Power Electronics for a Future Sustainable Society

At PCIM2022
May 11, 2022

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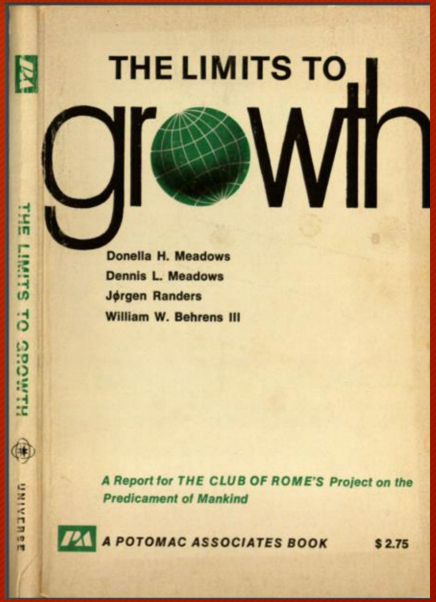
Kyushu Institute of Technology

-Special thanks to Josef-

The Limit to Growth?

- The Report for The Club of Rome in 1972
  - By D. H. Meadows, D. L. Meadows, J. Randers, W. W. Behrens III (MIT).
- *"And we hope that it will lead thoughtful men and women in all fields of endeavor to consider the need for concerted* ***action*** *now if we are* ***to preserve*** *the habitability of this planet for ourselves and* ***our children****. "*
- ***Compatibility*** *to "the dimensions of our* ***finite planet****"*



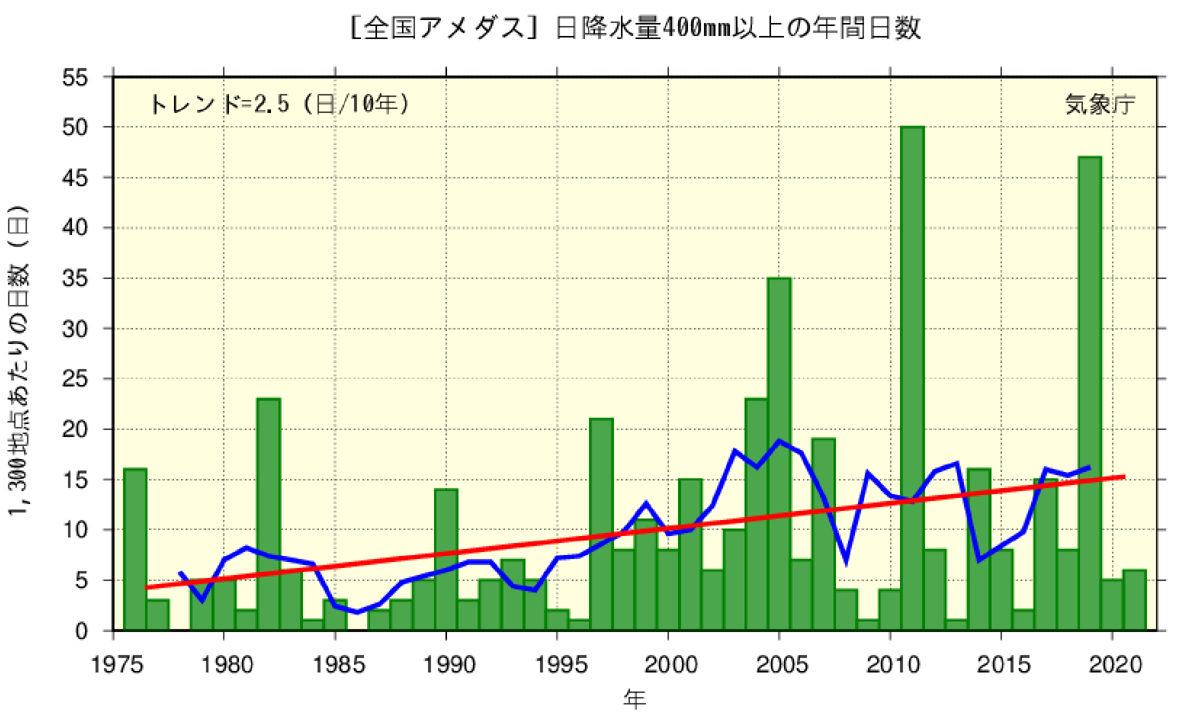
Reducing emissions [AND] Growing economy,,,

1. How far is our target? 2. What will be our contribution?

JMA: Japan Meteorological Agency, https://www.data.jma.go.jp/cpdinfo/extreme/extreme_p.html

Days of daily precipitation of over 400mm (1976-2021) by JMA data of extreme event

- Over 400mm/day: x1.8 (1976-2021)
- Over 50mm/day: x1.4 (1976-2021)
- Hot day >35C: x3.3 (1910-2021)
- Hot night >25C: x2.7 (1910-2021)



茨城県常総市の浸水状況

Typhoon 19, 2019:140 breach

Starting point

- Starting point to be shared:
- **The impacts of global warming of 1.5° C** above pre-industrial level,, in the **IPCC Special report**, 2018 responding to the invitation by COP21, Paris, 2016.

- Objective
  - **Analyze the gap** between **present and target**
  - **Analyze the contribution** of power electronics to filling the gap.

Global warming of 1.5°C

An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

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IPCC special report 2018

Agenda

- Review of **2030 target** to NZE2050 (UNFCCC, IPCC, IEA)
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Nationally determined contributions (NDCs), the ambitions toward 2030 (for COP26, UK)

- In conjunction with **COP26** in Glasgow, UK in 2021, 192 parties to the Paris agreements **submitted NDCs.**
- NDCs are **embodiments of efforts** by each country or region to **reduce GHG emissions**

(NDCs are in UNFCCC web page, link address see Ref. [9], original NDCs are freely accessible)

2030 Targets, based on NDCs submitted to UNFCCC before COP26

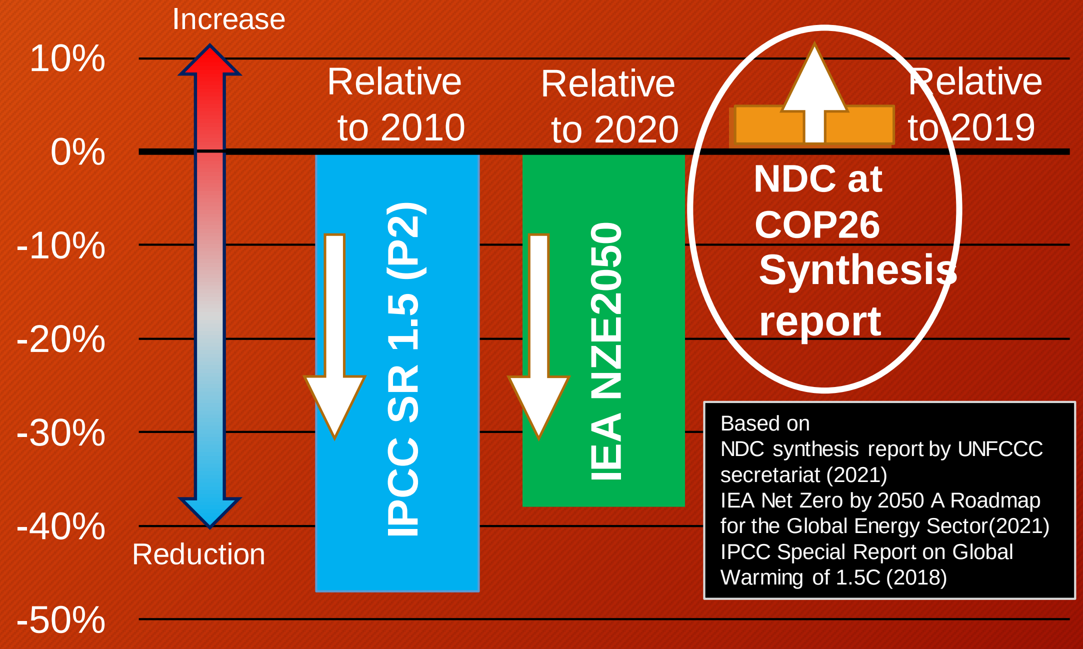
	Reference year	Reduction of	Reduction by
Japan	2013	GHG emission	46%
China	2005	CO2 emission/GDP	65%
India	2005	CO2 intensity/GDP	33~35%
Russia	1990	GHG emission	70%
EU	1990	GHG emission	55%
UK	1990	GHG emission	68%
Saudi Arabia	2019 (622MtCO2Eq)	GHG emission	278MtCO2Eq (eq. 44.6%)
US	2005	GHG emission	50~52%
Brazil	2005	GHG emission	43%

Does total of the reductions based on **NDCs** meet the **2030 target** for Net Zero 2050?

NDC synthesis report by UNFCCC secretariat (Sep. 2021)

- **A large gap** between NDCs synthesis impact net zero emission at 2050,
- Describing “*an urgent need for either a* ***significant increase*** *in the level* ***of ambition of NDCs*** *between now and 2030 or* ***a significant overachievement*** *of the latest NDCs, or a combination of both, in order to attain cost-optimal emission levels suggested in many of the scenarios considered by the IPCC for keeping warming well below 2° C or limiting it to 1.5° C.*”

CO_2 Emission Reduction Challenge in 2030 and UNFCCC prediction with NDCs at COP26

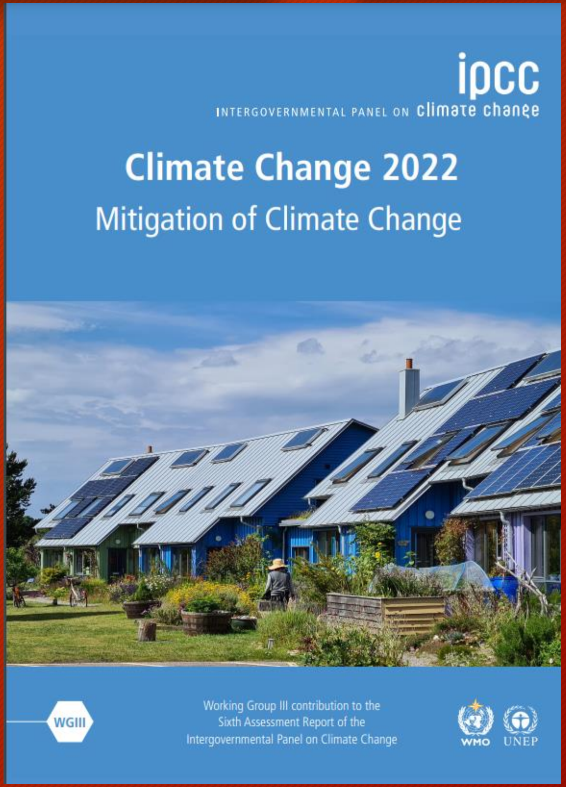


Based on
NDC synthesis report by UNFCCC secretariat (2021)
IEA Net Zero by 2050 A Roadmap for the Global Energy Sector(2021)
IPCC Special Report on Global Warming of 1.5C (2018)

Present level of ambitions **do not meet** 2030 target for NZE2050.

AR6 WG3: IPCC Contribution of Working Group III to the Sixth Assessment Report (April, 2022)

- Item C.1 in “Summary for Policymakers”
  - *Without a strengthening of policies beyond those that are implemented by the end of 2020, GHG emissions are projected to rise beyond 2025, leading to a median global warming of* ***3.2 [2.2 to 3.5] ° C by 2100*** *(medium confidence).*


ipcc
INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2022
Mitigation of Climate Change

WGIII
Working Group III contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change
WMO UNEP

No further action ➔ 3.2° C by 2100

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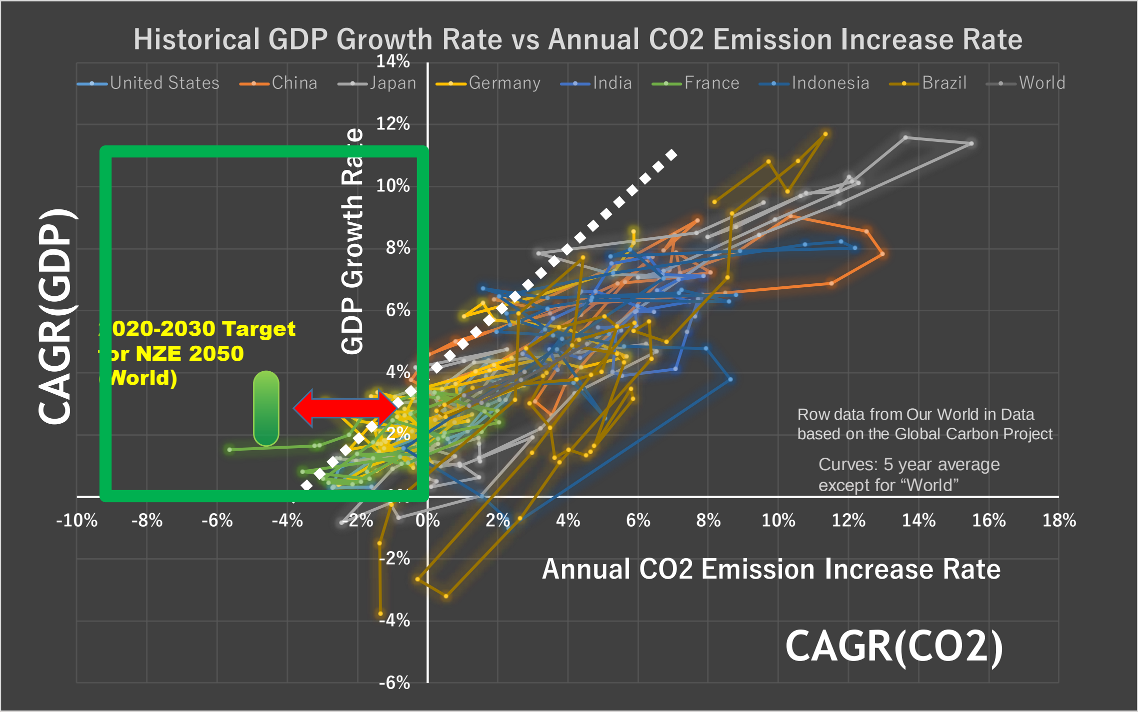
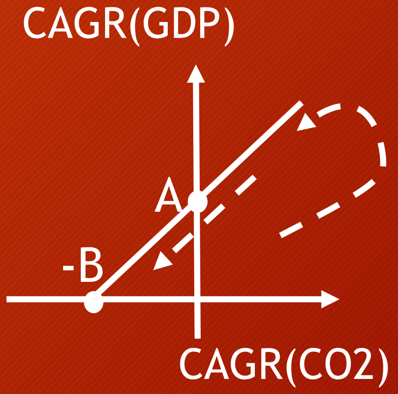
Scatter plot of historical CAGRs of GDP and CO2 emission for decades with NZE target

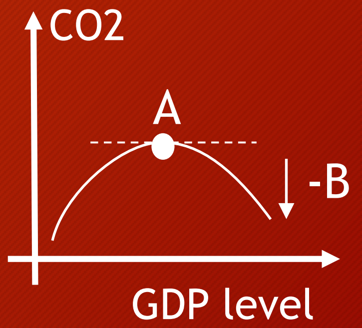
- The world economy in 2030 is expected to grow and become 24% to 45% larger than that in 2020, which are equivalent to 2.1 % to 3.7% of GDP average growth rate. IEA NZE2050[8]
- The world CO2 emission in 2030 need to be 37 % lower than 2020 according to IEA NZE2050, which is equivalent to -4.5 % of emission growth rate annually. IEA NZE 2050[8]



Row data from Our World in Data based on the Global Carbon Project

Curves: 5 year average except for "World"

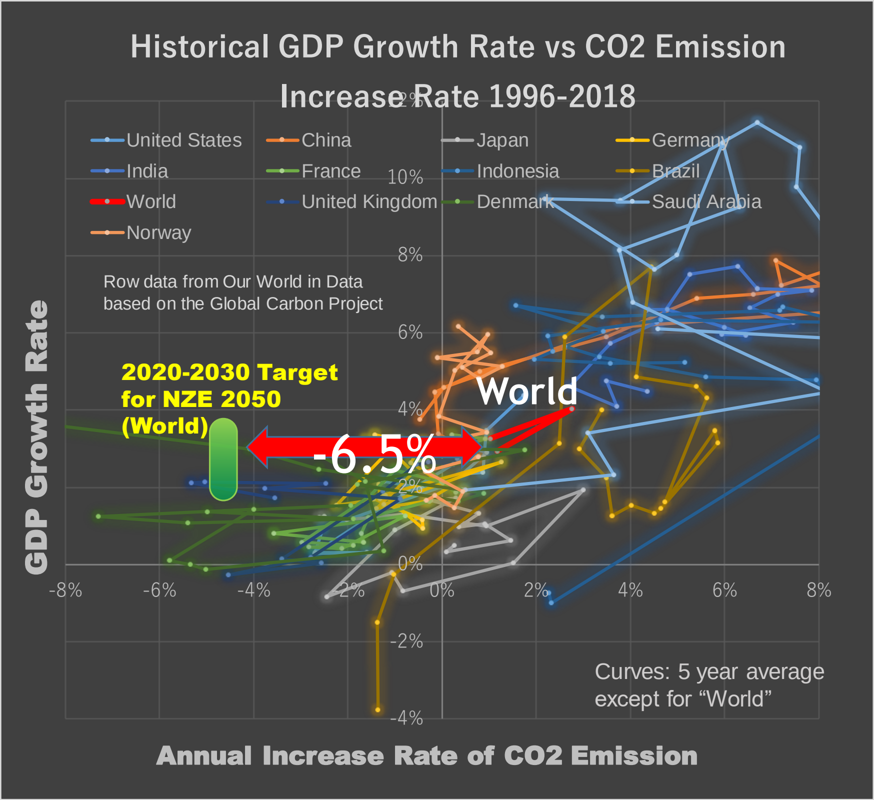




2030 target for NZE2050 is completely outside of scatter plot trend.

Gap between NZE2050 target for 2020-2030 and our present position

- 2030 target is the world target as a whole, not a target for individual country or region.
- The gap is -6.5% in CAGR of CO2 emission.



Historical GDP Growth Rate vs CO2 Emission Increase Rate 1996-2018

Row data from Our World in Data based on the Global Carbon Project

Curves: 5 year average except for “World”

Countries and regions of the “advanced economies” have to set even higher target for 2030.

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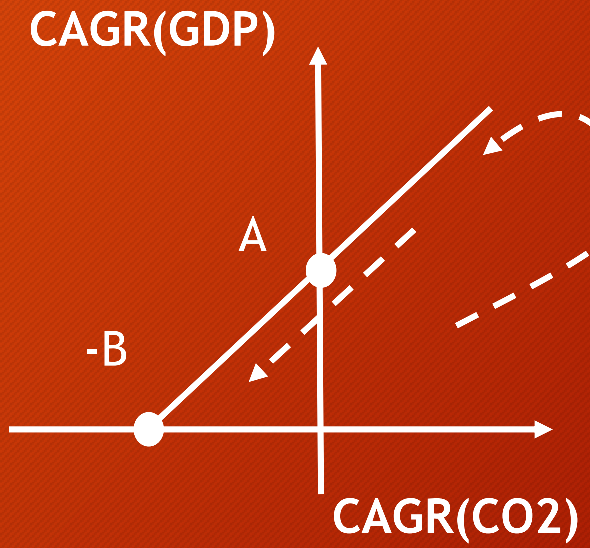
GDP-CO2 CAGR offset model introduction

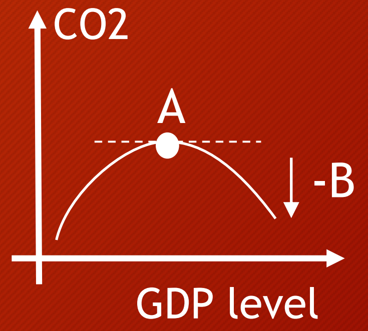
- “A” indicates achievable GDP growth rate without increase of CO2 emission
- “B” indicates CO2 emission reduction rate under zero growth of GDP.

$$CAGR(CO_2) = \frac{\mathrm{B}}{\mathrm{A}} \cdot CAGR(GDP) - B$$

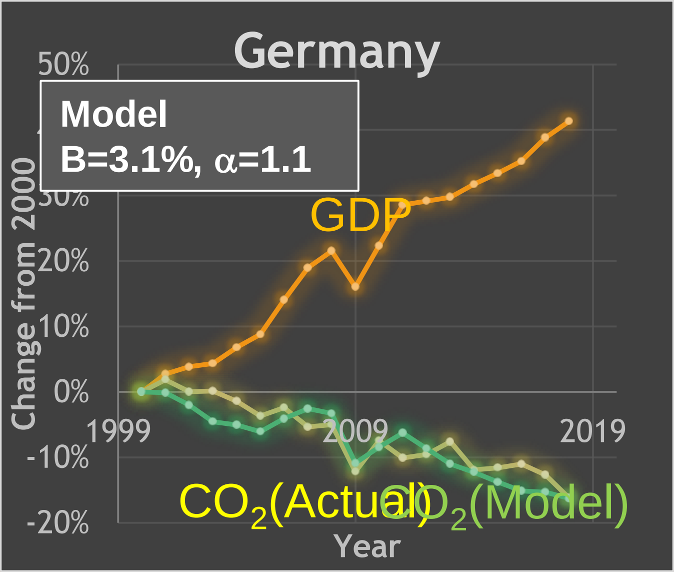
Solving the equation, we obtain,

$$CO_2 = K \cdot GDP^{\left(\frac{B}{A}\right)} \cdot e^{-Bt}$$

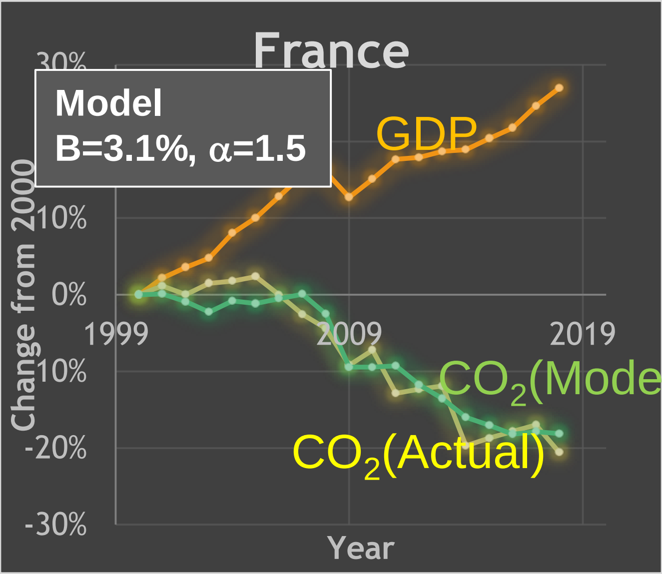




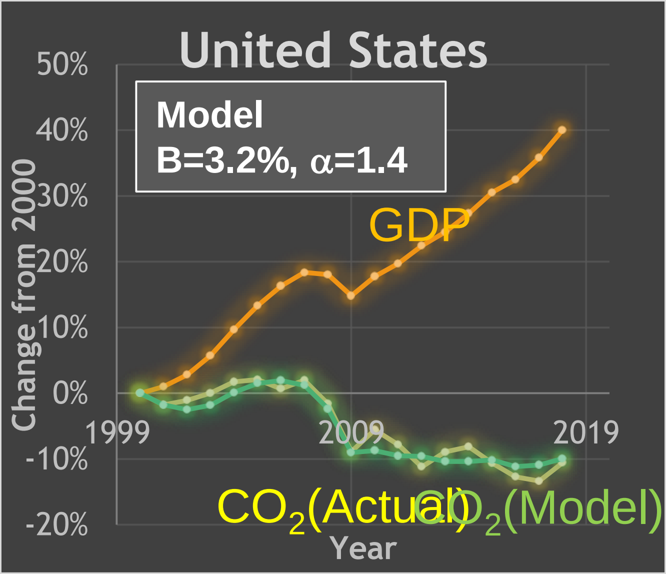
“A” relates emission peak point, “B” determines speed of emission reduction



Germany



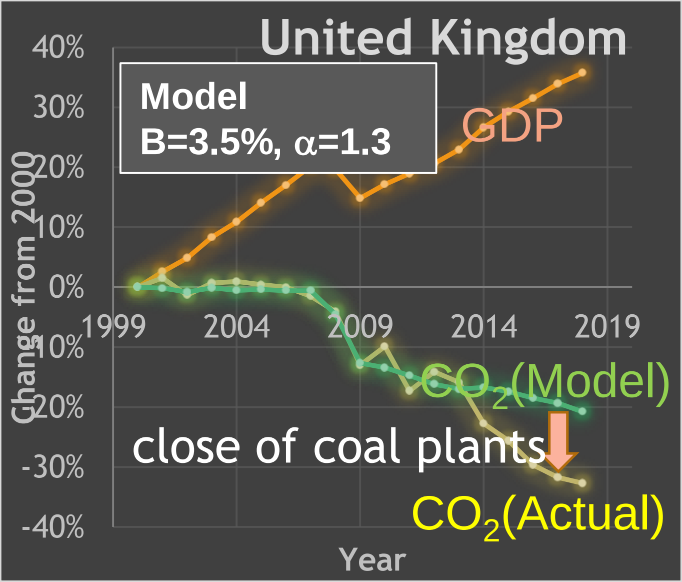
France



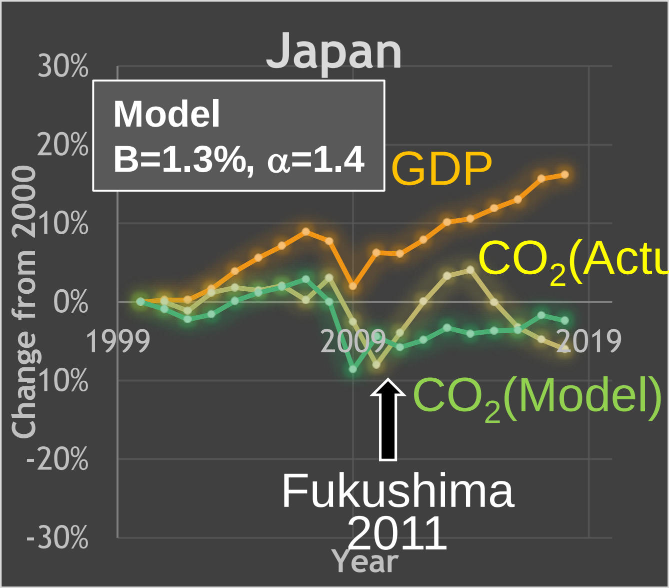
United States

Obtaining of B and α

- Input = GDP data
- "B" and "α=B/A" are fitted with actual CO2 emission data



United Kingdom

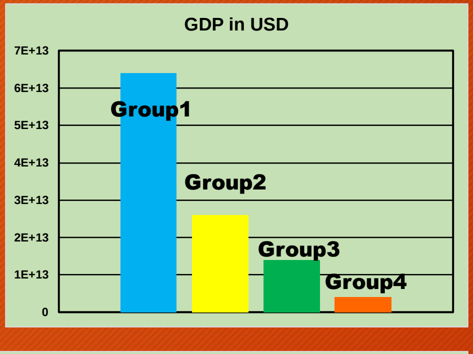


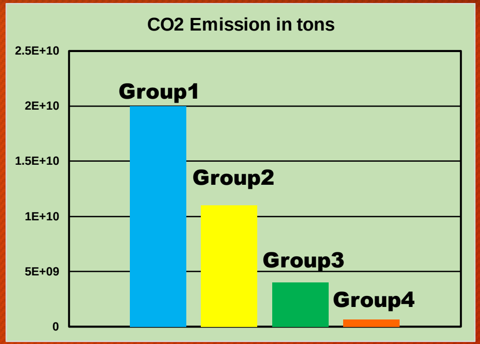
Japan

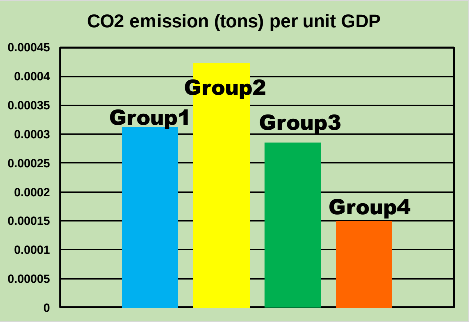
The model reproduced historical result of CO2 emission with simple fitting of constants A and B (or B and α).

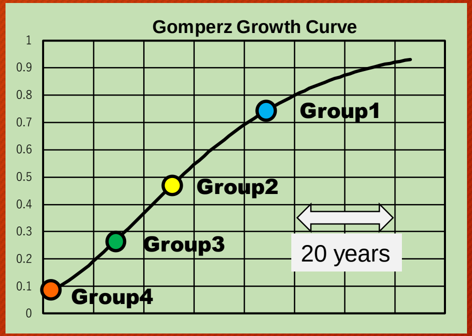
Global model of CO2-GDP CAGRs

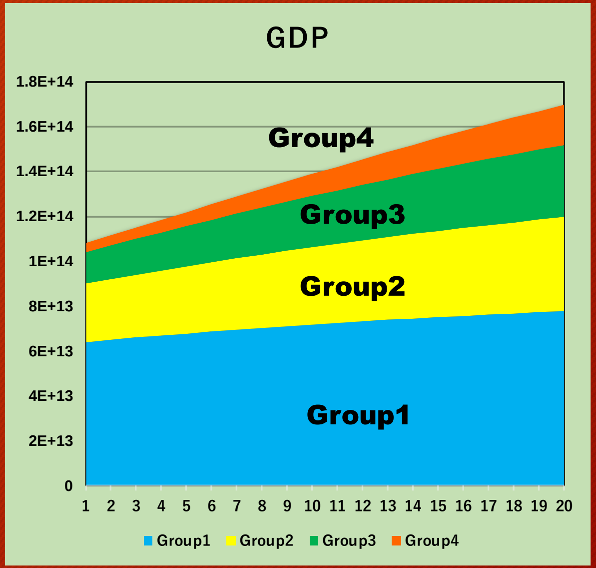
- Four groups represent hypothetical Global model
- Set **initial GDP and CO2 emission condition** for each group
- Assume **Gomperz curve** for GDP growth and set the initial position on the curve
- Apply the GDP to the offset model


GDP in USD


CO2 Emission in tons


CO2 emission (tons) per unit GDP

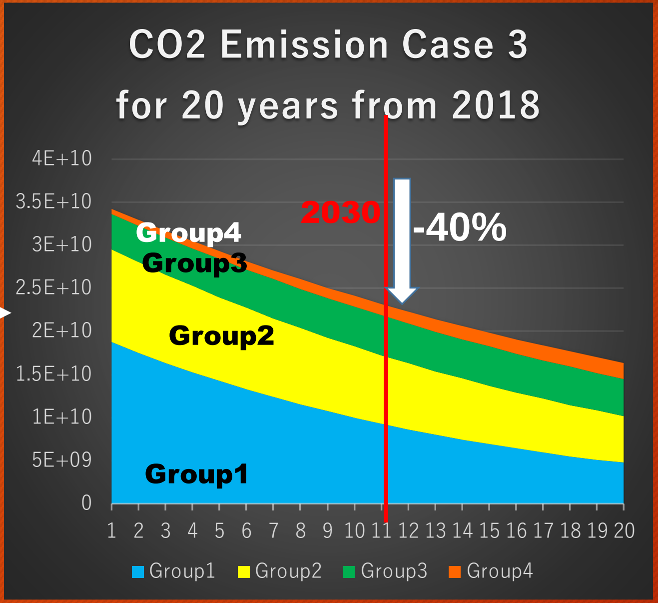

Gomperz Growth Curve

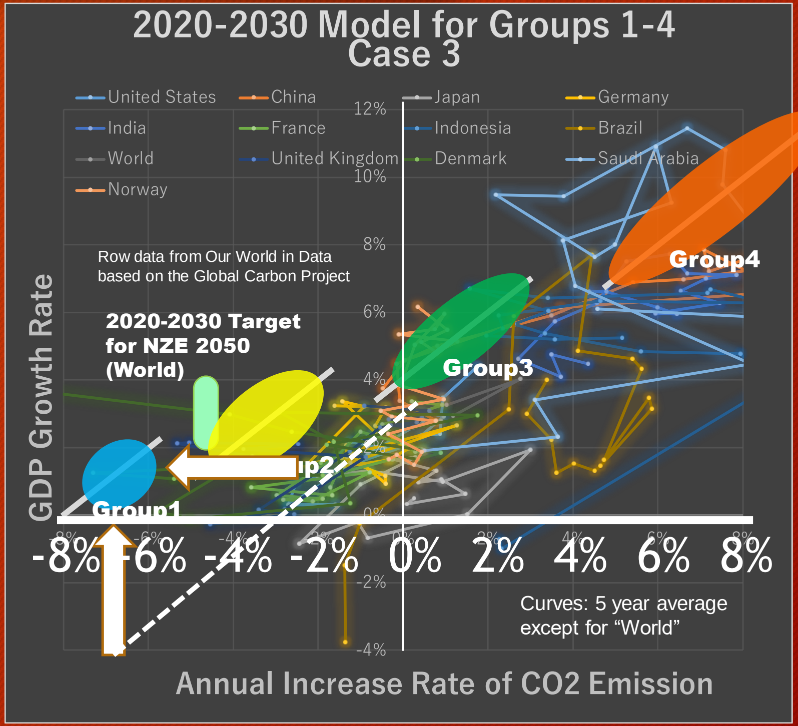

GDP

GDP values of the groups will be used for CO2 emission calculation

Calculated CO2 emission level at 2030

	Condition	@2030(ref. 20 18)
Case 1	A=B=2% for all groups	**+6.4%**
Case 2	A=B=4%, 3%, 2% and 1% for group 1, 2, 3 and 4 respectively	**-9.1%**
Case 3	A=B=8%, 6%, 4% and 2% for group 1, 2, 3 and 4 respectively	**-40.0%**





CO2 emission under the condition of Case 3 achieves -40% reduction in 2030. Parameter B=8% for Group1.

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Efficiency, Electrification and Flexibility

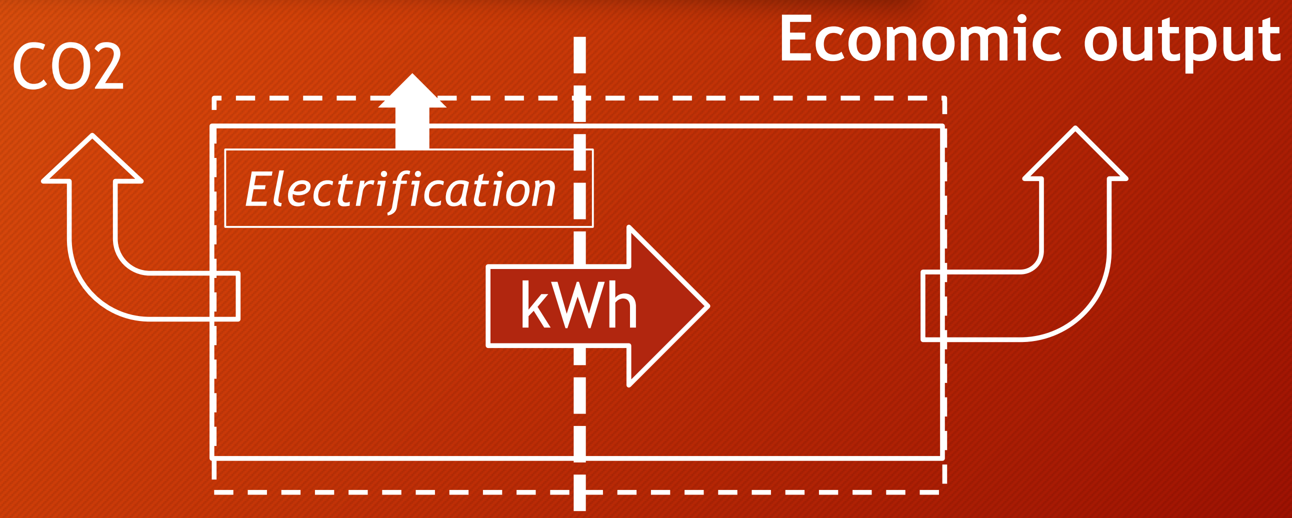
Efficiency of a converter ⇨ *Efficiency* of economic output

Electrification in final energy use ⇨ *Electrification* of economic activity

Flexibility of a power system ⇨ *Flexibility* to secure electrified economic activity under high VRE ratio

Contribution of power electronics

1. Increasing **Efficiency** of ~~power converters~~ ➔ **economic output** to unit electricity
2. Reducing CO2 emission intensity to unit electricity ➔ **Flexibility** to increase variable renewables ratio
3. Increasing **Electrification** in ~~final energy use~~ ➔ of **economic activity**



Ref. [17]
NREL
Report,
modified

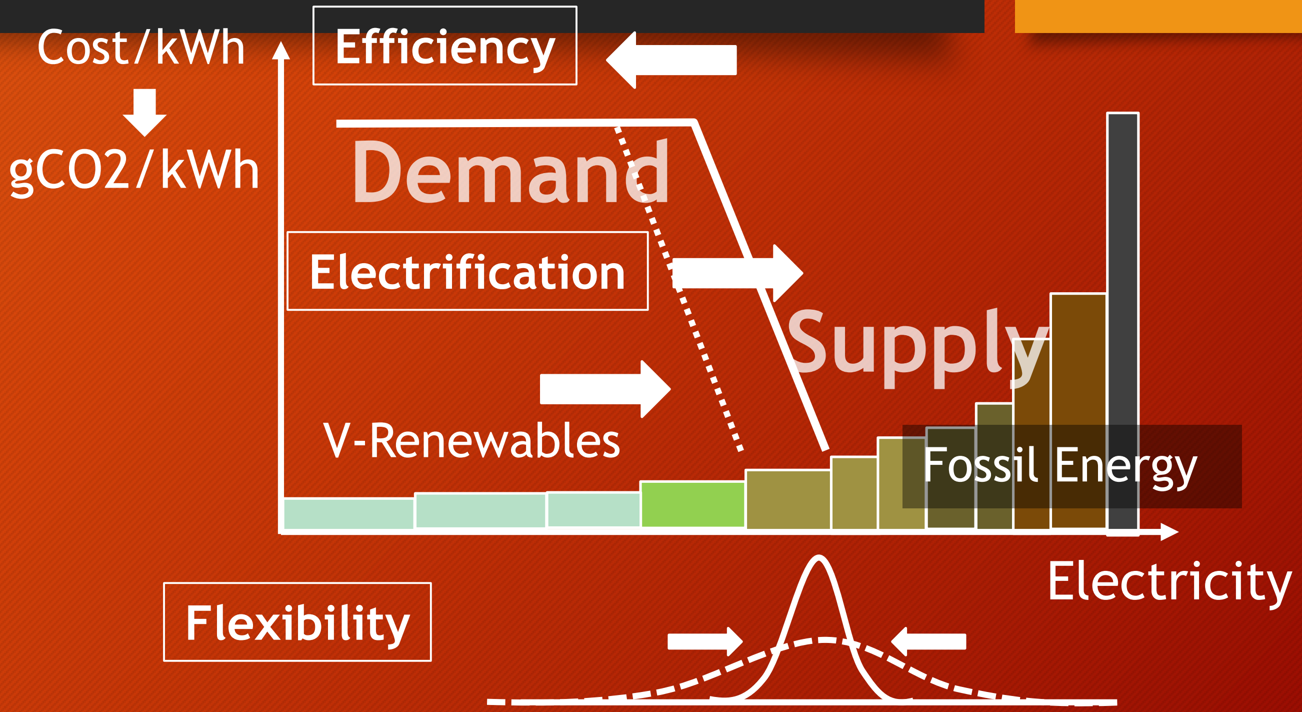
$$\Uparrow \frac{\textit{Economic output ``efficiency'' of unit electricity } [\text{X/kWh}]}{CO_2 \textit{ emission of unit electricity } [\text{gCO2/kWh}]}$$

Efficiency

Flexibility

Contribution of power electronics

1. gCO2/kWh will increasingly considered in energy pricing ➔ VREs are advantageous in energy market
2. **Efficiency** ➔ decrease in fossil electricity demand
3. **Electrification** ➔ more VREs installation
4. **Flexibility** ➔ Balancing demand and supply under high VRE ratio



Efficiency
of economic output

Electrification
of economic activity

Flexibility
to variable renewables

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[19] 32009L0028, found at https://eur-lex.europa.eu/
https://www.hptcj.or.jp/e/publication/tabid/368/Default.aspx

High Efficiency heating: air-conditioners (residential use of heat pumps)

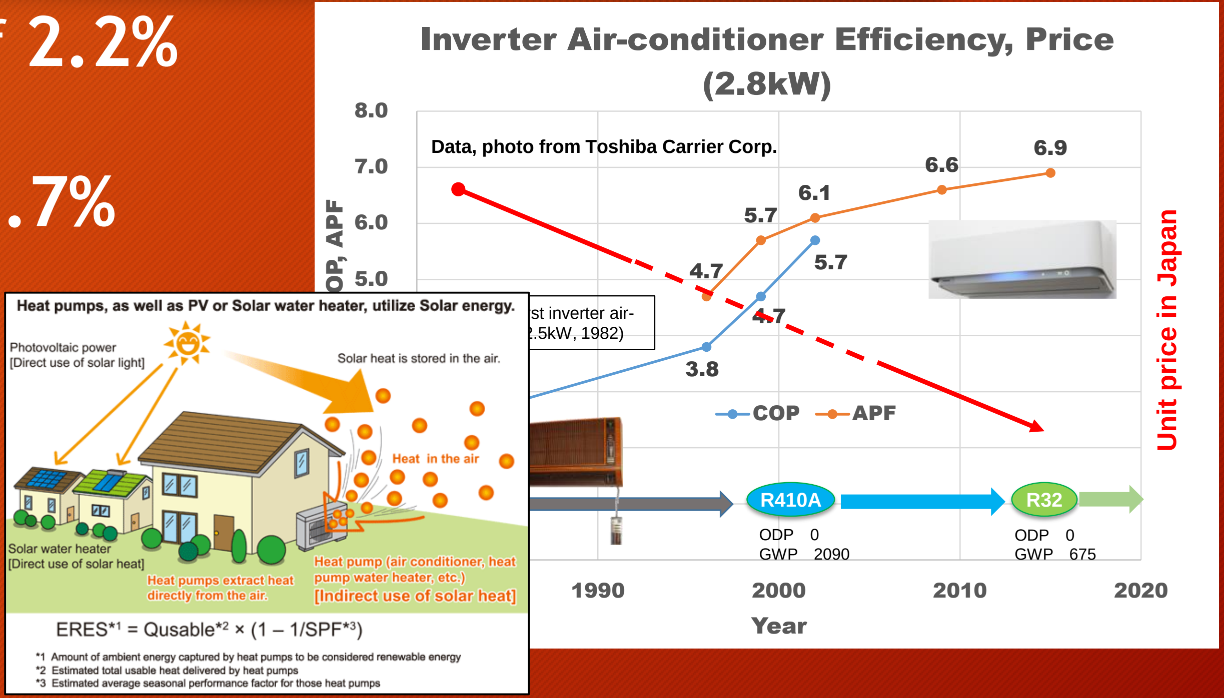
- Average efficiency improvement of **2.2% per year** for 40 years (Toshiba Carrier)
- Average price reduction ratio of **-2.7% per year** for 40 years (Toshiba Carrier)
- Countable as renewable energy

$$E_{RES} = Q_{usable} \cdot \left(1 - \frac{1}{SPF}\right)$$

EU directive [19]

ERES: Heat from ambient

Qusable: Heat to the room, SPF: “Efficiency”



$\mathrm{ERES}^{*1} = \mathrm{Qusable}^{*2} \times (1 - 1/\mathrm{SPF}^{*3})$

*1 Amount of ambient energy captured by heat pumps to be considered renewable energy
*2 Estimated total usable heat delivered by heat pumps
*3 Estimated average seasonal performance factor for those heat pumps

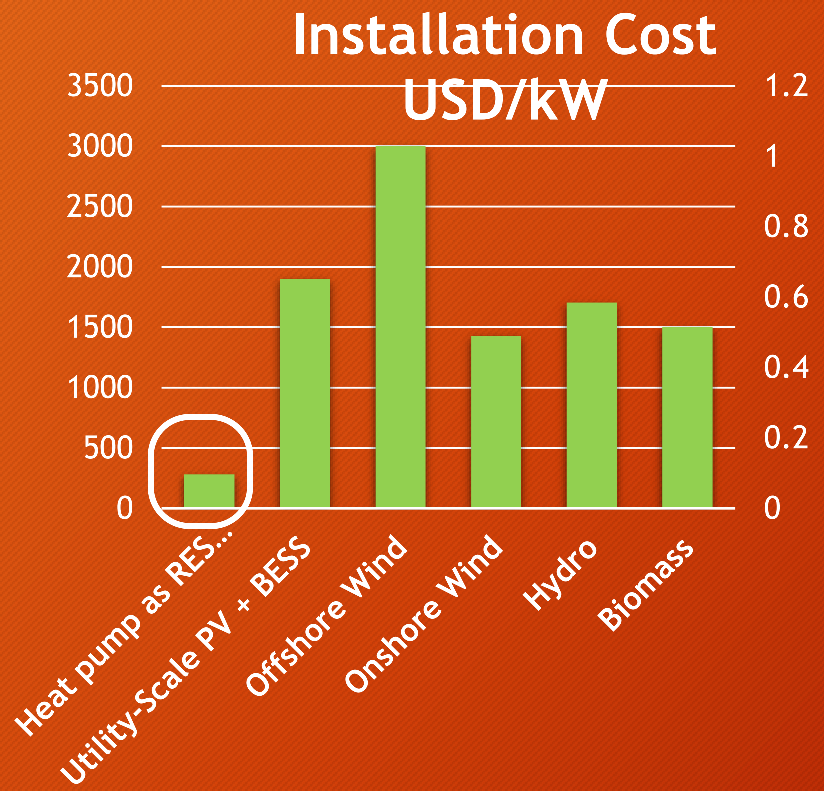
High performance **heat pumps ➔ High efficiency to generate heat** by replacing conventional heaters. Counted as Renewable Energy.

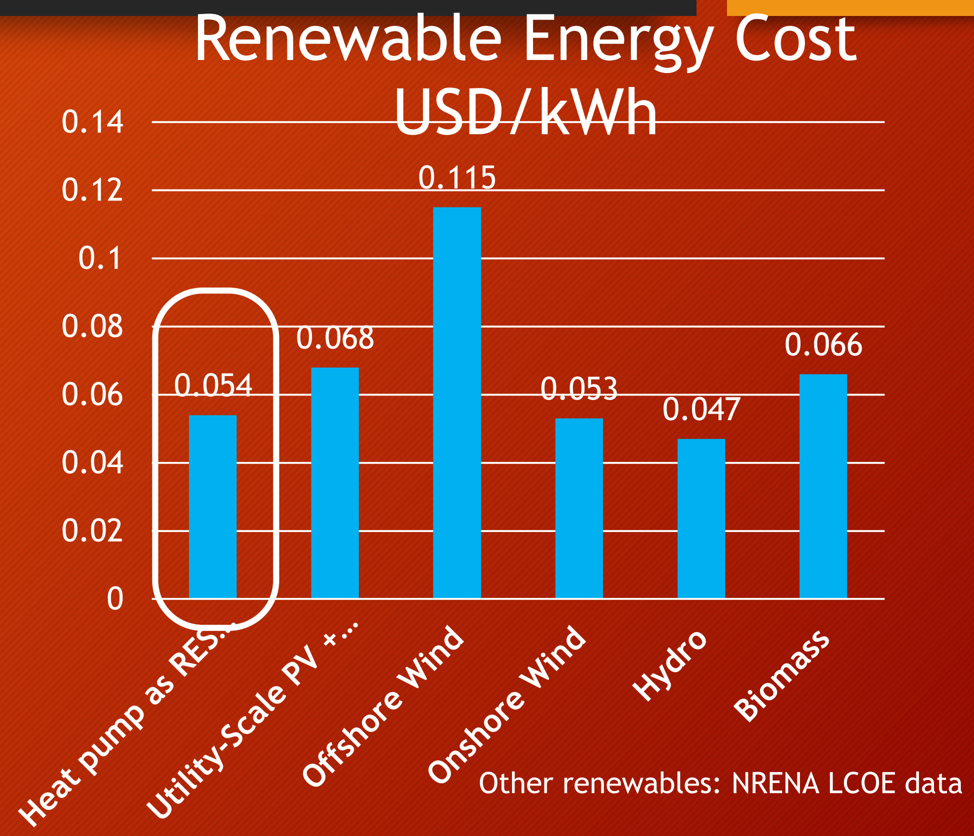
Cost comparison of renewable energies

$$E_{RES} = Q_{usable} \cdot \left(1 - \frac{1}{SPF}\right)$$

EU directive [19]

E_{RES}: amount of ambient energy captured by heat pumps to be considered as renewable energy
Qusable: estimated total usable heat by heat pumps
SPF: estimated average seasonal performance factor





Other renewables: NRENA LCOE data

Renewable energy by high efficiency heat pump is the lowest cost level

Generalization

EU directive [19], modified

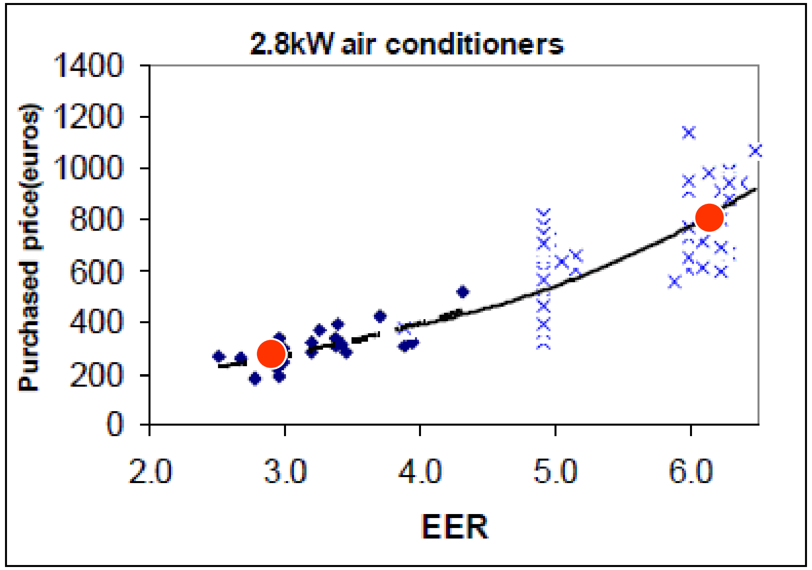
$$\Delta E_{RES} = X \cdot \left(\frac{1}{\eta_{old}} - \frac{1}{\eta_{new}} \right)$$

X: total output

$$\Delta Cost = \mathrm{Cost}_{\mathrm{new}} - \mathrm{Cost}_{\mathrm{old}}$$

Cost includes installation cost, running cost

Fig.16 Purchase prices of Japanese air conditioner



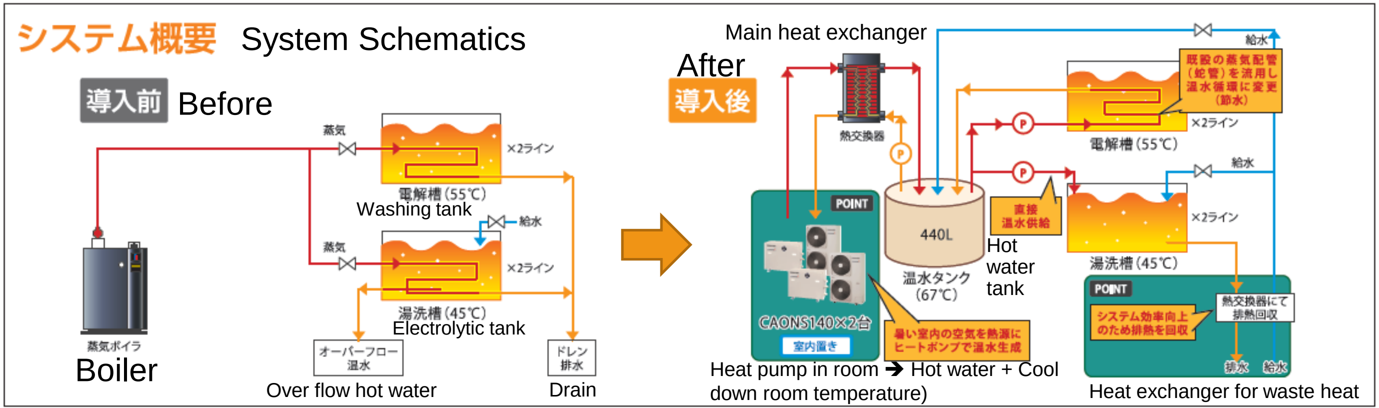
Efficiency: Direct / Indirect advantage to install

Heat pumps installation in industry replacing boilers or heaters

Data and figure: Toshiba Carrier Corp.

- Heat pump installation in industry
- Case 1: Replacement of electric **heaters by heat pumps** (*Efficiency*)
- Case 2: Replacement of a **boiler by heat pumps** (*Efficiency* and *Electrification*)
- Electric energy reduction by >50%, and which is equivalent to **efficiency improve rate of >3.5% per year** if the system is operated for 20 years.

Target	Replacement	Spec. of heat pump	System impact
Case 1: Cleaning process with hot liquid	Heater ➔Heat pump	Output 14kW COP 3.5 (Catalog) Liquid Temp 50-90°C	Electric energy -54% CO2 -28ton/year
Case 2: Preprocess to painting (shown in figure below)	Boiler ➔Heat pump	Output 14kW X2 COP 3.5 (Catalog) Liquid Temp 45°C, 55°C	Reduction of heat loss in plumbing Running cost reduction -62%



Industrial application of heat pumps impact to both **efficiency** and **electrification**

Examples of efficiency challenge

- **Compressed air systems**
  - 8.8 TWh or 3100 KtonCO2 per year in UK
  - Consuming substantially large electricity in manufacturing plants in Japan
  - Very low efficiency of 10% due to compressor, air leakage, pressure losses
  - Can be replaced by electric actuators in some application
- **Hydraulic systems**
  - Efficiency 35% to 50%
  - Large losses in fluid lines, pump, actuator and control valves
  - High maintenance cost, oil leakage, fire risk
  - Limit of downsizing

$$\Delta E_{RES} = X \cdot \left(\frac{1}{\eta_{old}} - \frac{1}{\eta_{new}} \right)$$

X: total output

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Electrification projection by IRENA "REmap" (end use energy)

Data source: IRENA (2018), Global Energy Transformation: A roadmap to 2050, download from www.irena.org/publications

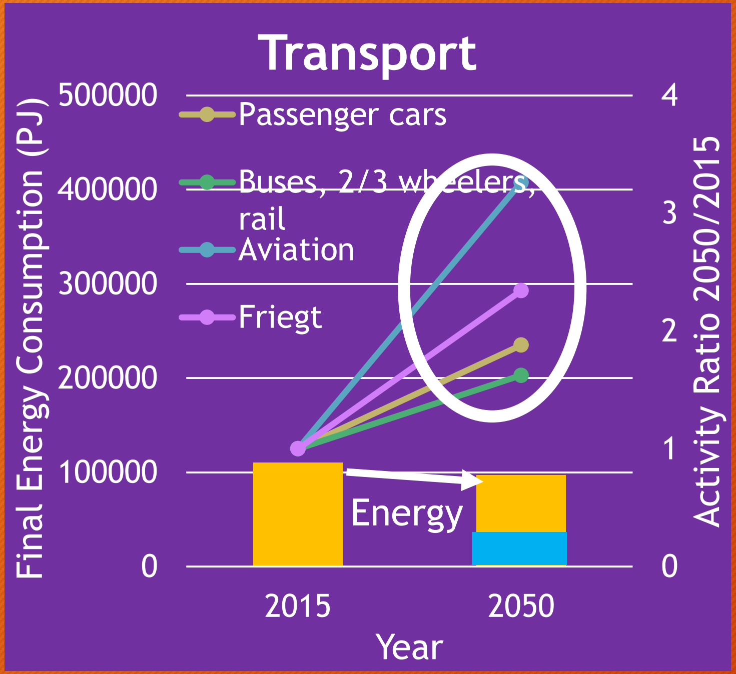
Sector	Electricity share in final energy 2015 → 2050	Renewable share in Electricity 2015 → 2050
Transport	1% → 33%	? % → 85%
Buildings	31% → 56%	23% → 85%
Industry	27% → 42%	26% → 85%

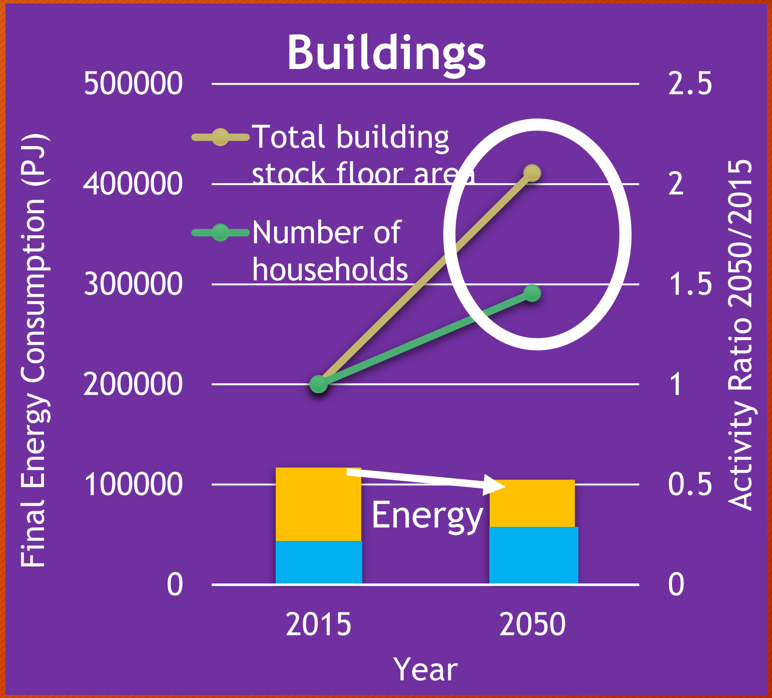
Electrification → High **Flexibility**

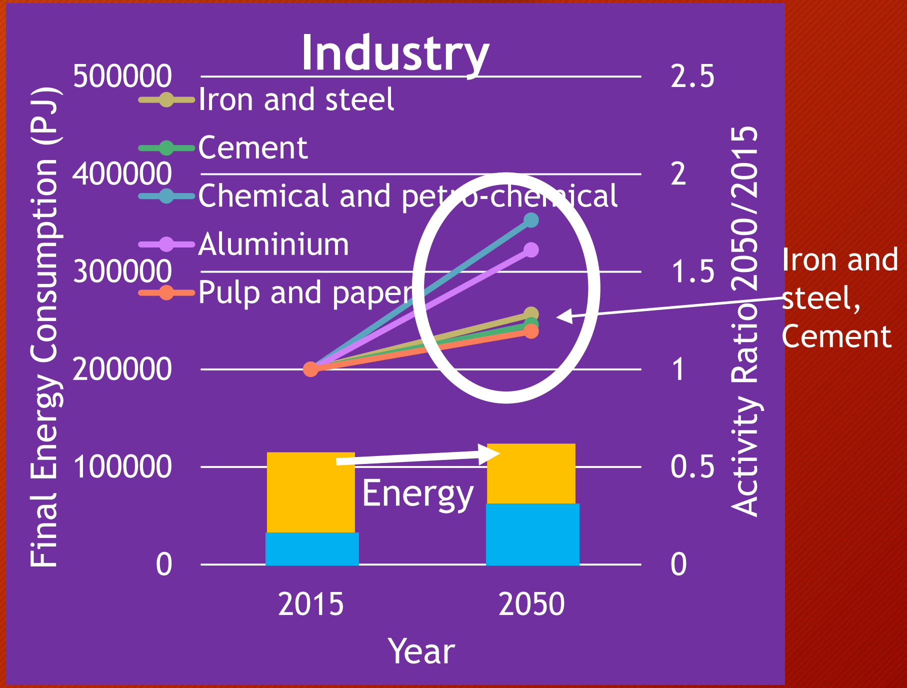
Data for the graph: IRENA (2018), Global Energy Transformation: A roadmap to 2050, download from www.irena.org/publications

Activity Increase and Energy Consumption shown in IRENA “REmap”

Data source: IRENA (2018), Global Energy Transformation: A roadmap to 2050, download from www.irena.org/publications

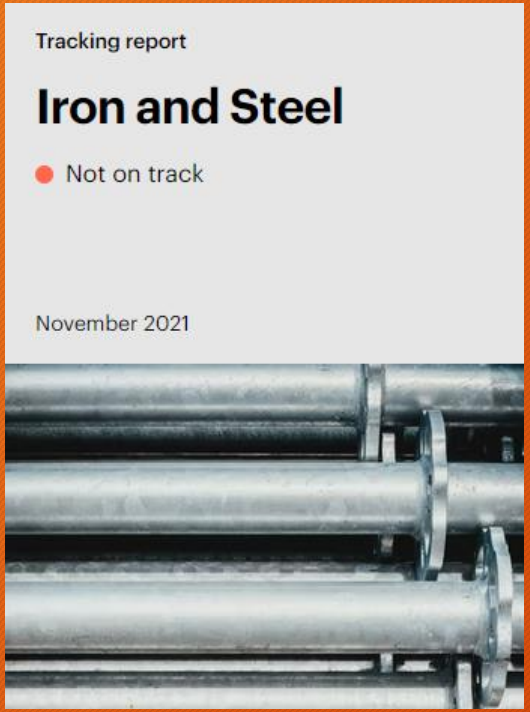






Electrification ➔ High **Efficiency**

Ion and Steel industry



Tracking report

Iron and Steel

● Not on track

November 2021

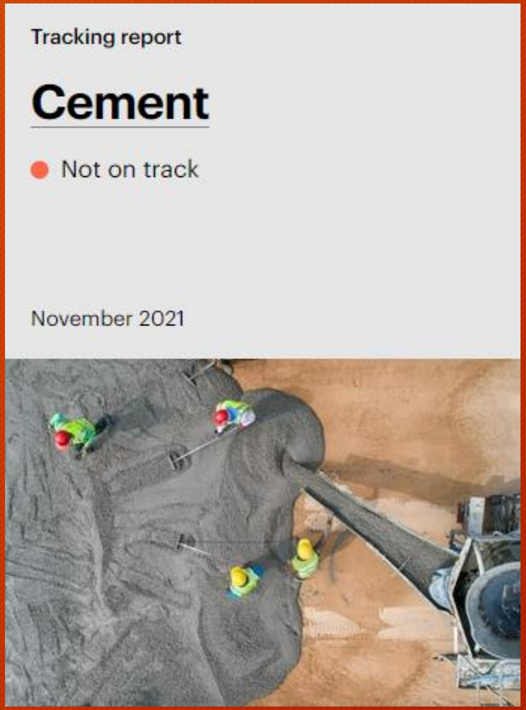
2.6 GtCO$_2$
=7% of the
global total

1.4 tCO$_2$/tIron

$Fe_2O_3+3CO \rightarrow 2Fe+3CO_2$

$3(12+2\times16)/2\times55.8=1.18$

Cement industry



Tracking report

Cement

● Not on track

November 2021

2.8 GtonCO$_2$
=8% of the
global total

0.6tCO$_2$/tCement

$CaCO_3 \rightarrow CaO + CO_2$

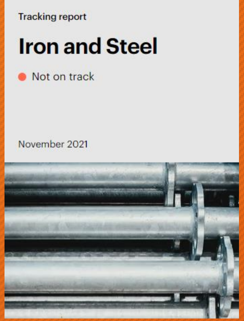
$(12+2\times16)/(40+16)=0.78$

Tons of production $\doteqdot$ Tons of emission

UK Governmnet, Industrial Decarbonisation Strategy, 2021
https://worldsteel.org/
BELLONA https://www.frompollutiontosolution.org/hydrogenuseinindustry

https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change
Technology Roadmap Low-Carbon Transition in the Cement Industry, IEA, 2018

Ion and Steel industry


Tracking report
Iron and Steel
Not on track
November 2021

- Carbon capture and storage (CCS)
- Electrolysis in ironmaking
- **Hydrogen** (H_2)-based ironmaking
  - $Fe_2O_3+3H_2 \rightarrow 2Fe+3H_2O$,
  - Huge electricity
- Maximizing scrap use, the **electric arc furnace**

Cement industry


Tracking report
Cement
Not on track
November 2021

- Carbon Capture and Storage (CCS)
- Alternative “Novel” Cements
- Clinker substitution
- Reduce use of cement in built environment
  - In Sweden, CemZero project to **electrify cement production.**

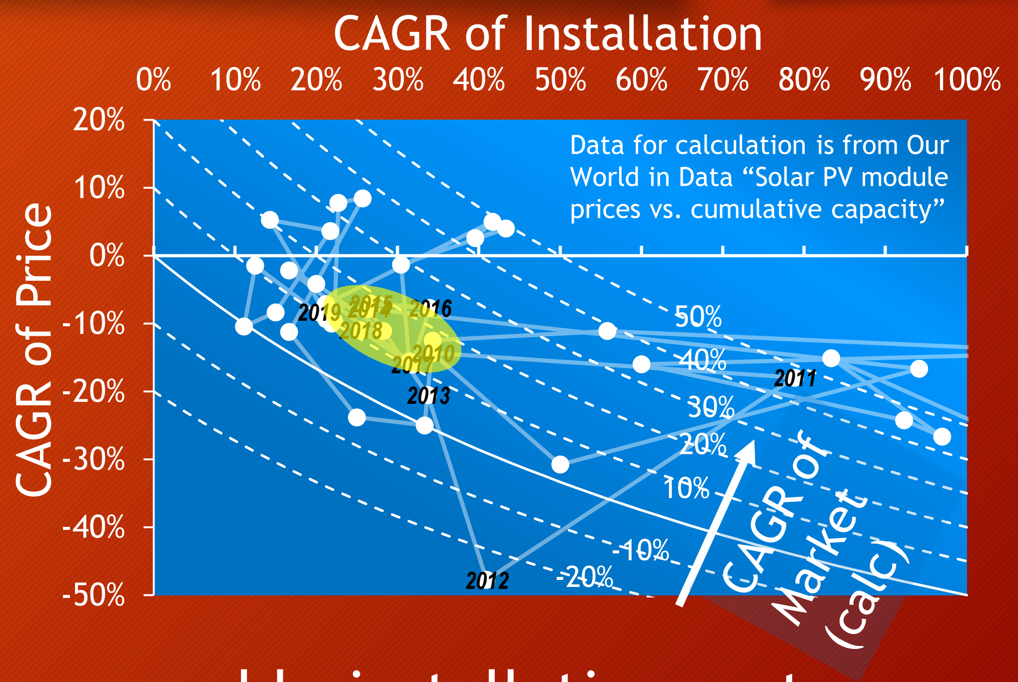
Ion and Cement industries can be big consumers of renewable energy toward 2050

Agenda

- Review of **2030 target** to NZE2050 (UNFCCC, IPCC, IEA)
- Analysis of the Gap: **CAGR(CO2) vs. CAGR(GDP)**
  - Historical **scatter plot analysis**
  - GDP-CO2 CAGR offset model
  - **Target for 2020-2030** for advanced economy to the NZE2050
- **Contribution** of power electronics
  - **Efficiency** to economic output
  - **Electrification** of economic activity
  - <u>**Flexibility** to variable renewables</u>
- Conclusion

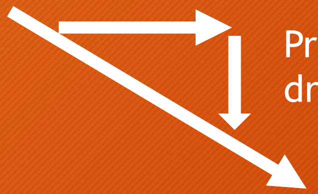
Learning rates of renewables, expansion of installation

Item	Learning Rate	Source
PV module	20%	Bloomberg New Energy Finance
Onshore wind	19%	
Li-ion Battery	19%	Hannah Ritchie, Our world in data, 2021
PV inverter	7%→19%	Agora report, Fraunhofer ISE, Current and Future Cost of Photovoltaics, 2015,
DRAM/Flash	35%	Walden Rhines, Predicting Semiconductor Business Trends After Moore's Law, 2019
Remaining Semis	23%	



Data for calculation is from Our World in Data "Solar PV module prices vs. cumulative capacity"

Learning rates



High learning rate of 19-20% for renewable installation cost

PV case:

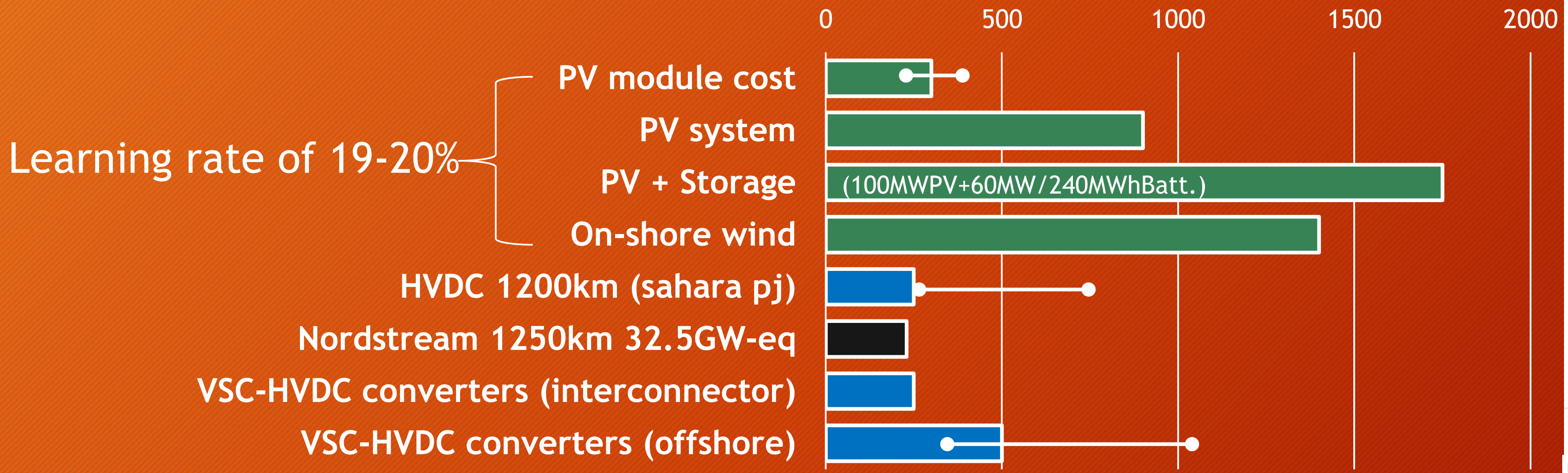
Installation growth >20% →Price down 10% + Market CAGR>10%

HVDC Transmission: Technology Review, Market Trends and Future Outlook Renewable and Sustainable Energy Reviews 112 (2019)
Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation, 2018, US-EIA
Review of investment model cost parameters for VSC HVDC transmission infrastructure, Electric Power Systems Research 151 (2017)
RENEWABLE POWER GENERATION COSTS IN 2020 , IRENA, 2021 / U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: NREL, Q1 2020

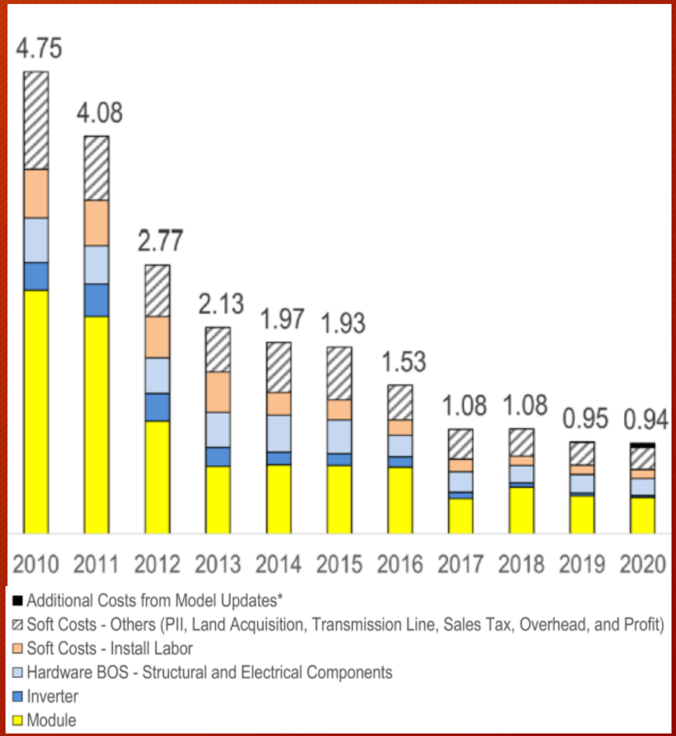
Raw data from, Review of investment model cost parameters for VSC HVDC transmission infrastructure, Philipp Härtel et al., Electric Power Systems Research 151 (2017), Table 3 and 4
U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020, NREL

Cost of flexibility?

per GW installation cost comparison (M euro/GW)



Utility scale PV USD/W NREL(2020)



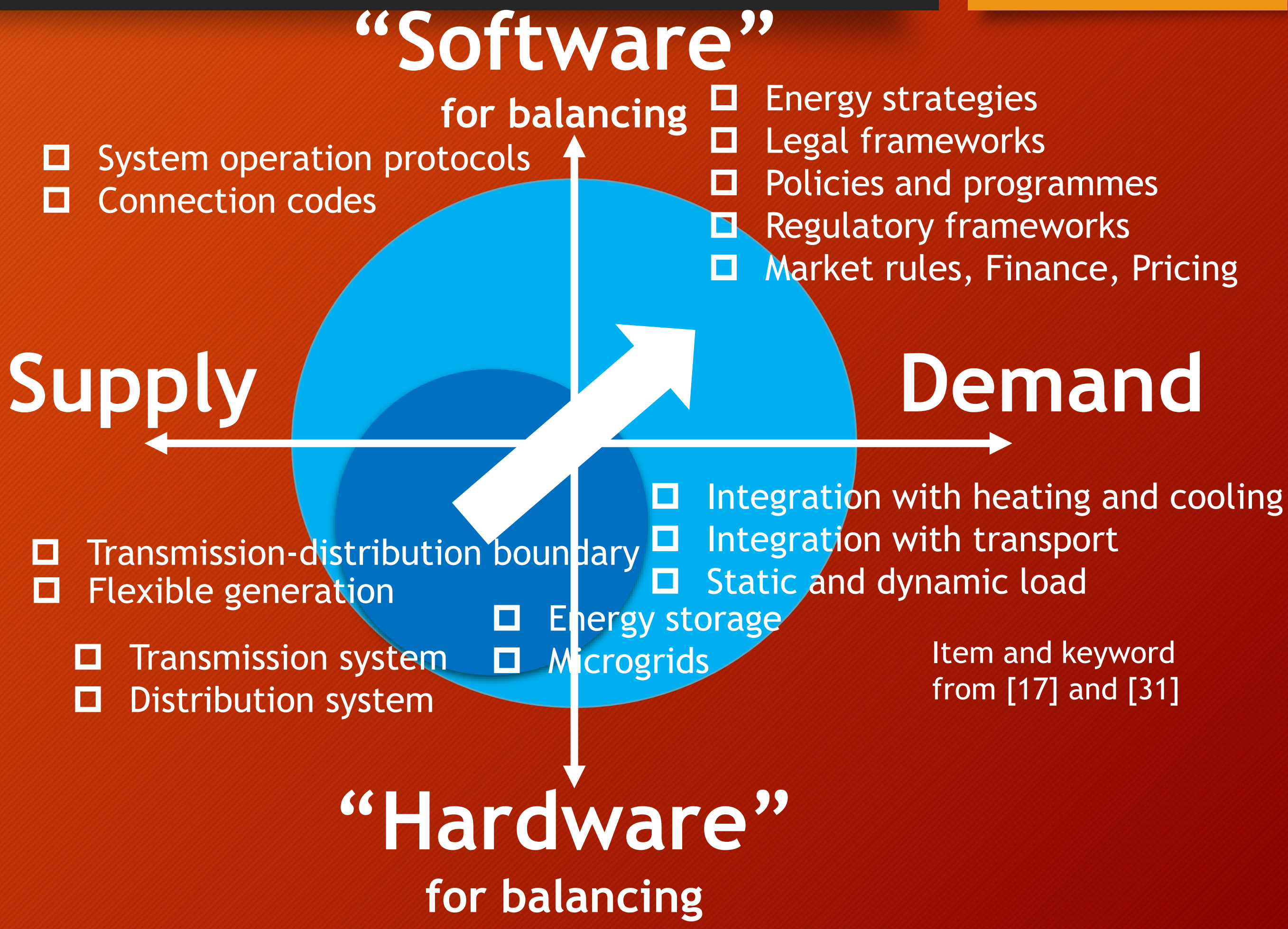
Cost of flexibility: Learning rate of 20%?

[17] “Status Report on Power System Transformation, A 21st Century Power Partnership Report,” NERL Technical Report, NREL/TP-6A20-63366, 2015
[30] “Status of Power System Transformation 2018, Advanced Power Plant Flexibility,” IEA 2018
[31] “Status of Power System Transformation 2019, Power System Flexibility” IEA 2019, https://www.iea.org/reports/status-of-power-system-transformation-2019
[*]Projected Costs of Generating Electricity,2020 Edition, IEA and NEA

Flexibility for responding to increased variable renewables

- **Demand and Supply: symmetric** in flexibility
- **“Software” to maximize the flexibility**

“the contribution to costeffectively secure the electrified economic activity under high renewable share”



“Software”
for balancing

☐ Energy strategies
☐ Legal frameworks
☐ Policies and programmes
☐ Regulatory frameworks
☐ Market rules, Finance, Pricing

☐ System operation protocols
☐ Connection codes

Supply

Demand

☐ Integration with heating and cooling
☐ Integration with transport
☐ Static and dynamic load

☐ Transmission-distribution boundary
☐ Flexible generation

☐ Energy storage
☐ Microgrids

☐ Transmission system
☐ Distribution system

“Hardware”
for balancing

Item and keyword from [17] and [31]

Efficiency, Electrification and Flexibility

Efficiency of a converter ⇨ ***Efficiency*** of economic output

Electrification in final energy use ⇨ ***Electrification*** of economic activity

Flexibility of a power system ⇨ ***Flexibility*** to secure electrified economic activity under high VRE ratio

Conclusions

- Starting point: the impacts of global warming of 1.5° C above pre-industrial level.
- “Advanced economy” need to contribute to realize higher reduction rate of CO2 emission

- Efficiency of economic output
- Electrification of economic activity
- Flexibility to secure electrified economic activity under high VRE ratio

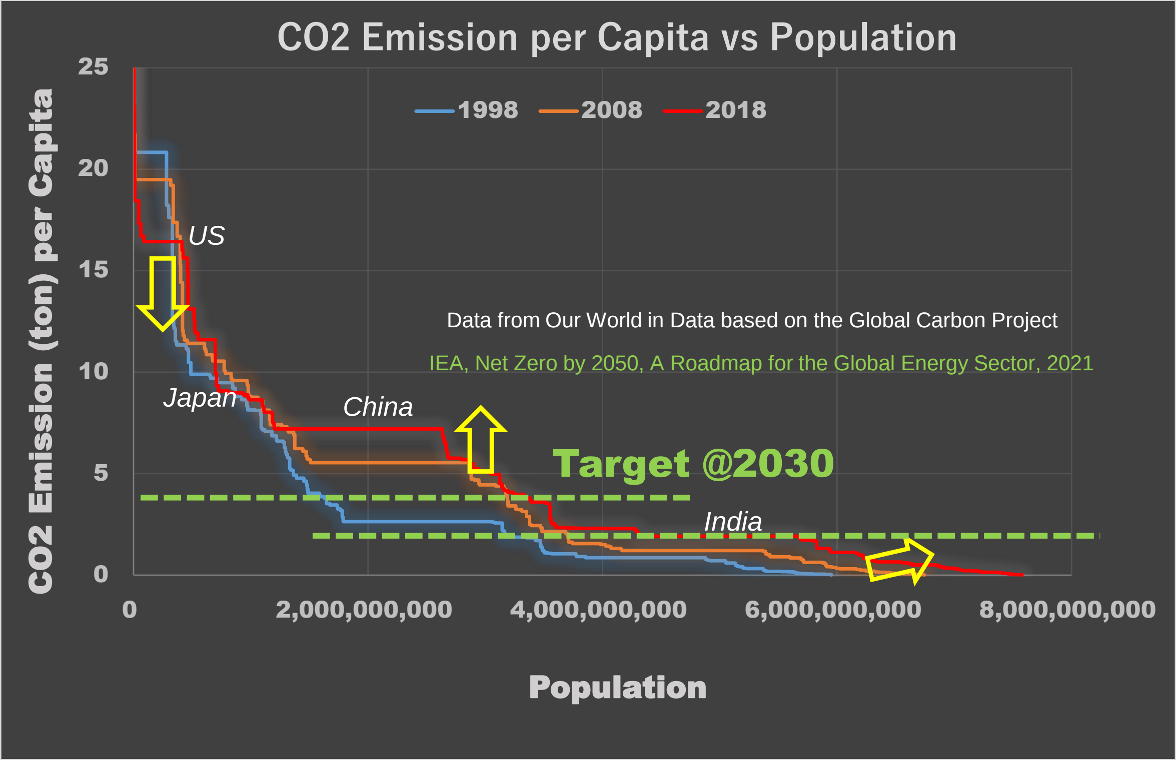
Acknowledgments

- We would like to express our deepest gratitude to the following researchers who contributed to the discussions and information sharing for this presentation.
- Mr. Takahisa Endo (Toshiba Carrier Corp.)
- Dr. Noriko Kawakami (Toshiba Mitsubishi-Electric Industrial Systems Corp. (TMEIC))
- Dr. Kazufumi Yuasa (NTT Facilities Inc.)

Backup

Emission in years of 1998, 2008, 2018 and the 2030 target for NZE2050

- High CO2 intensity countries reduced the emission in 20 years from 1998 to 2018, but,
- The emission levels **far exceed** the **3.5 ton per capita target** to be reached in 2030 for NZE2050 scenarios.

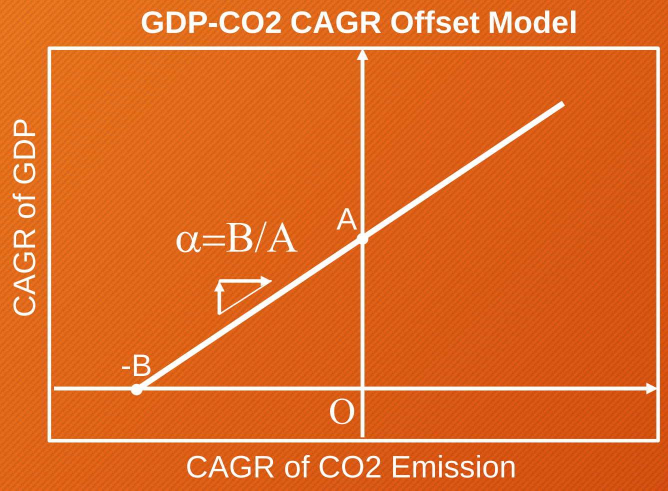


Data from Our World in Data based on the Global Carbon Project

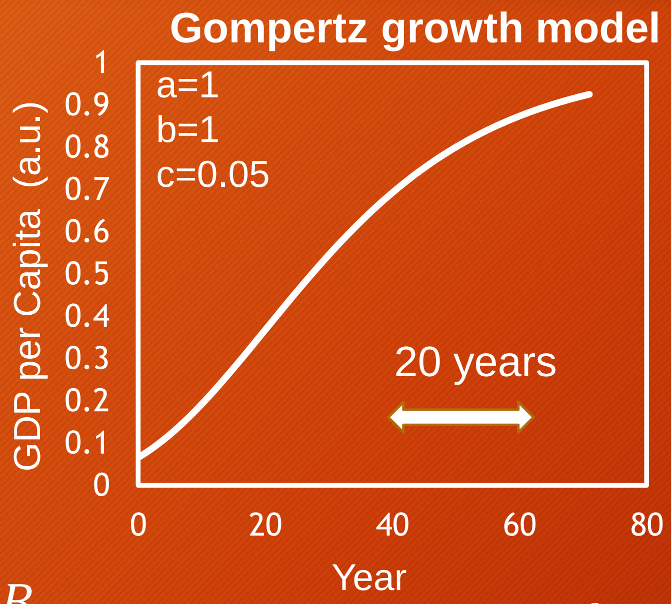
IEA, Net Zero by 2050, A Roadmap for the Global Energy Sector, 2021

How wide **the gap** between **the reducing and the growing**?

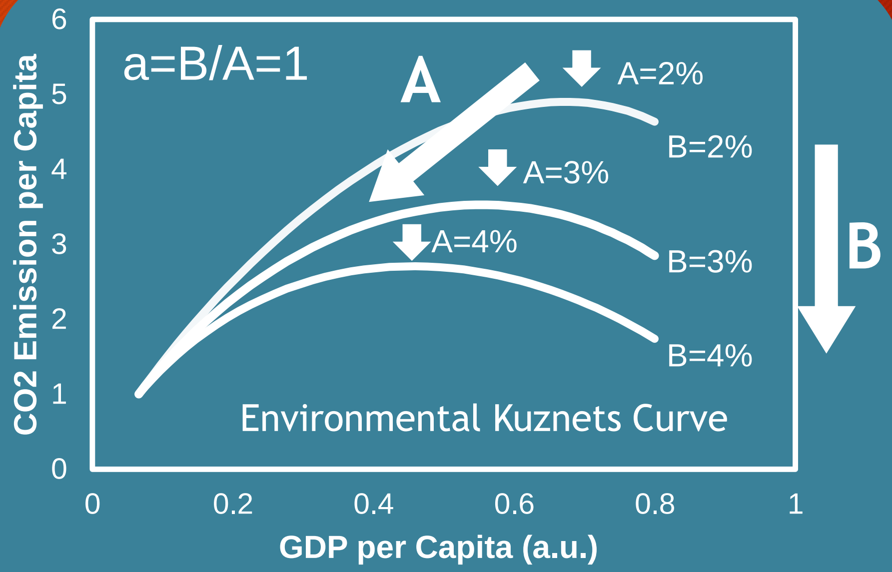
Constants A and B in the GDP-CO2 CAGR offset model



$$CAGR(CO_2) = \frac{B}{A} \cdot CAGR(GDP) - B$$



$$GDP(t) = a \cdot e^{-e^{b-c \cdot t}}$$

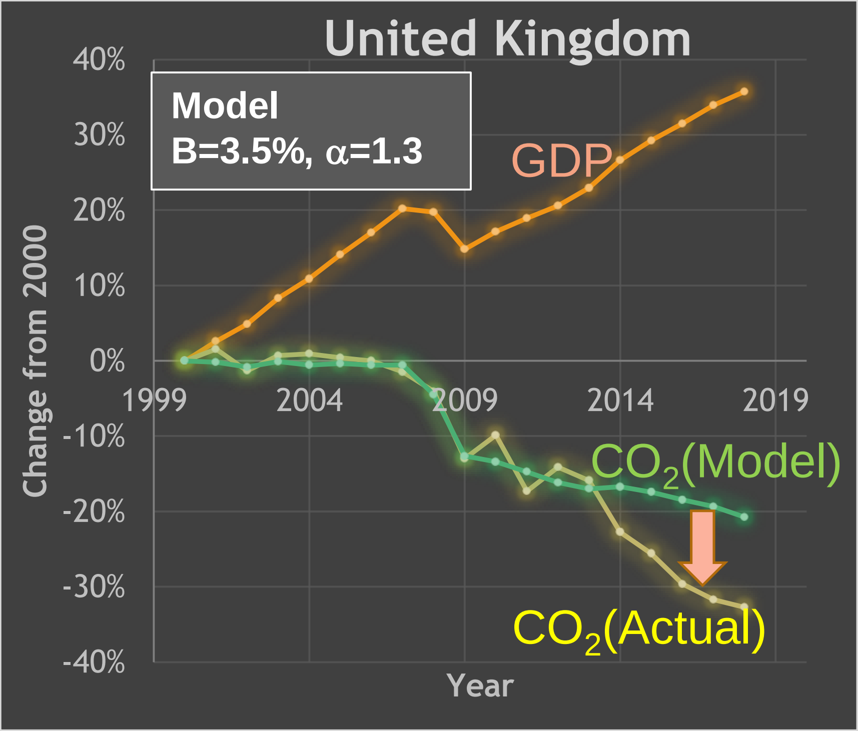


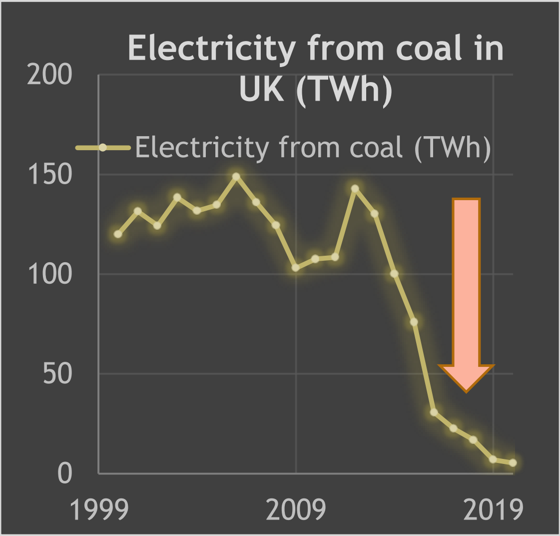
$$CO_2 = K \cdot GDP^{\left(\frac{B}{A}\right)} \cdot e^{-Bt}$$

“A” relates emission peak point, “B” determines speed of emission reduction

GDP-CO2 CAGR offset model with UK data

- Input = GDP data
- “B” and “α=B/A” are fitted with actual CO2 emission data
- Model agree with actual CO2 emission up to 2013
- Result of strong measure of close of coal plants appeared as the difference of the model from actual data.

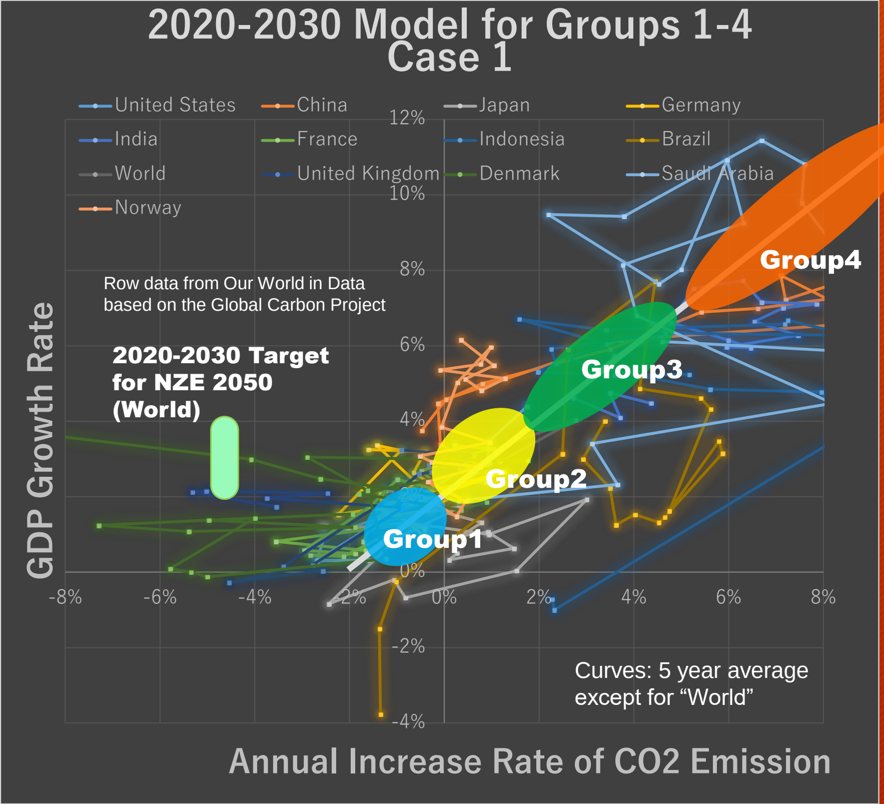




The model reproduced historical result of CO2 emission with simple fitting of constants A and B (or B and α).

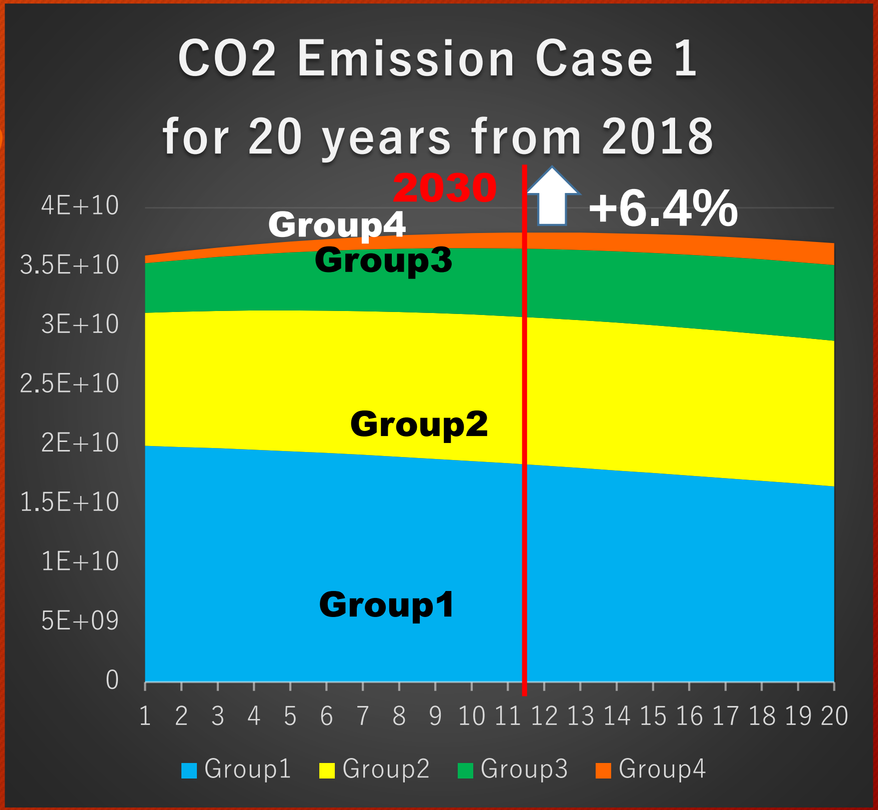
Case 1

	Condition	@2030(ref. 2018)
Case 1	A=B=2% for all groups	+6.4%
Case 2	A=B=4%, 3%, 2% and 1% for group 1, 2, 3 and 4 respectively	-9.1%
Case 3	A=B=8%, 6%, 4% and 2% for group 1, 2, 3 and 4 respectively	-40.0%



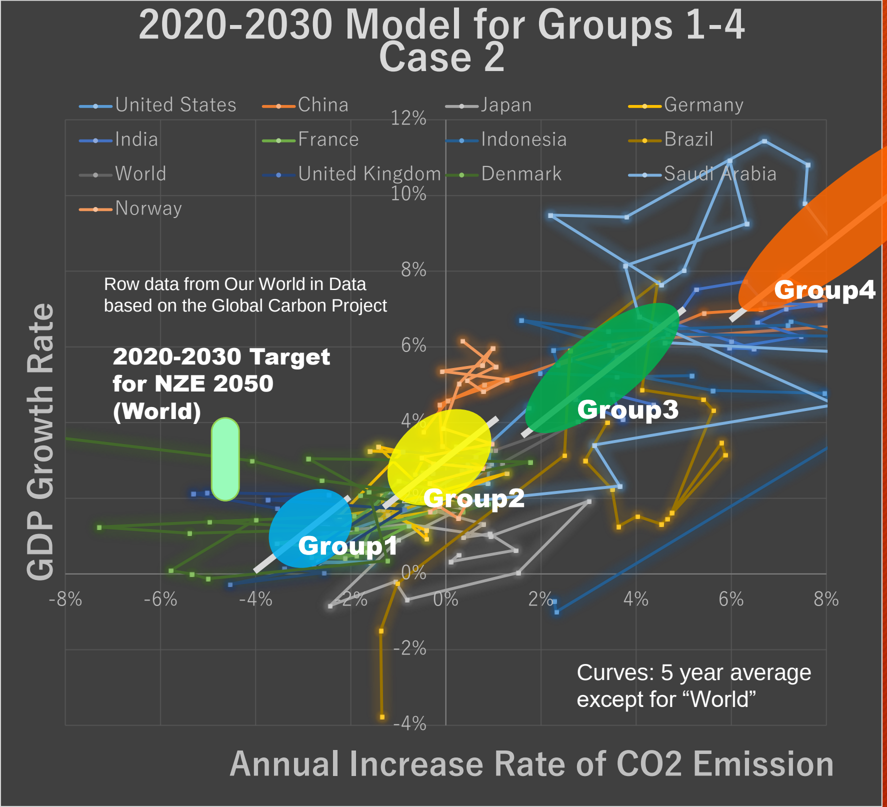
Row data from Our World in Data based on the Global Carbon Project

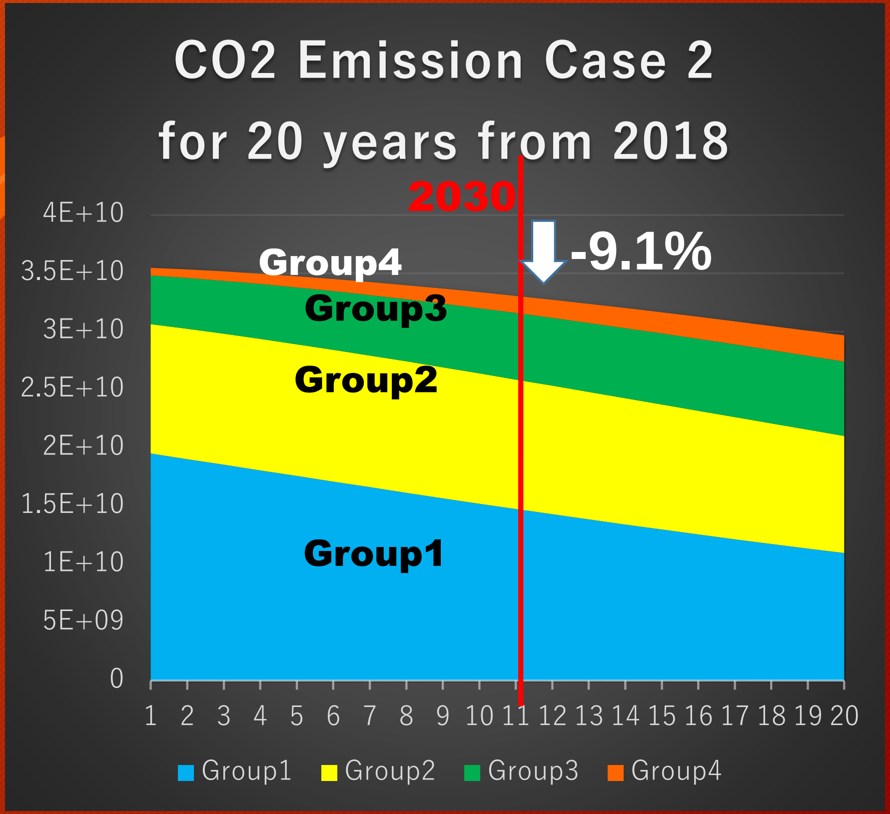
Curves: 5 year average except for "World"



Case 2

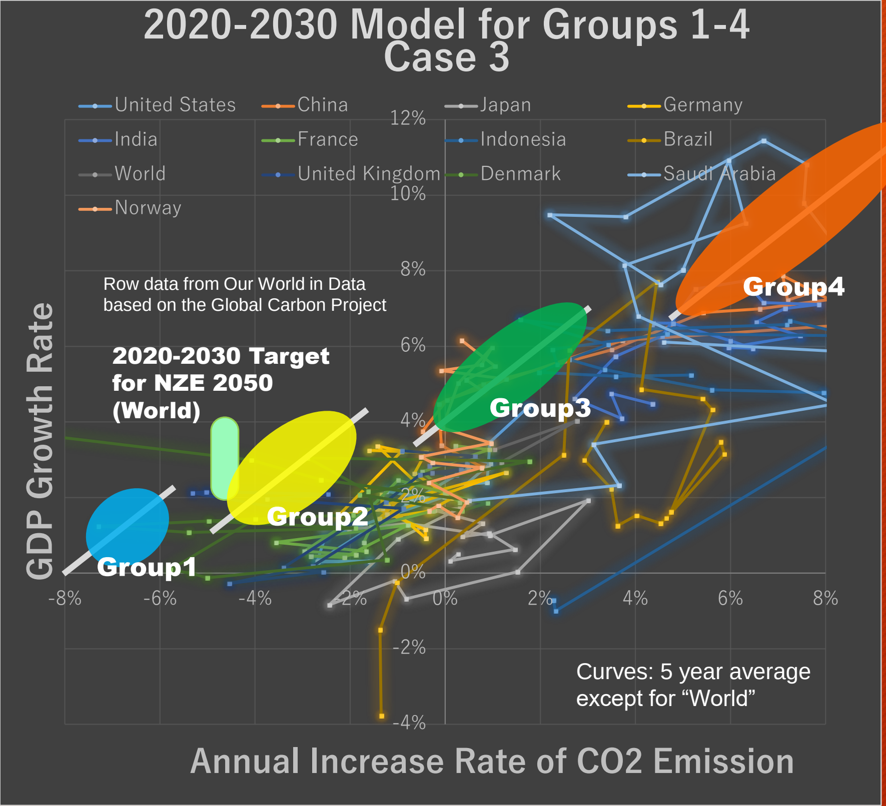
	Condition	@2030(ref. 2018)
Case 1	A=B=2% for all groups	+6.4%
Case 2	A=B=4%, 3%, 2% and 1% for group 1, 2, 3 and 4 respectively	-9.1%
Case 3	A=B=8%, 6%, 4% and 2% for group 1, 2, 3 and 4 respectively	-40.0%





Case 3

	Condition	@2030(ref. 2018)
Case 1	A=B=2% for all groups	+6.4%
Case 2	A=B=4%, 3%, 2% and 1% for group 1, 2, 3 and 4 respectively	-9.1%
Case 3	A=B=8%, 6%, 4% and 2% for group 1, 2, 3 and 4 respectively	-40.0%

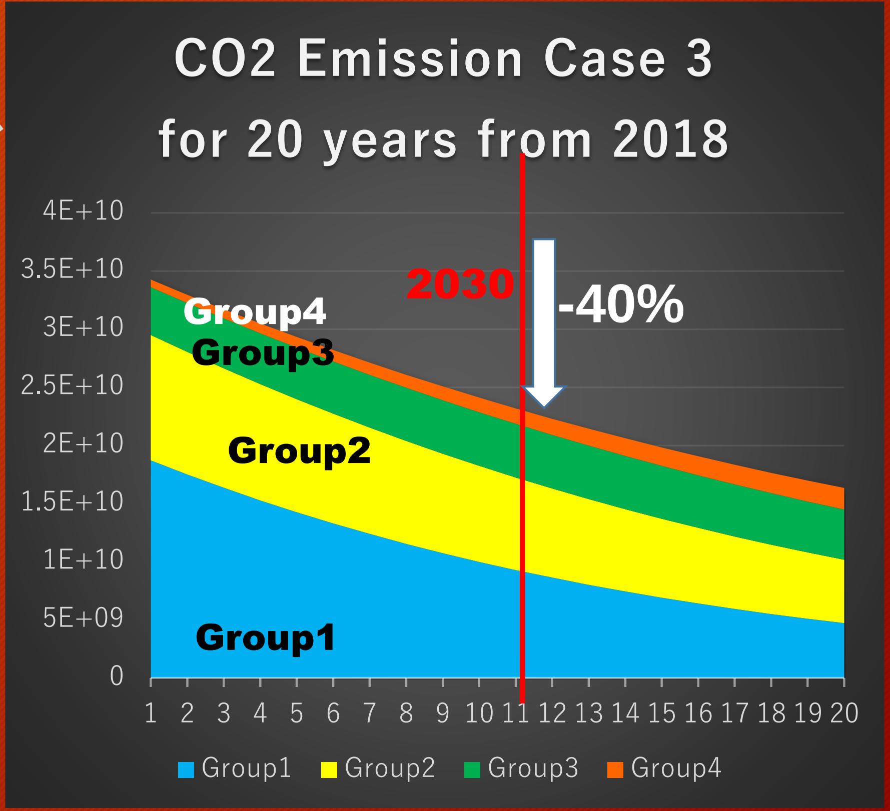


2020-2030 Model for Groups 1-4
Case 3

Row data from Our World in Data based on the Global Carbon Project

2020-2030 Target for NZE 2050 (World)

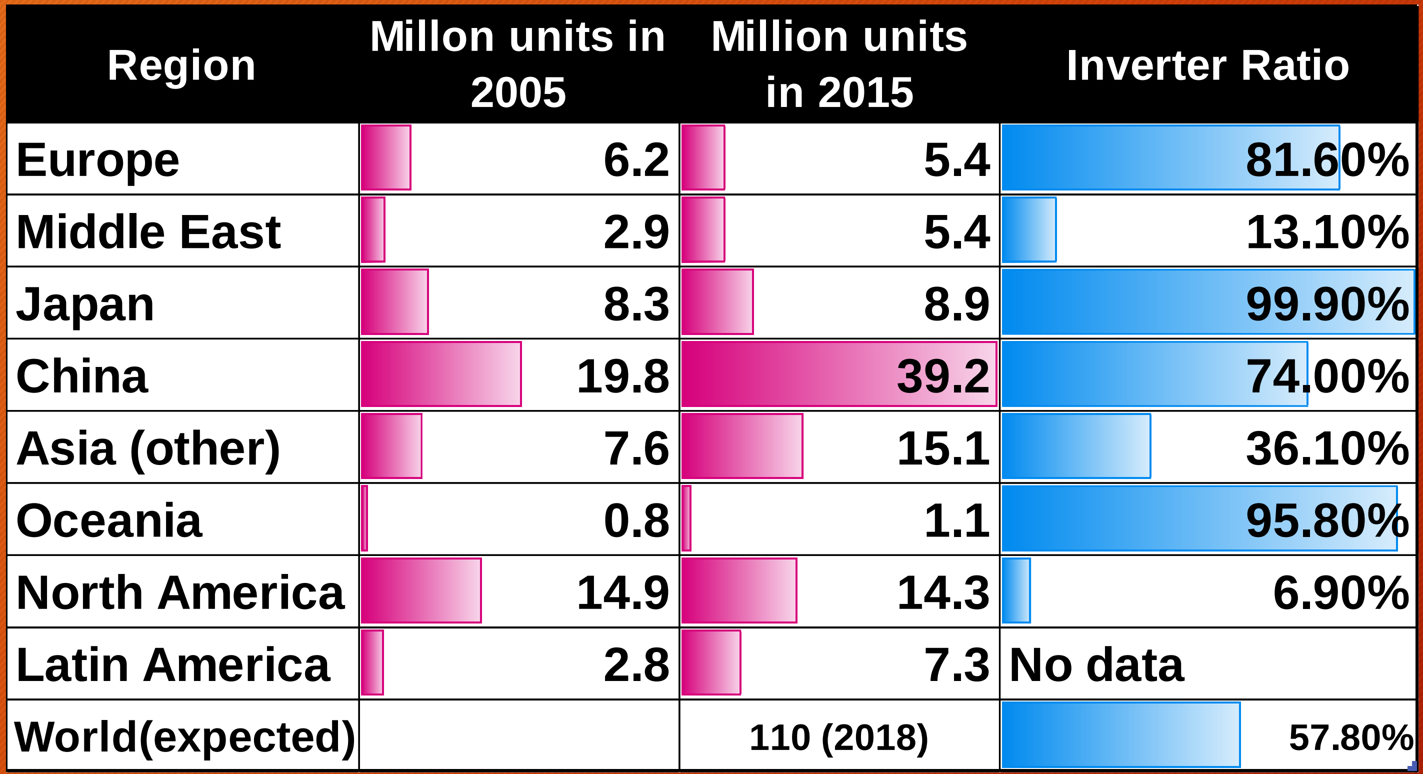
Curves: 5 year average except for “World”



CO2 Emission Case 3
for 20 years from 2018

“World Air Conditioner Demand by Region,”, Japan Refrigeration and Air Conditioning Industries Association, 2019, https://www.jraia.or.jp/english/statistics/index.html

Air Conditioner shipment, inverter ratio



Region	Millon units in 2005	Million units in 2015	Inverter Ratio
Europe	6.2	5.4	81.60%
Middle East	2.9	5.4	13.10%
Japan	8.3	8.9	99.90%
China	19.8	39.2	74.00%
Asia (other)	7.6	15.1	36.10%
Oceania	0.8	1.1	95.80%
North America	14.9	14.3	6.90%
Latin America	2.8	7.3	No data
World(expected)		110 (2018)	57.80%

CAGR of Efficiency of economic output, the Impacts

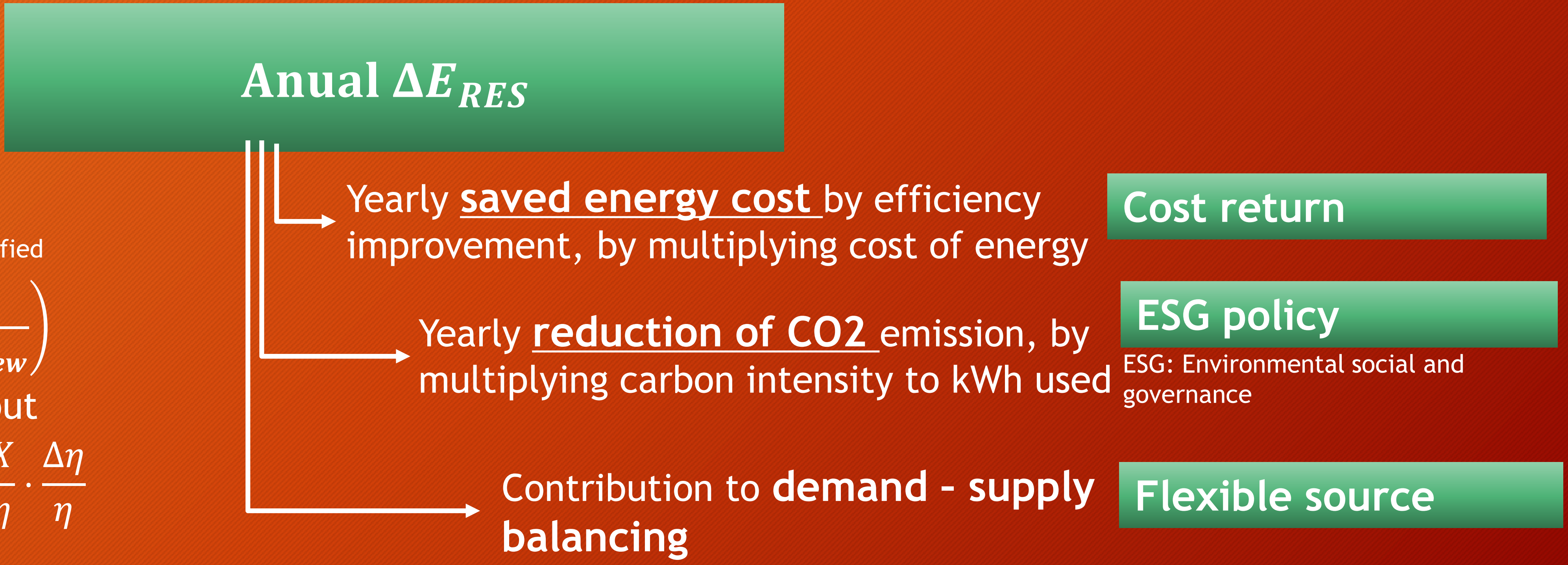
η: Efficiency of Economic output to unit electricity

EU directive [19], modified

$$E_{RES} = X \cdot \left(\frac{1}{\eta_{old}} - \frac{1}{\eta_{new}} \right)$$

X: Economic output

$$\Delta E_{RES} = -X \cdot \Delta\left(\frac{1}{\eta}\right) = \frac{X}{\eta} \cdot \frac{\Delta\eta}{\eta}$$



Anual ΔE_{RES}

Yearly **saved energy cost** by efficiency improvement, by multiplying cost of energy

Cost return

Yearly **reduction of CO2** emission, by multiplying carbon intensity to kWh used

ESG policy

ESG: Environmental social and governance

Contribution to **demand - supply balancing**

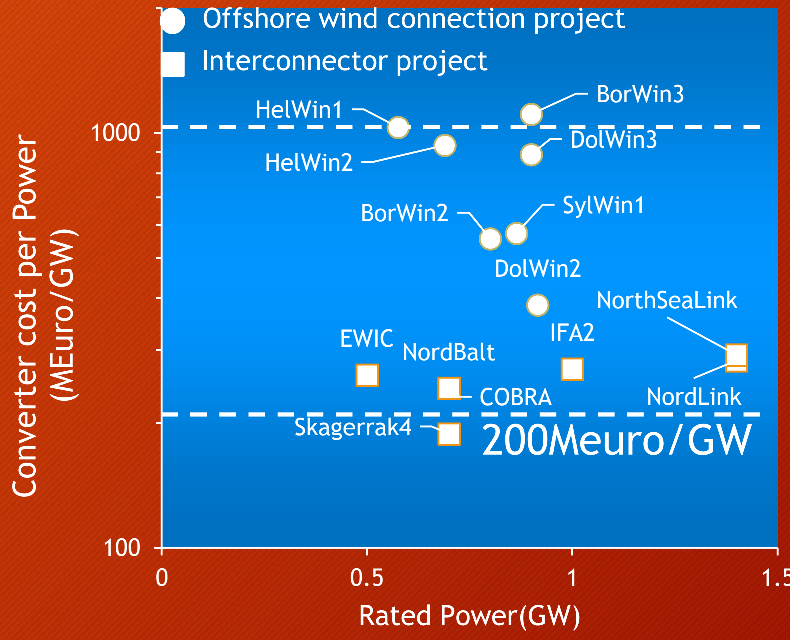
Flexible source

Efficiency: Direct / Indirect advantage to install

HVDC Transmission: Technology Review, Market Trends and Future Outlook Renewable and Sustainable Energy Reviews 112 (2019)
Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation, 2018, US-EIA
Review of investment model cost parameters for VSC HVDC transmission infrastructure, Electric Power Systems Research 151 (2017)
RENEWABLE POWER GENERATION COSTS IN 2020 , IRENA, 2021 / U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: NREL, Q1 2020

Cost of flexibility?

	N-Gas	Electricity	Remark
World wide capacity	N-Gas, 4400 bcm (eq.2600GW)	Electricity 7200GW	HVDC Cost, 750 mile, 1000USD/mile/MW (EIA) 1400Meuro for 1300km 5GW (SaharaWind) 2000Meuro for 2000km 6GW Natural Gas pipeline, 1250km, 55bcm/y = 32.5GW, Generation efficiency=0.45, 7.40G Euro, (Fact Sheet, Nord Stream by numbers, 2013)
Pipe line, HVDC Cost Example	Pipe line 230M Euro/GW (1250km, 55bcm)	HVDC >250M Euro/GW (1200km, 6GW)	



VSC-HVDC Converter Cost in MEuro/GW

Raw data from, Review of investment model cost parameters for VSC HVDC transmission infrastructure, Philipp Härtel et al., Electric Power Systems Research 151 (2017), Table 3 and 4.

- Learning rate of 19-20% and,
  - PV module cost 200-400Meuro/GW
  - PV system installation cost 900Meuro/GW
  - PV + Storage installation cost 1750Meuro/GW (100MWPV+60MW/240MWhBatt.)
  - On-shore wind installation cost 1400Meuro/GW

Flexibility

- “the ability of a power system to reliably and costeffectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply”[31]

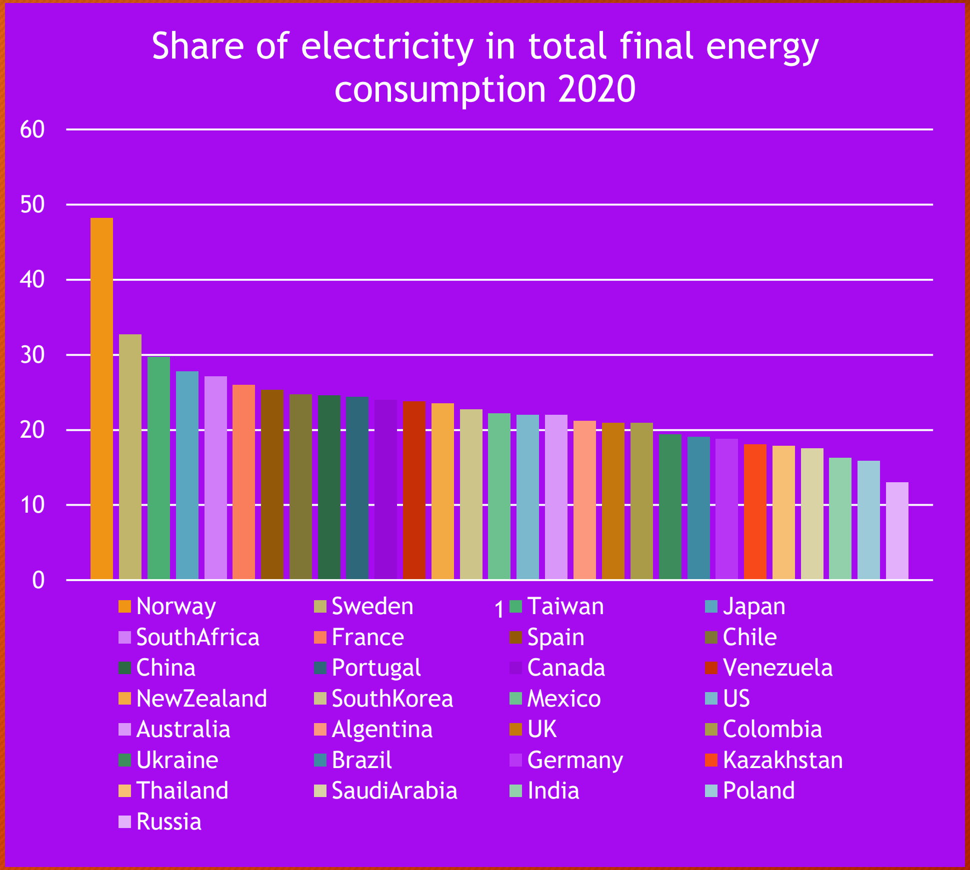
PE-segment

- “the contribution to costeffectively secure the electrified economic activity under high renewable share”

Flexibility

to secure electrified economic activity under high VRE ratio

Share of electricity in total final energy



Data from https://yearbook.enerdata.net/electricity/share-electricity-final-consumption.html