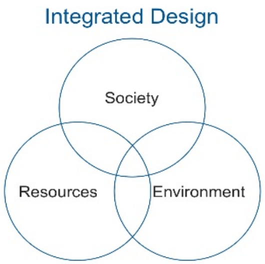
5th International Conference on Smart Energy Systems
Copenhagen, 10-11 September 2019



Introducing sector coupling to utilize renewable resources for regional decarbonization in Japan

Naoya Nagano and Toshihiko Nakata

Tohoku University, Japan

AALBORG UNIVERSITY DENMARK
reINVEST
sEEnergies
Fonden Energi- & Miljødata www.emdfonden.dk
UN environment
DISTRICT ENERGY IN CITIES INITIATIVE
Innovation Fund Denmark
4DH

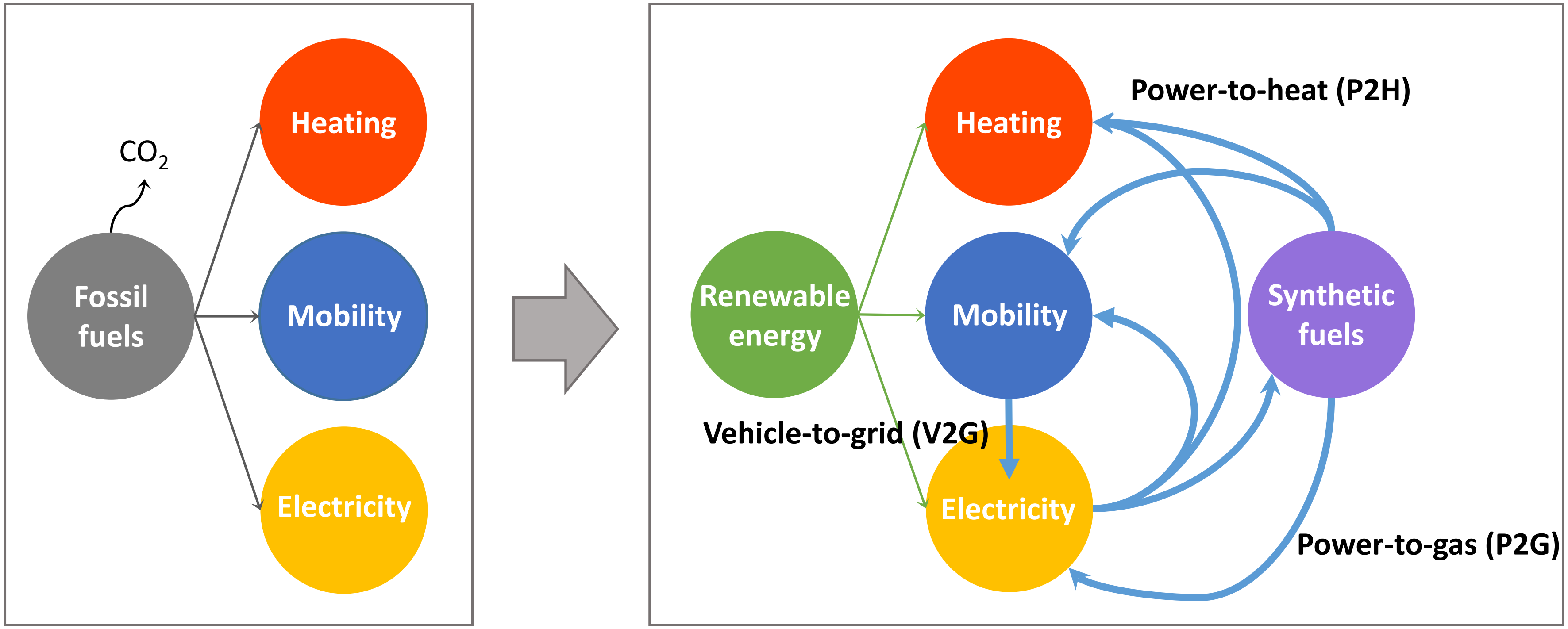
Outline

1. Introduction
2. Methodology
3. Results and discussion
4. Conclusions

Outline

1. Introduction
2. Methodology
3. Results and discussion
4. Conclusions

The concept of sector coupling



Conventional energy system **Future smart energy system**

Sector coupling is..

The concept that facilitate utilization of variable renewable energies by making flexible paths between electricity sector and other sectors (Heating, Mobility sector).

Research question and objective

Is "sector coupling" a promising solution for decarbonization and sustainability?

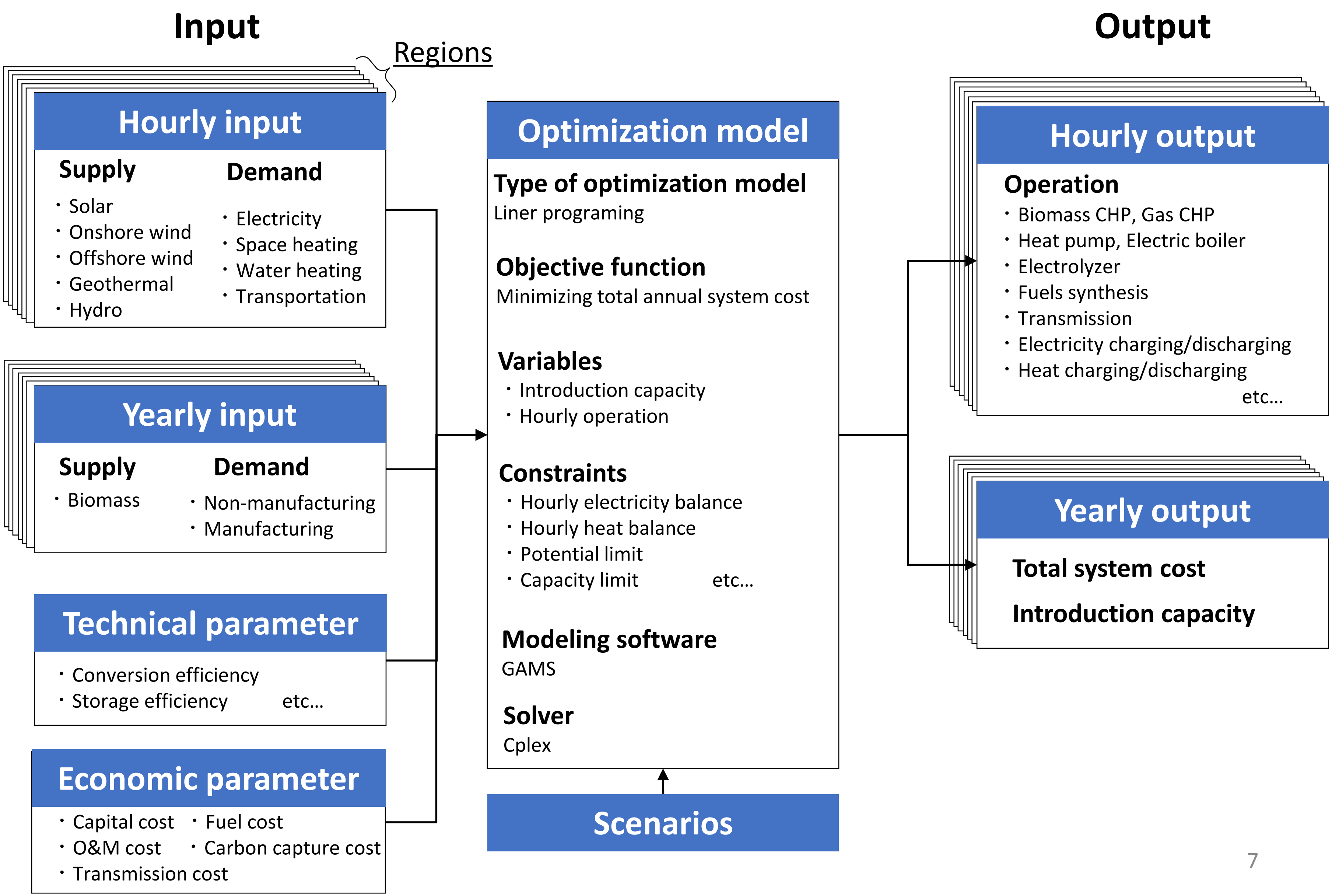
Clarify the effects of introducing "sector coupling" to regional energy systems.

- Develop the optimization model for designing energy system considering sector coupling.
- Compare the performance of designed energy systems based on scenario analysis.

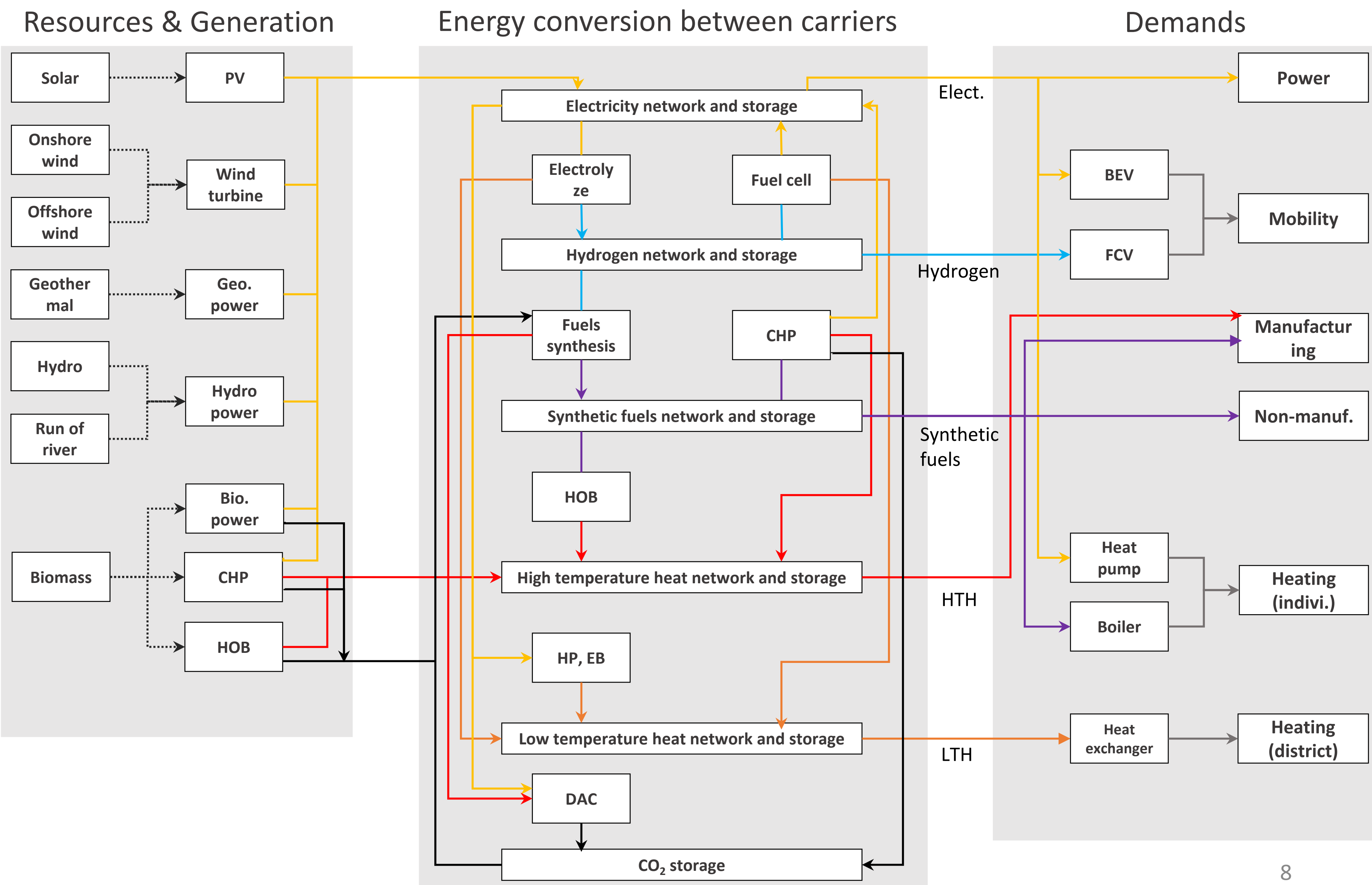
Outline

1. Introduction
2. Methodology
3. Results and discussion
4. Conclusions

Overview of energy system design



System configuration



Optimization model

The type of optimization: Liner Programming

Objective function

$$min.\, C^{total} = \sum_{r}\left\{\sum_{t} c_t \cdot Cap_{r,t} + \sum_{t_{cc}} c_{t_{cc}} \cdot CC_{r,t_{cc}}\right\} + c_{etrs.} \cdot \sum_{i}\sum_{h} et_{i,elect.}(h)$$

Capital and O&M   Carbon capture   Transmission

Constraints on introduction capacity

$$0 \leq Cap_{r,tg} \leq Pot_{r,t_g}$$

(The introduction capacity must be under the potential)

Cap	: Capacity	r	: Region
CC	: Captured carbon	t	: Technology
c	: Unit cost	t_{cc}	: Technology of carbon capture
Pot	: Introduction potential	t_g	: Technology of energy generation

Constraints on energy balances

Electricity

$$\sum_{tg} Cap_{r,e,tg} \cdot op_{r,e,tg}(h) + etrs_r(h) + ec'_r(h) = edmd_r(h) + ec_r(h) + echg_r(h)$$

Generation　Transmission　Conversion (From)　Demand　Conversion (To)　Charging

Low temperature heat of DHS

$$lthr_{r,elz.}(h) + lthr_{r,FC}(h) + lthc'_r(h) = lthdmd_r(h) + lthchg_r(h)$$

Heat recovery from electrolyzer & Fuel cell

High temperature heat

$$\sum_{n} hthr_{r,n}(h) + lthc'_r(h) = sup_{r,hth}^{manuf.}(h) + sup_{r,hth}^{DAC}(h)$$

Heat recovery from fuels synthesis　Supply to manufacturing　Supply to DAC

Manufacturing

$$\sum_{h} \left\{ sup_{r,hth}^{manuf.}(h) + \sum_{n} sup_{r,n}^{manuf.}(h) \right\} = dmd_r^{manuf.}$$

Energy demand of manufacturing

Given (op, edmd, lthdmd, $dmd^{manuf.}$)

Constraints on energy storage

Electricity

$$esto_r(h) = (1 - \eta_{leak.}) \cdot esto_r(h-1) + echg_r(h)$$

$$0 \leq esto_r(h) \leq Cap_{r,e,ts}$$

The storage capacity

Low temperature heat of DHS

$$lthsto_r(h) = (1 - \eta_{leak.}) \cdot lthsto_r(h-1) + lthchg_r(h)$$

$$0 \leq lthsto_r(h) \leq Cap_{r,lth,ts}$$

Hydrogen

$$hysto_r(h) = hysto_r(h-1) + \eta_{elz.} \cdot e2hy_r(h) - hy2e_r(h) - \sum_{n} hy2n_r(h)$$

$$0 \leq hysto_r(h) \leq Cap_{r,hy,ts}$$

The type of fuels

Synthetic fuels

$$nsto_r(h) = nsto_r(h-1) + \eta_n \cdot hy2n_r(h) - n2c_r(h) - sup_{r,n}^{manuf.}(h) - sup_{r,n}^{nmanuf.}(h)$$

$$0 \leq nsto_r(h) \leq Cap_{r,n,ts}$$

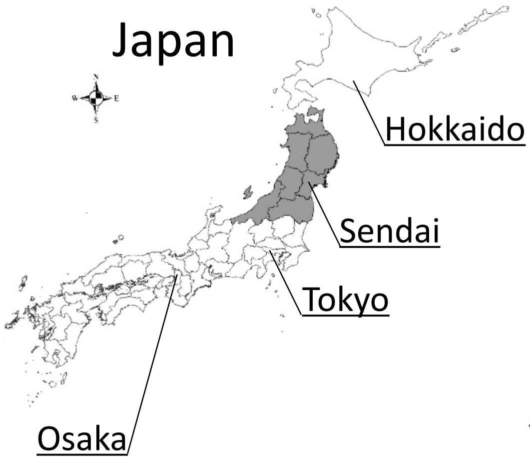
Technical and economic parameters

Technology	efficiency [-]	Overnight cost [JPY/unit]	O&M cost [JPY/unit]	Unit	Ref.
Solar	1.00	294,000	6,000	kW_e	[1]
Onshore wind	1.00	300,000	6,000	kW_e	[1]
Offshore wind	1.00	565,000	22,500	kW_e	[1]
Run of river	1.00	10,000,000	171,591	kW_e	[1]
Geothermal	1.00	790,000	33,000	kW_e	[1]
Heat pump	※COP of Heat pump $6.81 - 0.121\Delta T + 0.00063\Delta T^2$	131,250	1,961	kW_{th}	[2],[3]
Electric boiler	0.98	1,125	11.3	kW_{th}	[4]
Electrolyzer	0.66	300,000	15,000	kW_e	[5]
Methanation	0.83	75,000	3,000	kW_f	[5]
Methanol synthesis	0.79	125,000	5,000	kW_f	[5]
DME synthesis	0.80	125,000	5,000	kW_f	[5]
Fuel cell	0.42	405,375	3,125	kW_e	[6]
Stationary battery (Li-ion)	0.95	68,250	863	kWh	[6]
Hot water tank	0.90	2,310	23.1	kWh	[3]
Hydrogen storage	1.00	16,250	0	kWh	[6]

e; elect., th; thermal, f; fuel

[1] Ministry of Economy, Trade and Industry, Agency for Natural Resources and Energy, Power Generation Cost Verification Working Group
[2] I. Staffell et al.; A review of domestic heat pumps, Energy Environ. Sci., 5(2012), pp.9291-9306.
[3] M. Dahl at al.; "Cost sensitivity of optimal sector-coupled district heating production systems", Energy 166 (2019), 624 – 636.
[4] S. Brynolf et al.; Electrofuels for the transport sector: A review of production costs, Renewable and Sustainable Energy Reviews, 81(2018), pp.1887-1905.
[5] B. Zakeri, S. Syri; Electrical energy storage systems: A comparative life cycle cost analysis, Renewable and Sustainabl Energy Reviews, 42(2015), pp.569-596.
[6] H-M. Henning, Andreas Palzer; "A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies-Part1: Methodology", Renewable and Sustainable Energy Reviews, 30(2014), pp.1003-1018.

Target area



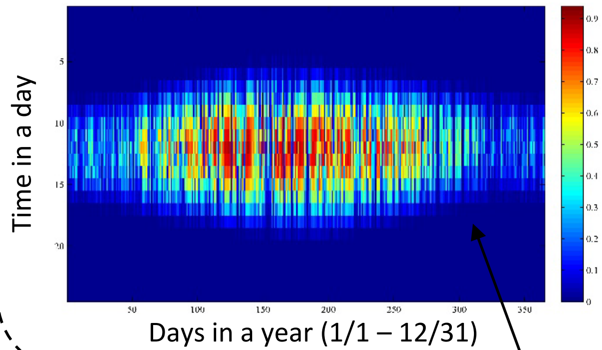
- **Tohoku region** (the northeastern part of Japan.)
- 9% of the country's population lives in 21% of the national land.
- Total electricity consumption: 74.5 TWh
- Potential of introduction capacity
  Solar: 26.9 GW
  Onshore wind: 68.4 GW
  Offshore wind: 223.7 GW

The renewable energy potential is sufficient to satisfy the energy demand.

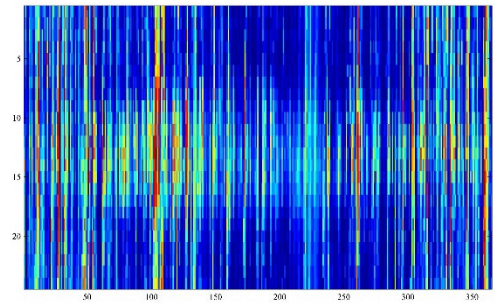
Hourly data for model input

Estimated from actual climate data

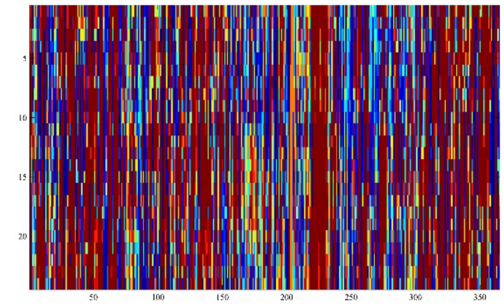
Solar



Onshore wind



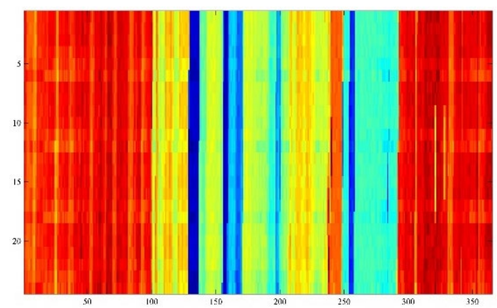
Offshore wind



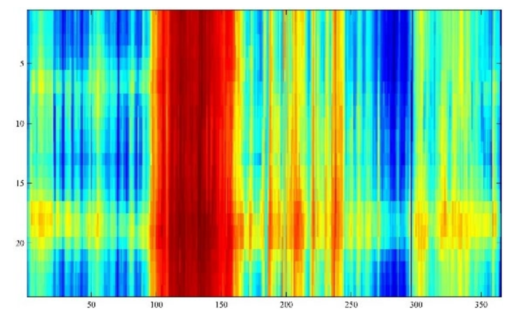
Standardized by capacity

Actual energy data

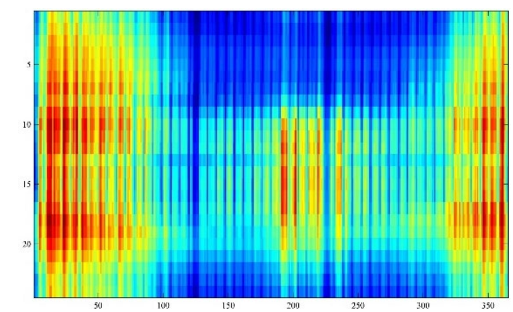
Geothermal



Hydro



Electricity demand



Ref.

・Ministry of Land, Infrastructure, Transport and Tourism, Japan Meteorological Agency; Past weather data download, https://www.data.jma.go.jp/gmd/risk/obsdl/ (Accessed; 2019.6.12).

・Japan Oceanographic Data Center; Coastal Maritime Meteorology Climate Data, https://www.jodc.go.jp/jodcweb/JDOSS/index_j.html (Accessed; 2019.6.12).

・Tohoku Electric Power Co.,INC.; Electricity forecast for 6 prefecture in Tohoku and Niigata area, http://setsuden.tohoku-epco.co.jp/graph.html (Accessed; 2019.6.12).

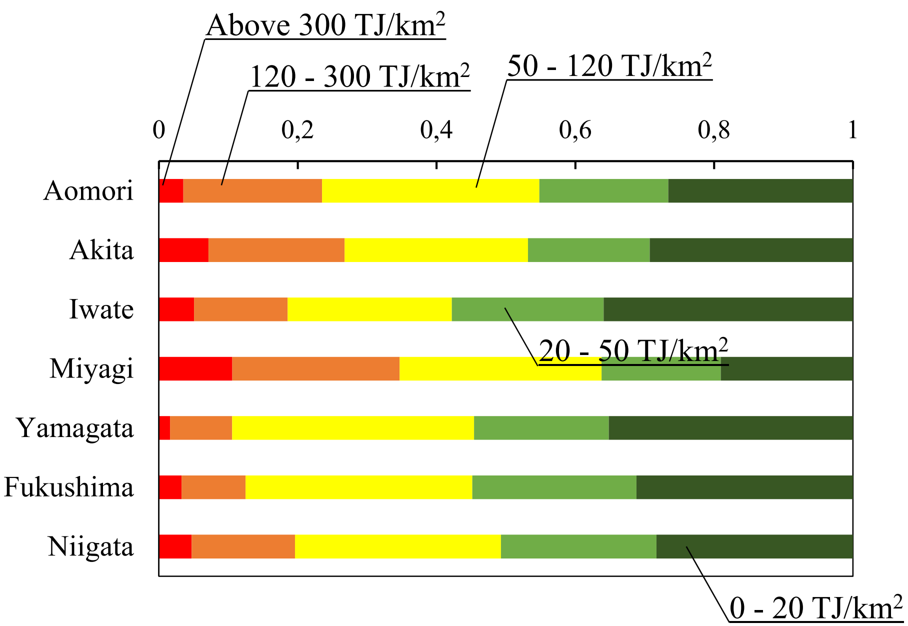
・Shin'ya Obara et al.; "Electric and heat power supply network of Hokkaido in consideration of the leveling effect by a wide-area interconnection of wind-farm and solar-farm", Transactions of the JSME (in Japanese), 83(2017), No.856.

Heat demand density map in Tohoku region

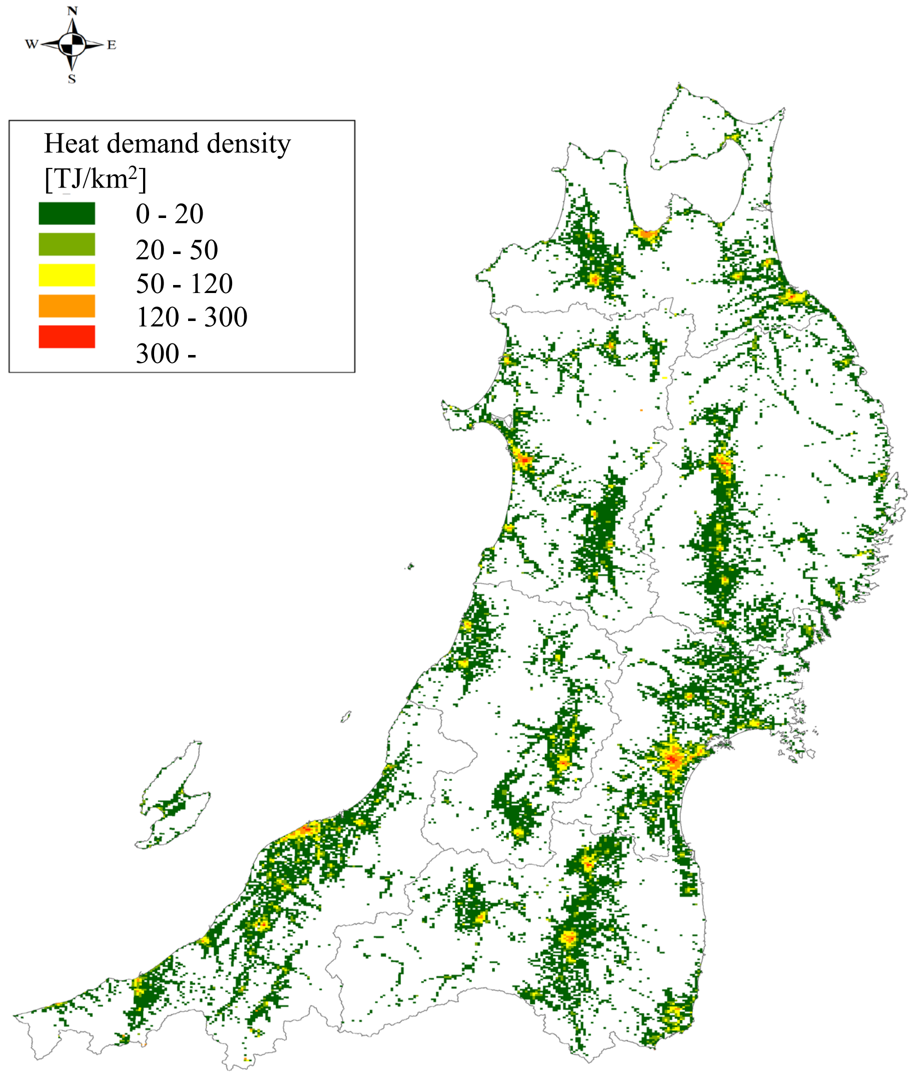
Definition of heat demand

- Space & water heating
- Residential and commercial sector

Calculation is based on the method in *S.Fujii et al.,* ***"Design and Analysis of District Heating Systems Utilizing Excess Heat in Japan"****, energies, 2019*

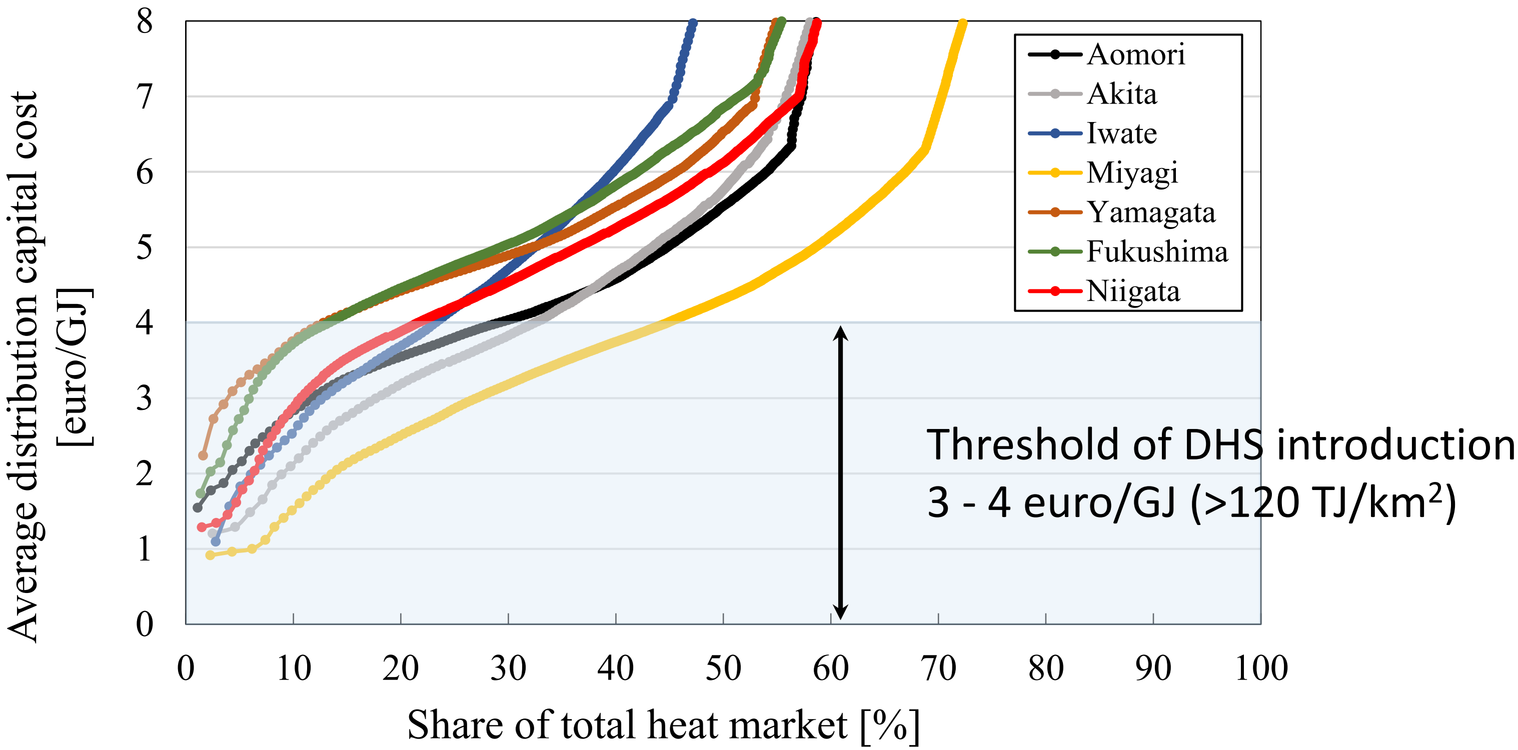


The classification of heat demand density

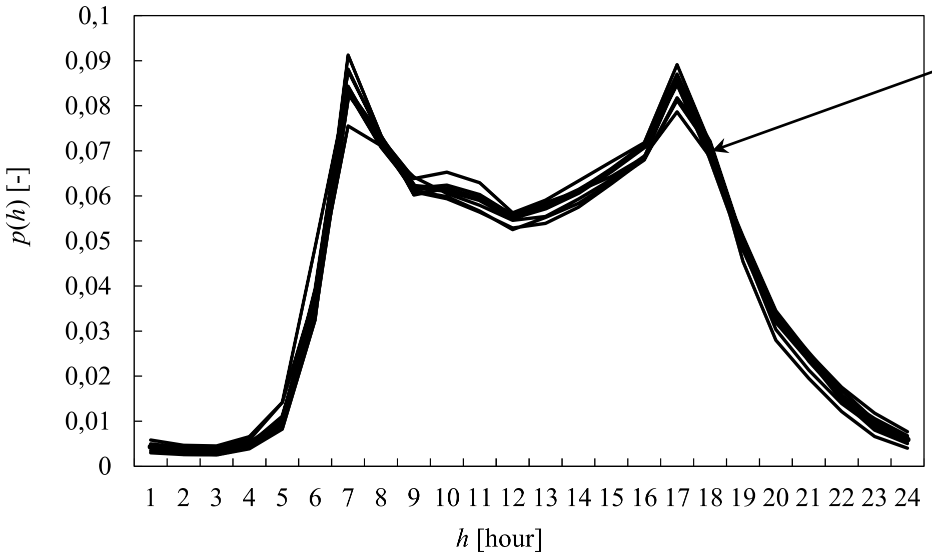


Capital cost of DHS distribution

Calculation is based on the method in
S. Frederiksen, S.Werner, ***"District heating and cooling"****,2012*
U. Persson et al., ***"Heat roadmap Europe: Heat distribution costs"*** *,Energy 176, 2019*



Estimation of vehicle-to-grid limit



$p(h)$: Percentage of the number of traveling car [-]

$x(h)$: The number of cars traveling at h [vehicle]

α : The rate of operation in a day [-]

β : The number of trip in a day [trip/vehicle]

N : The total number of existing car [vehicle]

$$p(h) = \frac{x(h)}{\sum_h x(h)}$$

$$\sum_h x(h) = N \cdot \alpha \cdot \beta$$

$$x(h) = N \cdot \alpha \cdot \beta \cdot p(h)$$

The allowed charge/discharge quantity at h

$$\boldsymbol{V2G_{max}(h) = \gamma \cdot f \cdot \big(N - x(h)\big) = \gamma \cdot f \cdot (1 - \alpha \cdot \beta \cdot p(h)) \cdot N}$$

The ratio of V2G participation; $\gamma = 1$

The charge/discharge power per vehicle; $f = 6$ [kW/vehicle]

Outline

1. Introduction
2. Methodology
3. Results and discussion
4. Conclusions

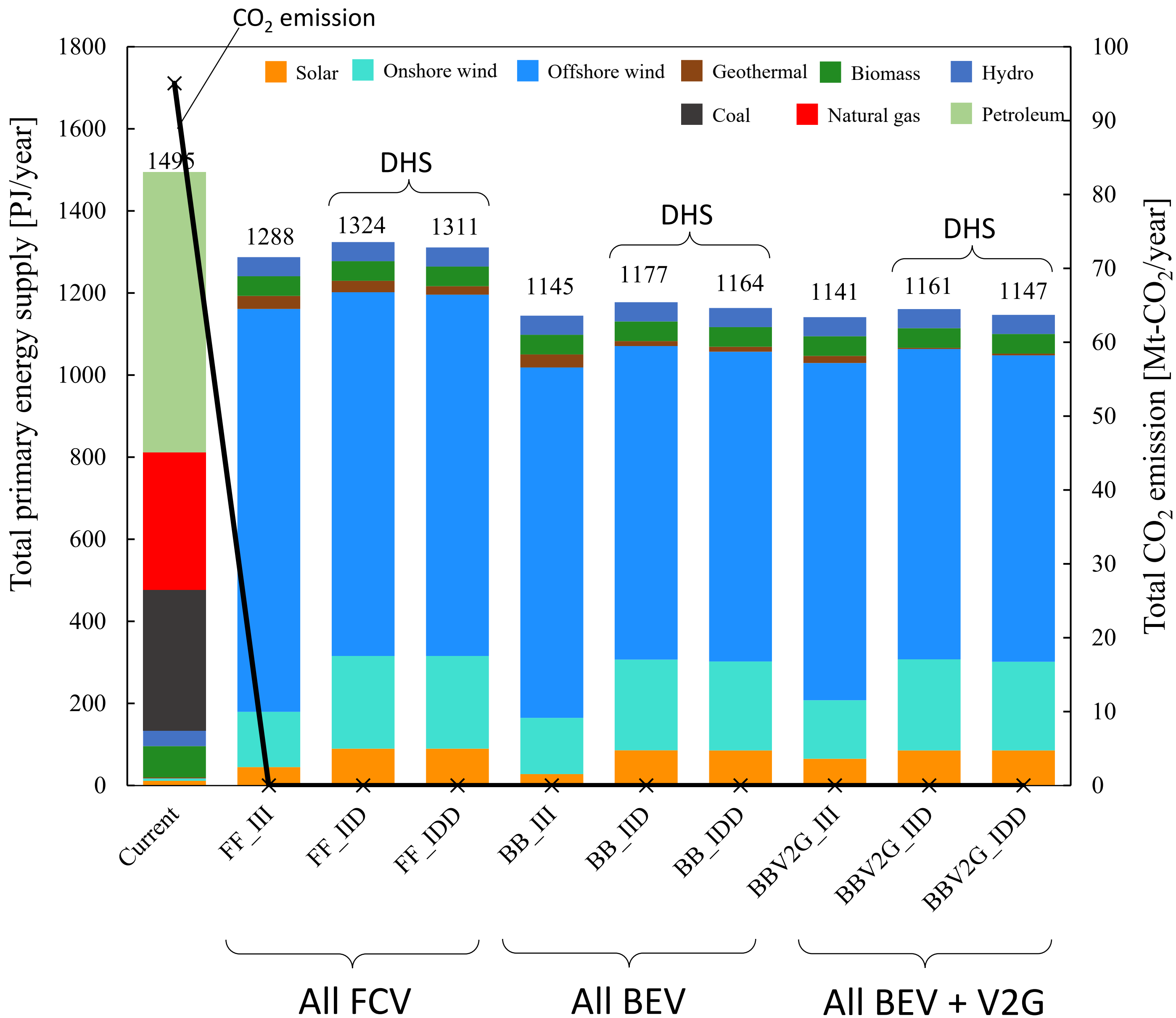
Scenarios definition

Scenario	Transportation demand	
	Passenger	Freight
Trs_All FCV	FCV 100%	FCV 100%
Trs_All BEV	BEV 100%	BEV 100%
Trs_All BEV+V2G	BEV 100%+V2G	BEV 100%+V2G

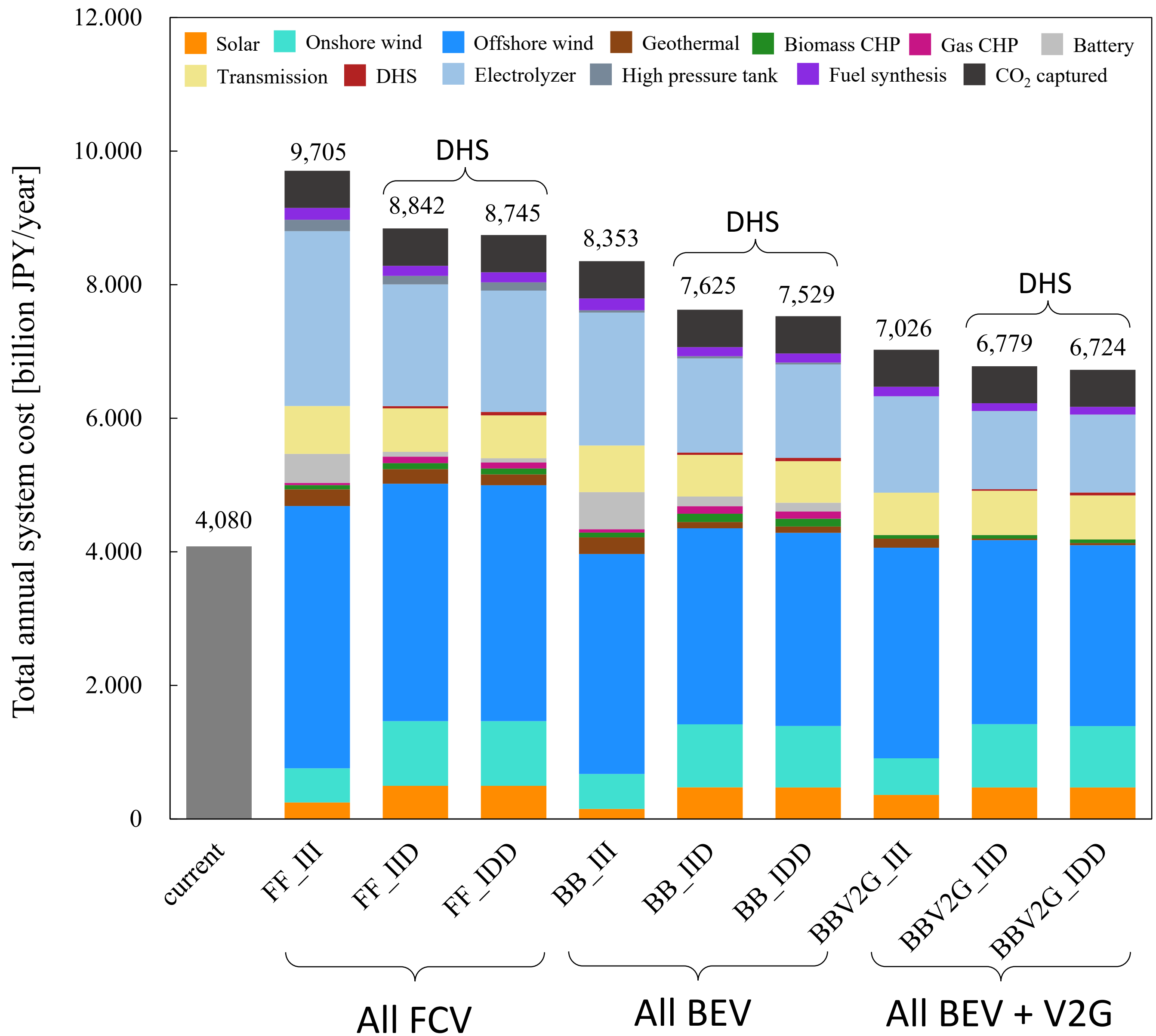
Scenario	Space and water heating demand		
	Heat demand density [TJ/km^2]		
	Low (<120)	Mid. (120-300)	High (>300)
HD_III	Individual	Individual	Individual
HD_IID	Individual	Individual	DHS
HD_IDD	Individual	DHS	DHS

※Heat supply for individual heating area is all met by heat pump.

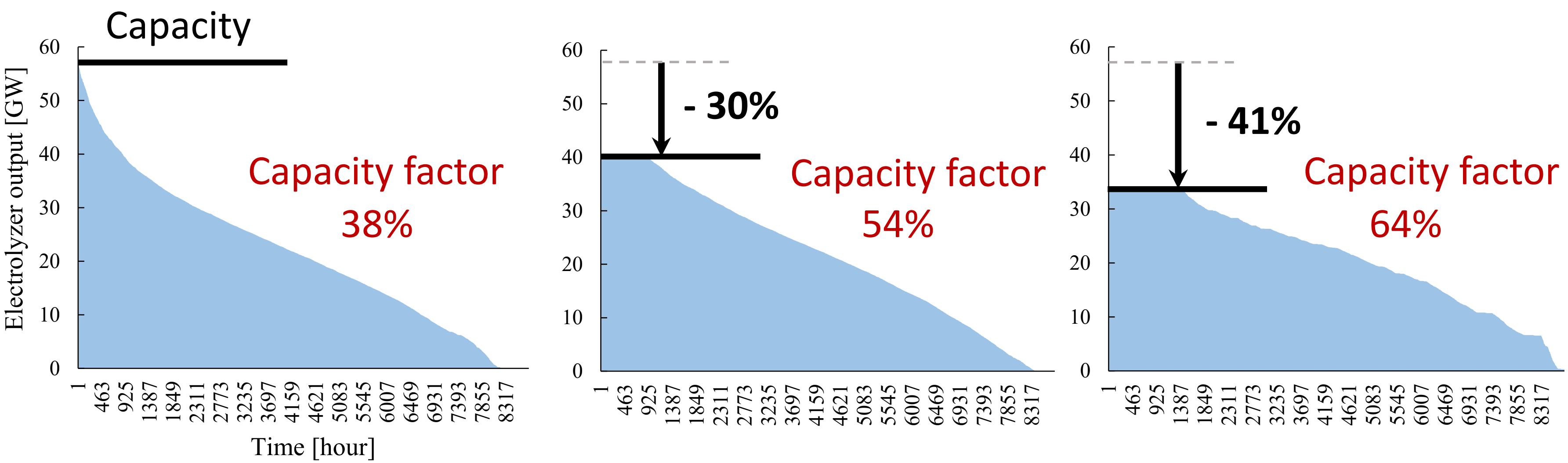
TPES and CO_2 emissions



Annual system cost configuration



Cost reduction of electrolyzer



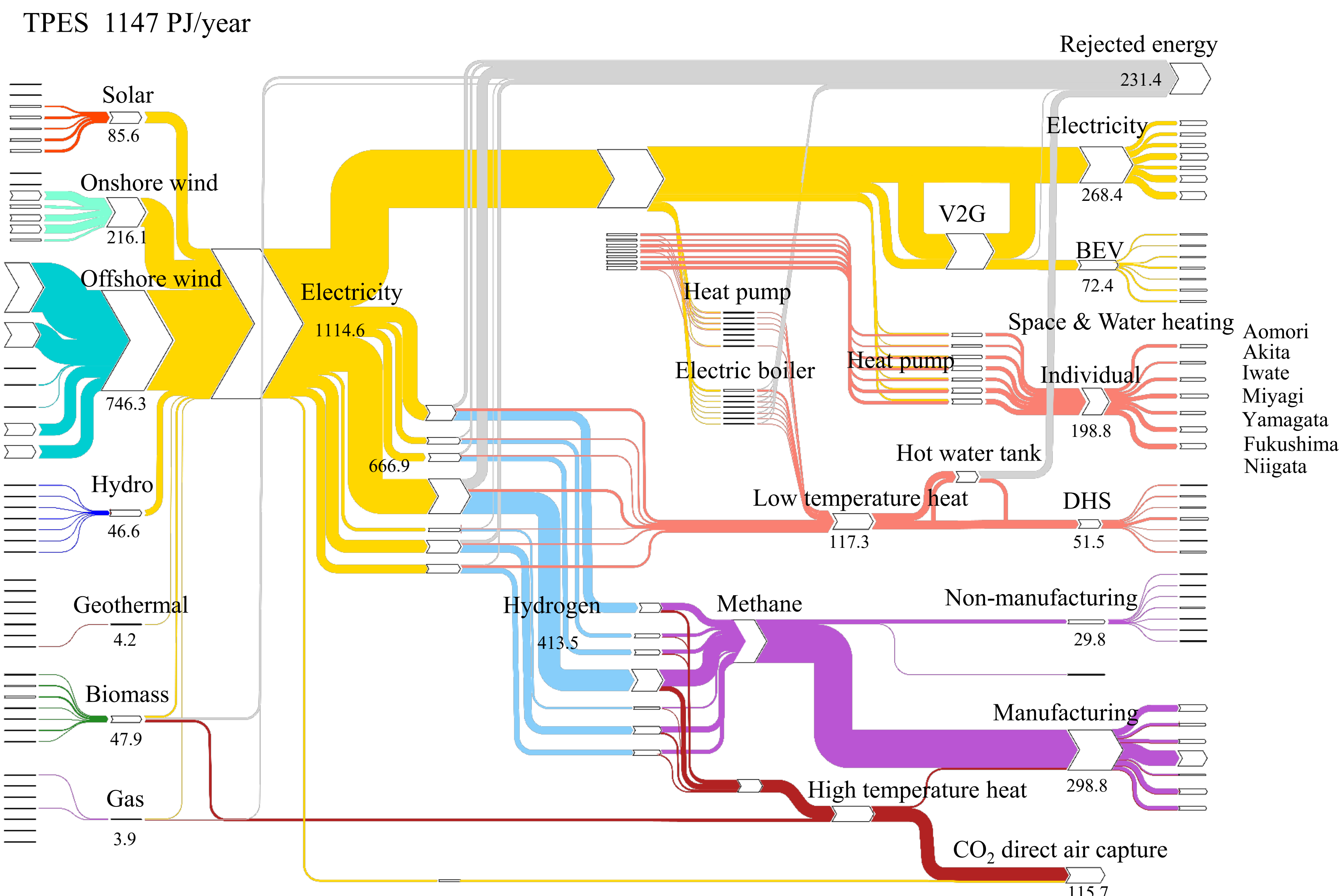
(a) All BEV, **Individual heating** (b) All BEV, **District heating** (c) All BEV+**V2G**, **District heating**

The improvement of capacity factor due to the smoothing effect

The capital cost reduction of electrolyze & methanation.

In addition to improving the flexibility of electricity grid, district heating and V2G can also contribute to reducing the production cost of electrofuels.

Energy flow (all BEV+V2G and DHS scenario)



Outline

1. Introduction
2. Methodology
3. Results and discussion
4. Conclusions

Conclusion

- We have developed an optimization model for designing energy system considering sector coupling.
- We have applied this model to Tohoku region in Japan and conducted scenario analysis.
- As a result..

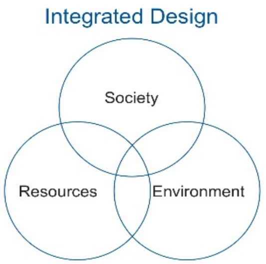
➢ Compared with the current energy system, **TPES decreases** in each scenario but **the total cost increases from 60% to 150%**.

➢ In each scenario, the model has feasible solutions for decarbonization.

➢ The introduction of district heating and V2G contributes to **not only giving flexibilities for electrical sector but also reducing electrolyze cost**.

➢ Total cost is the lowest by considering district heating and V2G.

➢ In this case, the total annual system cost is 6,724 billion JPY/year and TPES is 1147 PJ.



Thank you for your attention.