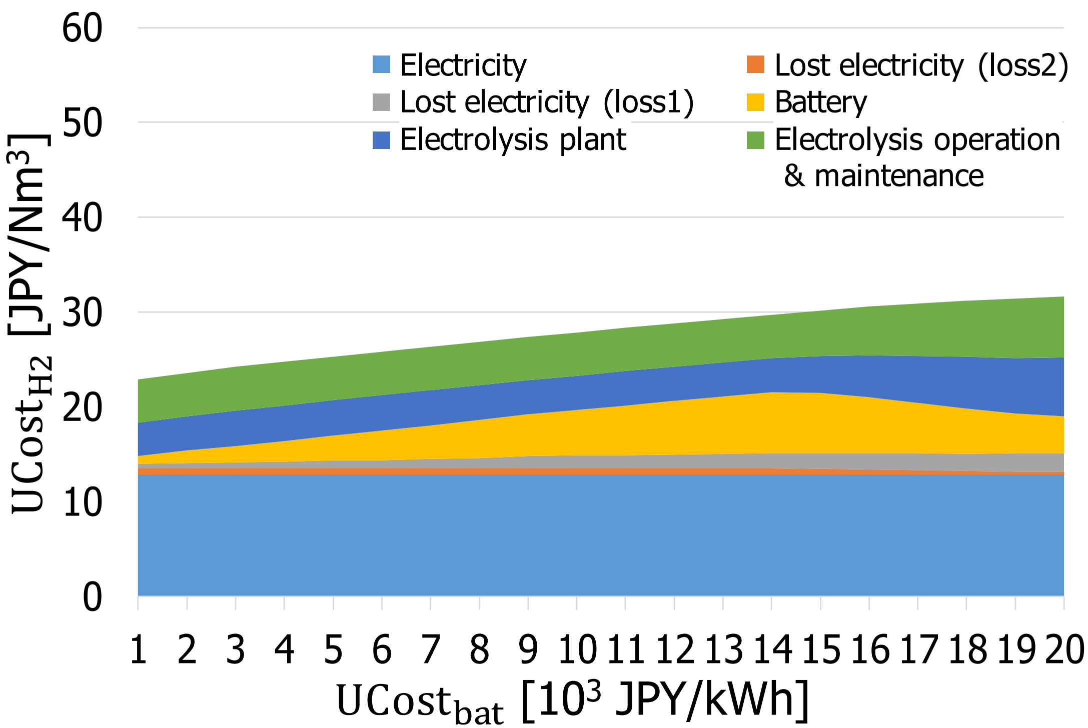
PV Electricity (for electrolysis + loss)

※Electrolyzer Cost : 50,000 JPY/kW

- ✓ Electricity cost dominant
- ✓ Battery cost of 15,000 JPY/kWh →Change of trend

Cost Breakdown

Kikuchi *et al.*, Int J H_2 Energy, **44** (2019) 1451



Battery cost = Unit cost (JPY/kWh) × Installed capacity (kWh)

from 20,000 JPY/kWh to 14,000 JPY/kWh

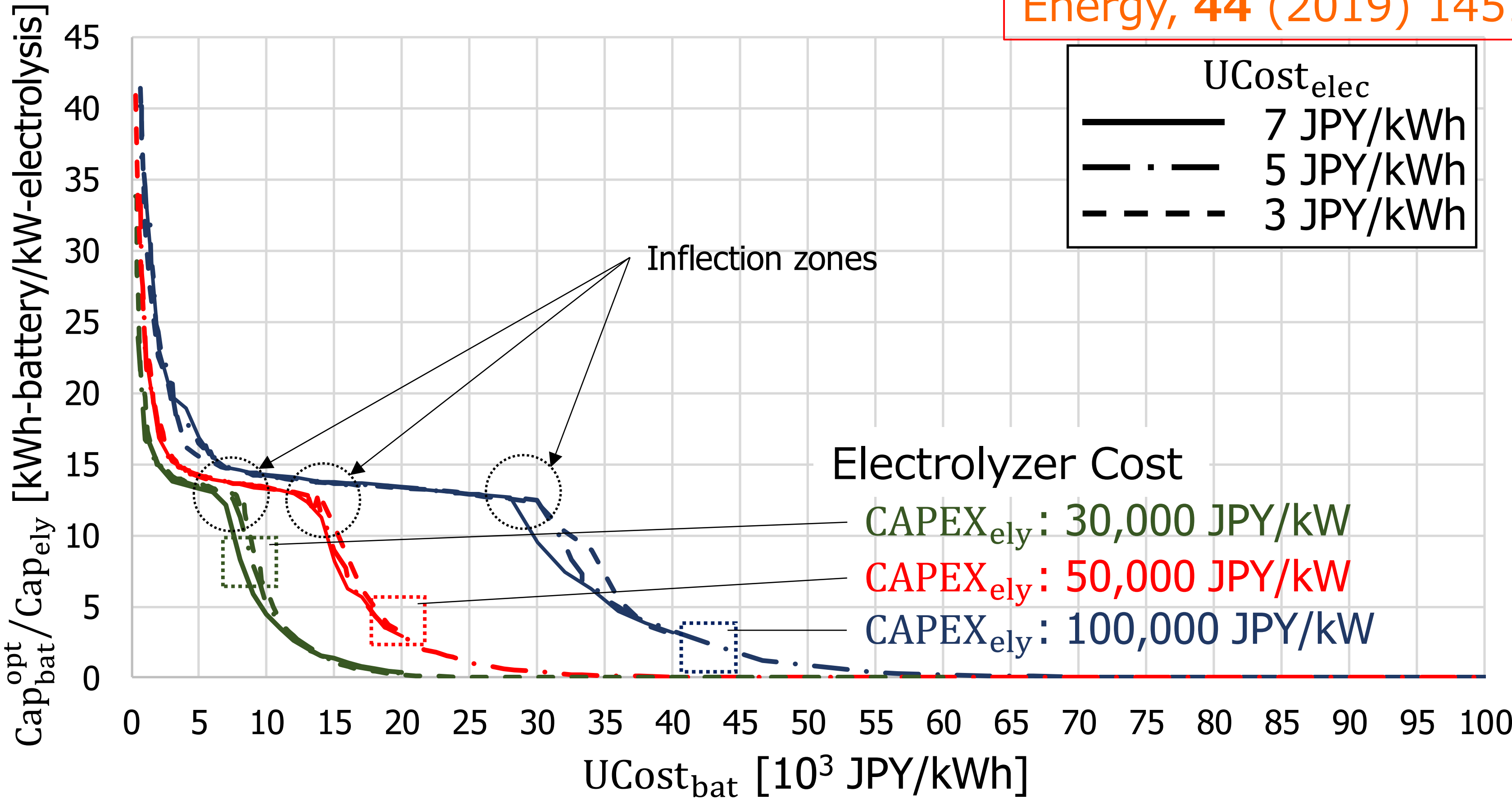
Installed capacity increases, Unit cost decreases

from 14,000 JPY/kWh to lower

Installed capacity reaches plateau, Unit cost decreases

Battery Installation

Kikuchi *et al.*, Int J H_2 Energy, **44** (2019) 1451



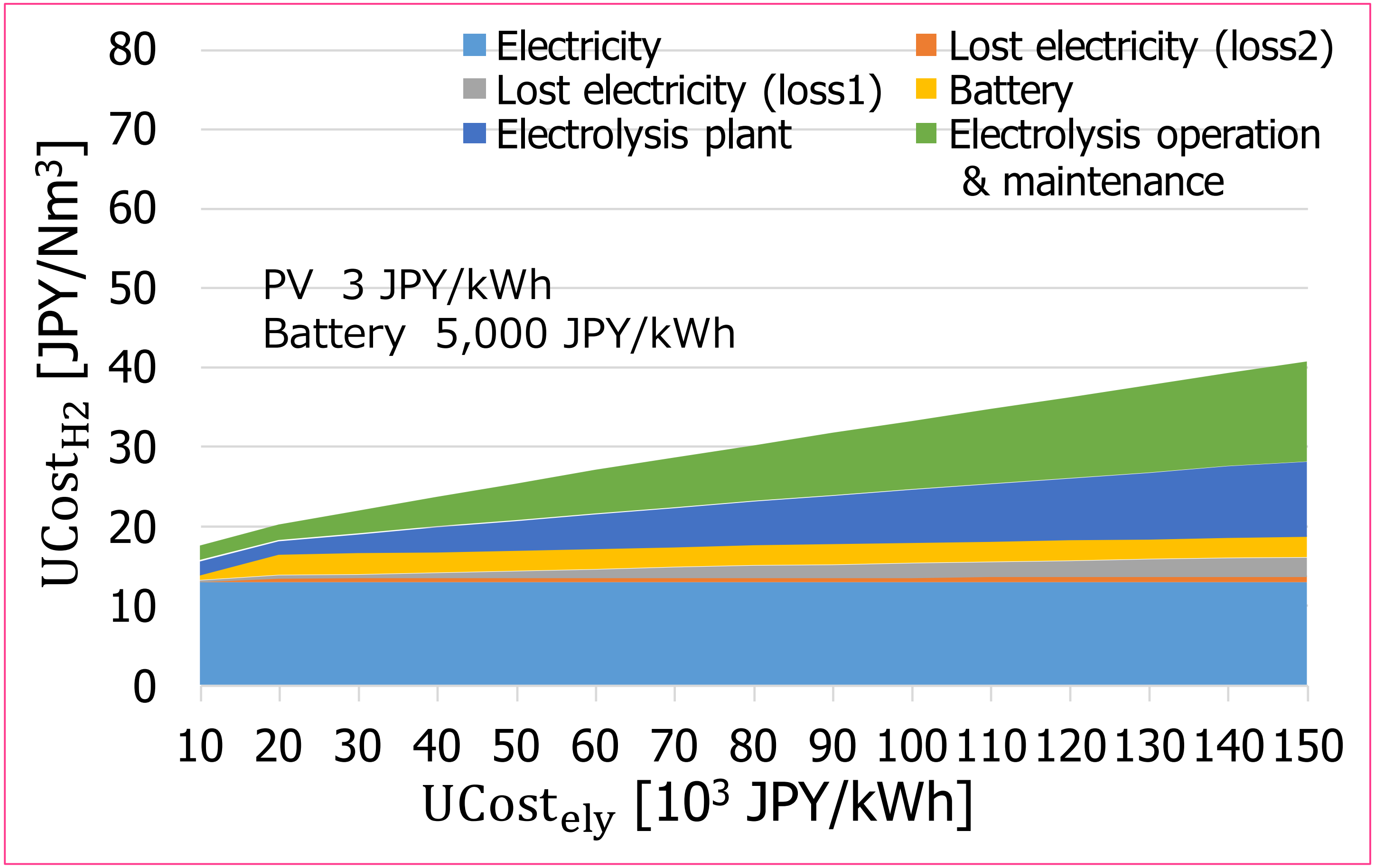
Threshold for battery installation

〇Cost for electrolyzer

×Electricity cost（≒PV cost)

Cost Breakdown

Kikuchi *et al.*, Int J H_2 Energy, **44** (2019) 1451



Toward Bright Future Vision

Academia : Deep-decarbonation Vision
Economically Rational Renewable Hydrogen

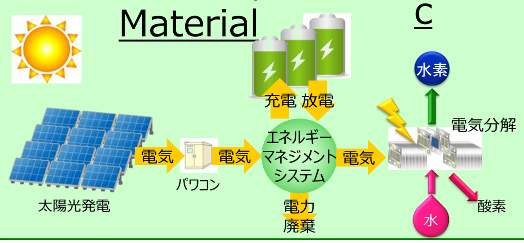
Systems Engineering

Battery

H_2・Fuel Cell

Chemistry・Material

Photovoltaic



Regional Stake-holders

Renewable
  Grid connection difficulty
  Decreasing benefit

Local Government
  No future vision !
  Infrastructure dependency on big company !
  No local employment !

Consumer
  Battery expensive !
  H_2・Fuel Cell expensive !

Large Enterprises

Utility Company
  Vision for business growth??

Fuel Cell Supplier
  Economic benefit ??
  Small market
  ⇒Expensive

Battery Supplier
  Subsidy dependent !

Implementation of systems by
  sharing region-specific problems
  creating bright future vision &
  transition scenario toward the vision

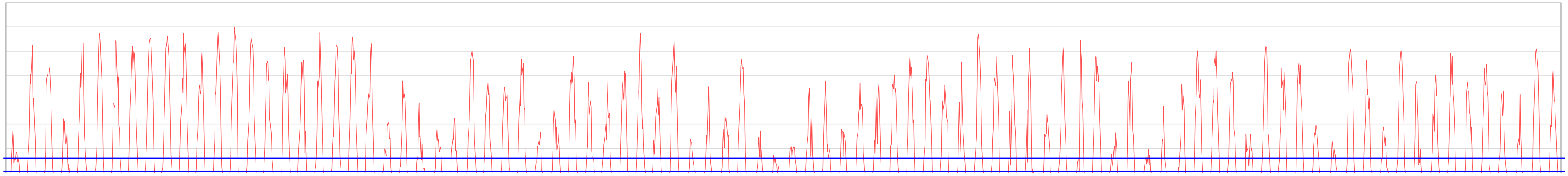
Summary

○Changing landscape toward 80% GHG emission reduction overviewed

○We proposed an integrated H_2 production system as an option for massive penetration of variable renewables

○Battery-assist can reduce CAPEX of Electrolyzer and increase capacity ratio of electrolyzer

○System optimization indicates rational H_2 production by future development of component technologies



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