Lecture 1

Concept of Energy System, Sustainability and Sustainable Energy

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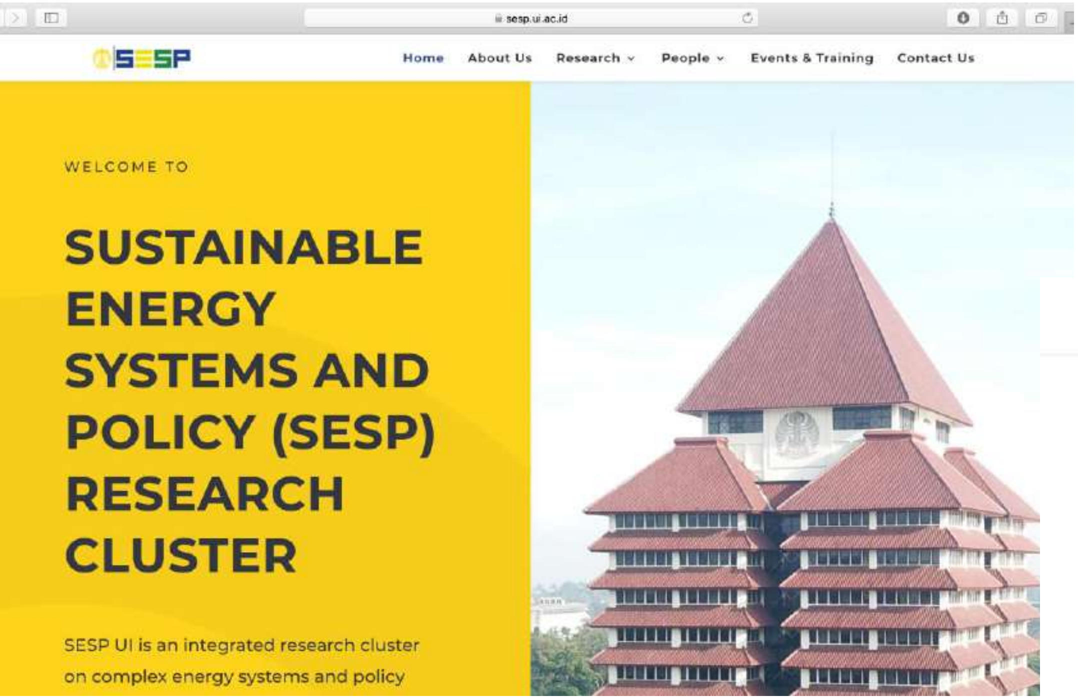
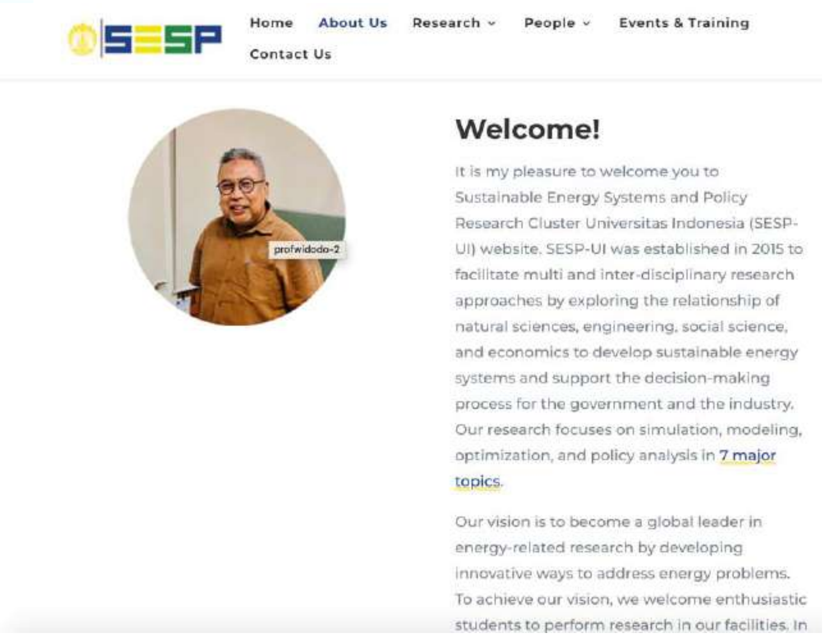
Prof. Widodo is currently Chairman of UI Net Zero Inititative, Head of Institute for Energi Transition FTUI, the editorial board of Journal of Gas Science and Engineering - Elsevier, Head of research cluster Sustainable Energy Systems and Policy -Universitas Indonesia (http://sesp.ui.ac.id/), and senior member of American Institute of Chemical Engineers (AIChE).

He has served as director of the Center for Energy Studies, Universitas Indonesia (PEUI) from 2004 to 2007, Head of the Department of Chemical Engineering Universitas Indonesia, from 2007 to 2013, chairman of the Association of Higher Education in Chemical Engineering Indonesia (APTEKINDO) 2009-2012, and member of the National Research Council (DRN) - technical commission energy (2014-2019), and Head of Master Program in Energi Systems Engineering 2022-2024.

Prof Widodo research focus include: (i) Sustainable energy system transition and policy analysis and (ii) Natural gas systems and management. Prof. Widodo has published more than 135 scientific journals and 5 books, and has graduated 22 PhD and was guiding 9 PhD students.

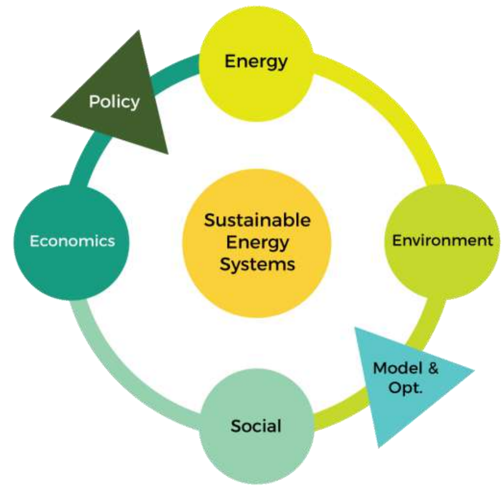
My Research Cluster





http://sesp.ui.ac.id/

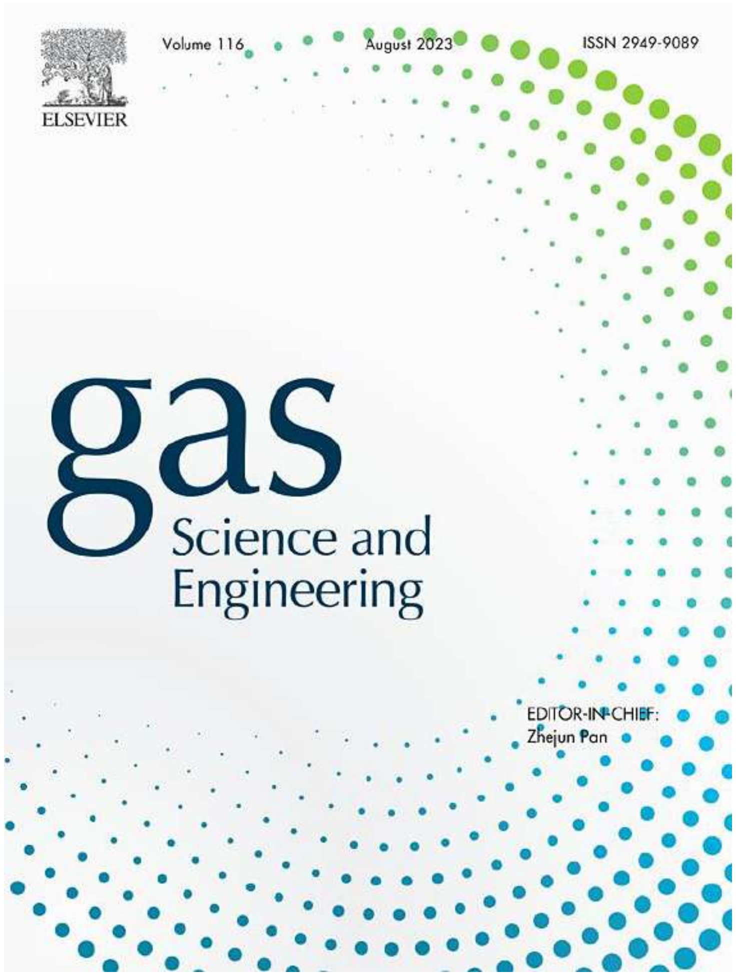
Research facilities at SESP UI



SESP UI is an integrated research cluster on complex energy systems and policy analysis, trying to understand the environmental, economic and social impacts of energy systems transition. Our research approach is holistic by multi-dimension and multi-scale energy modeling and analysis.

TIMES GAMS MATLAB aspentech LEAP

My Journal



https://www.sciencedirect.com/journal/gas-science-and-engineering/about/aims-and-scope

What is Sustainable Energy?

- https://www.youtube.com/watch?v=7PrMaAY39sY
- https://www.youtube.com/watch?v=HidOuj-cUC0
- https://www.youtube.com/watch?v=sj1YRBqoJr4

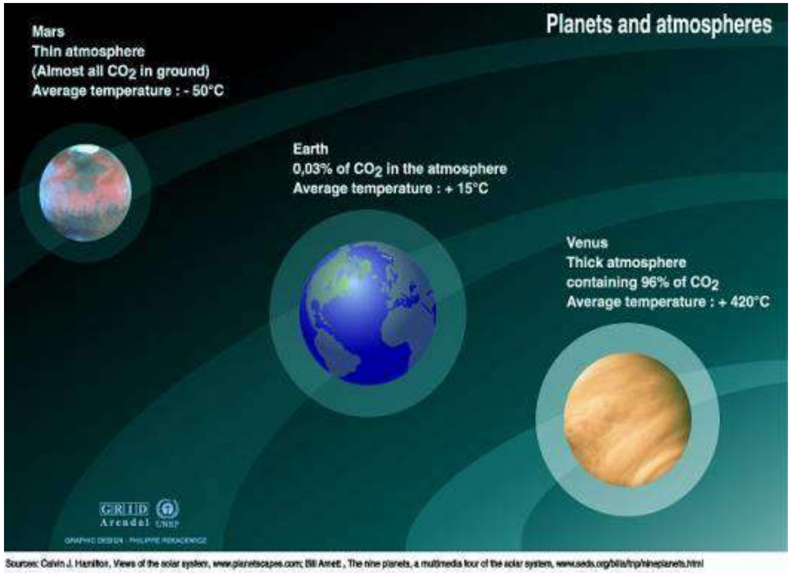
Outline

- Current energy status and drivers
- What is energy systems?
- Concept of sustainability
- What is sustainable energy?
- Energy-economic-environment-social relationships
- Key enablers technologies for sustainable energy system transition

Current energy status and drivers

The energy slaves of modern man

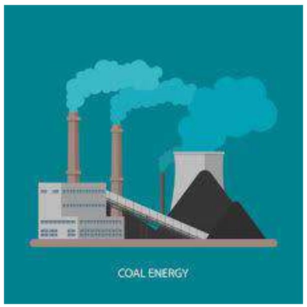
Frying the Earth

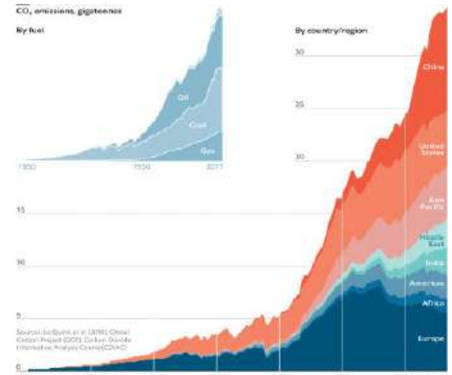


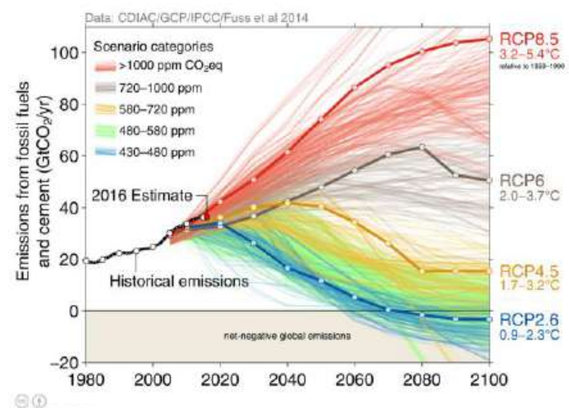
World oil consumption
85 m bpd → burn → CO_2, H2O
Indonesia oil consumption
1.1 m bpd → burn → CO_2, H2O

Source: C J Campbell, 2000

Energy and Climate change – Two ways relationship

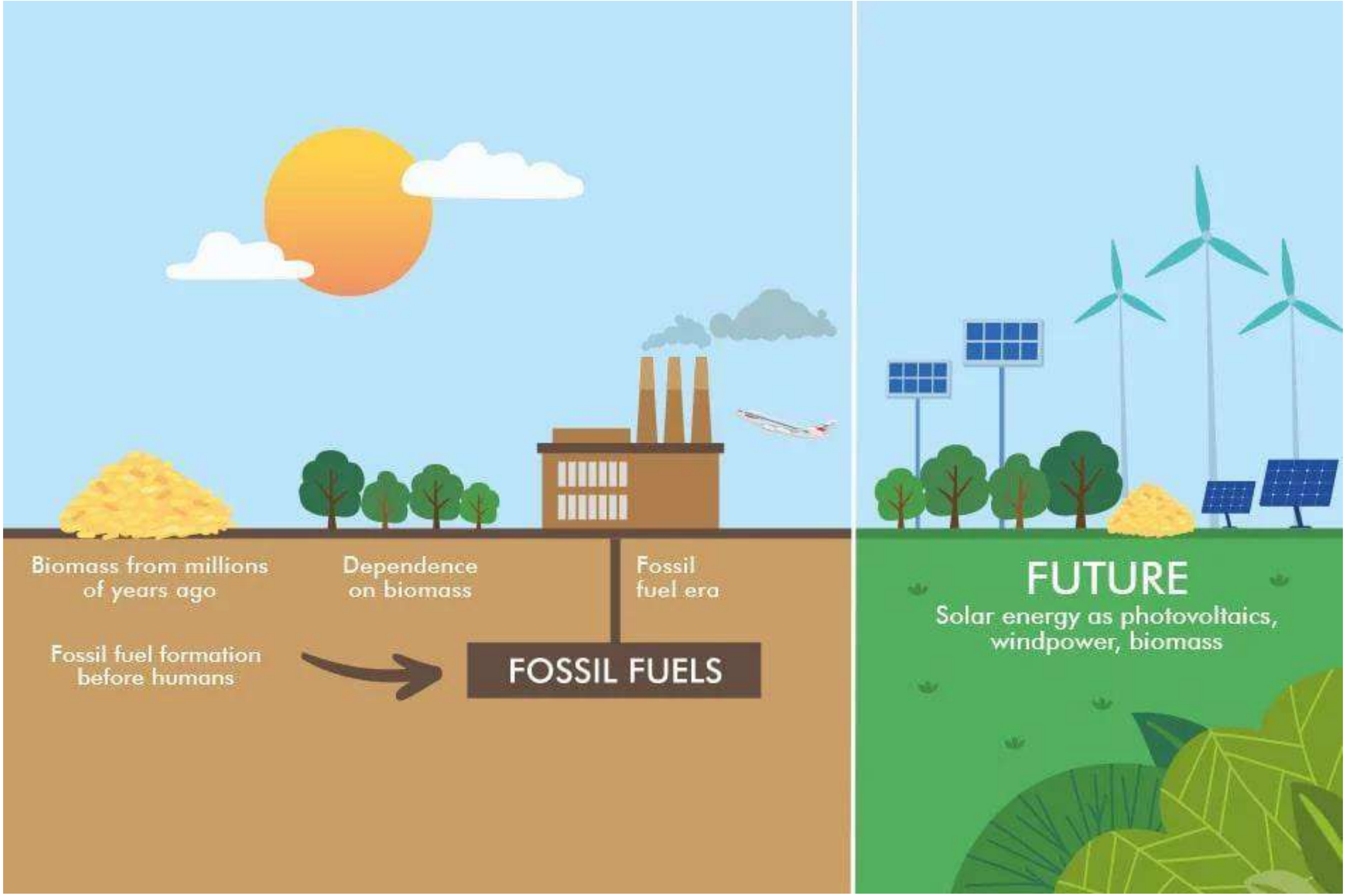






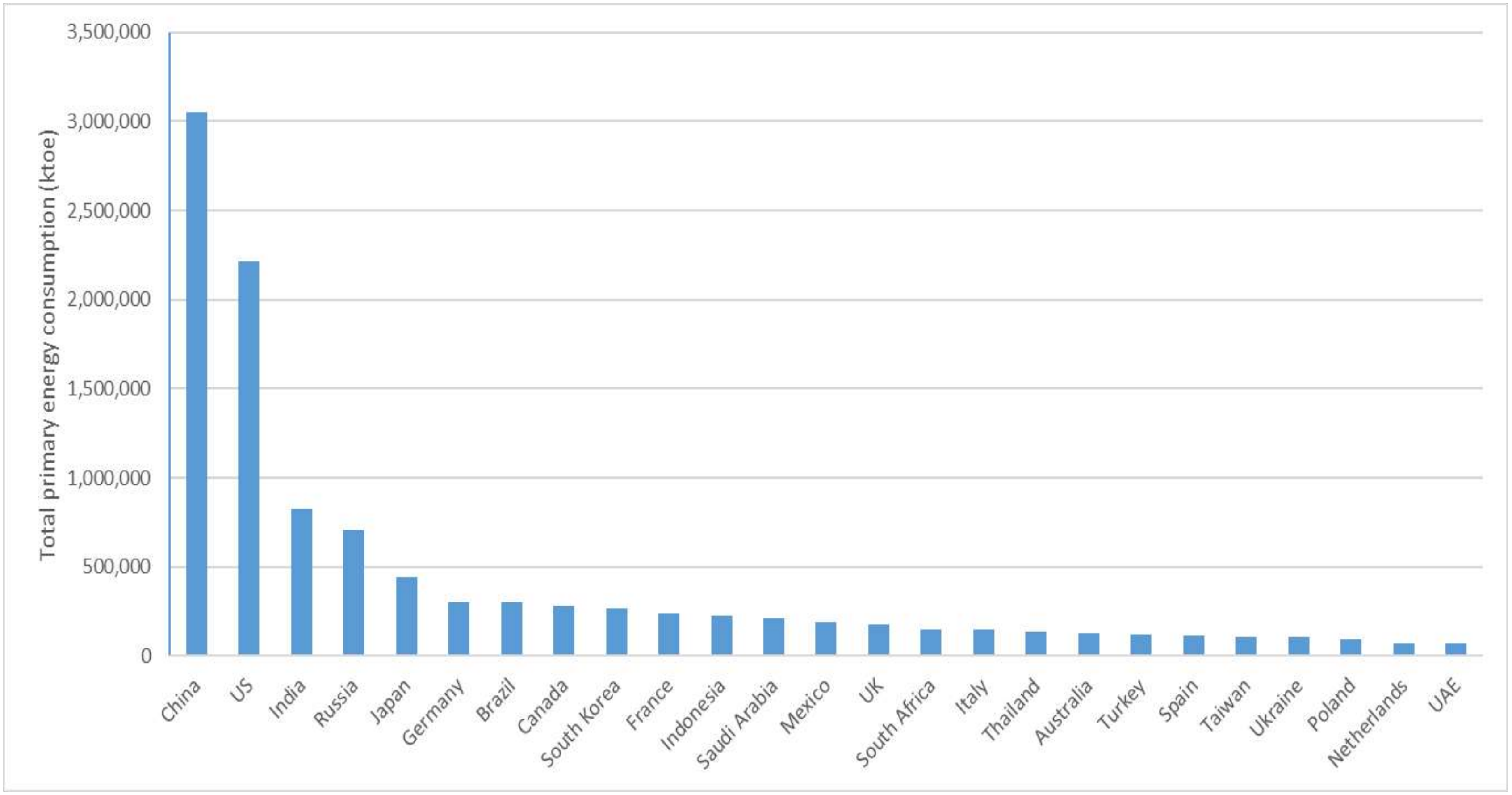
Energy transition
Energy transformation

PARIS2015
COP21·CMP11



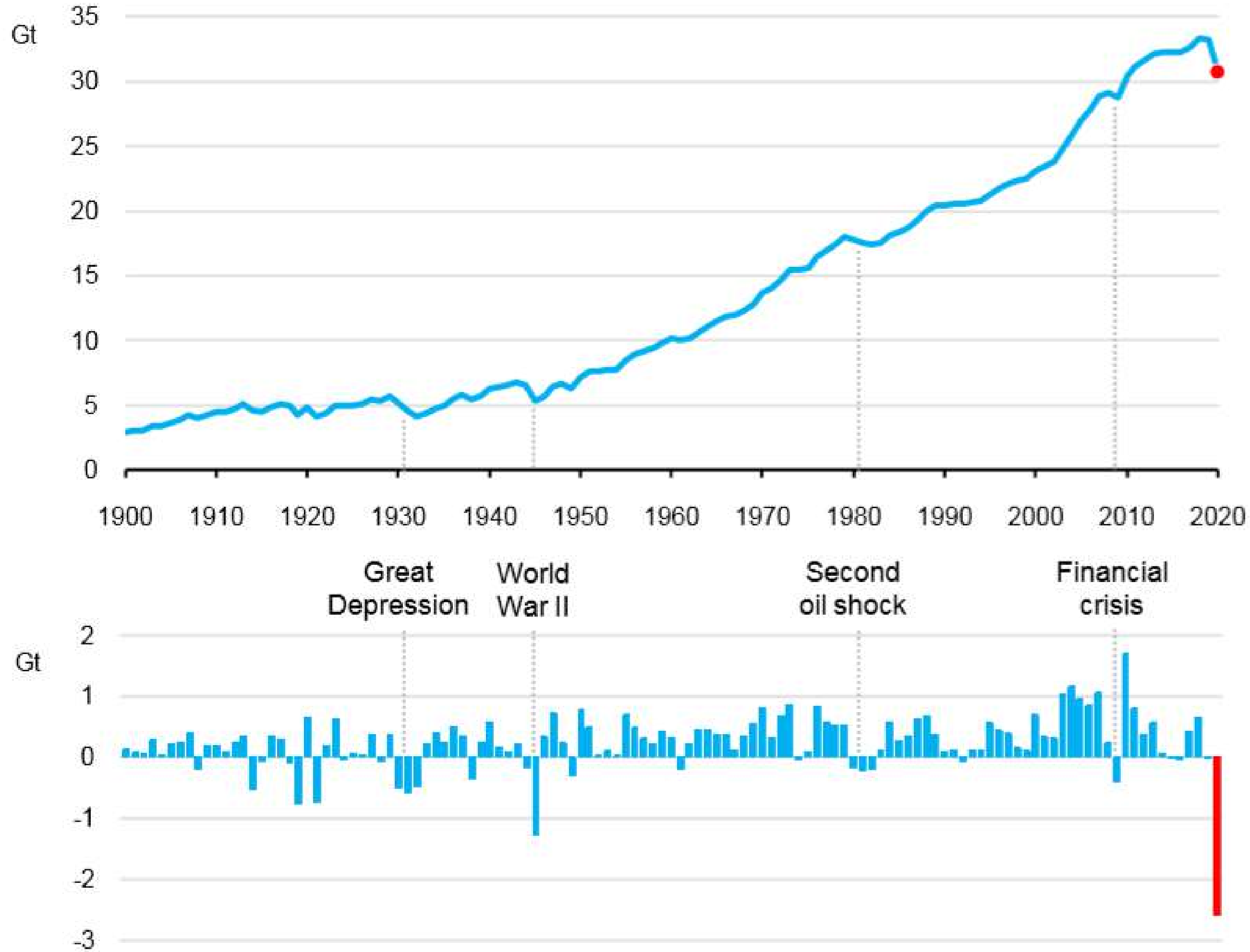
Source: routledge

Top Energy Consumers Worldwide



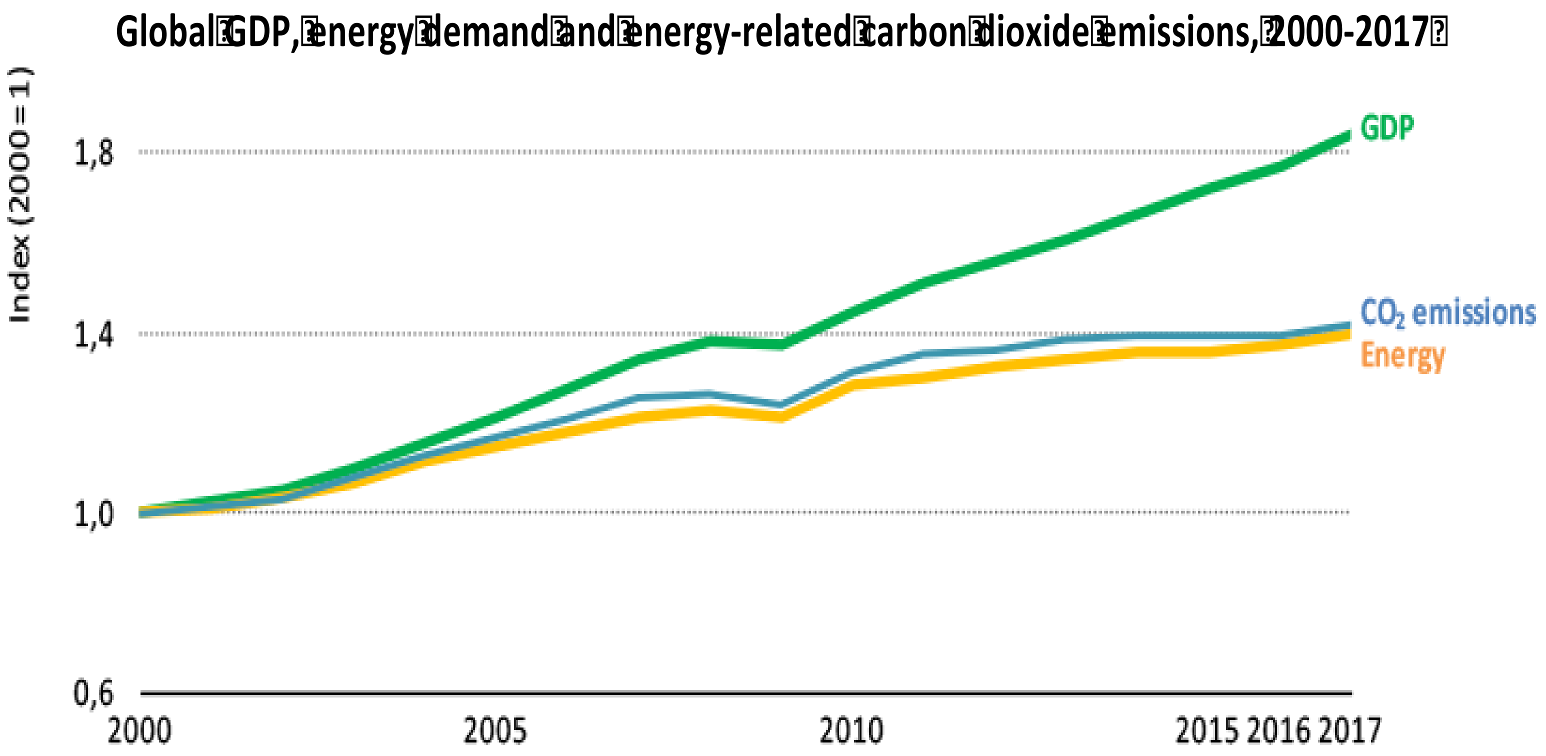
Source: ACEEE, 2018

Global energy-related CO2 emissions and annual change



Source: IEA, 2020

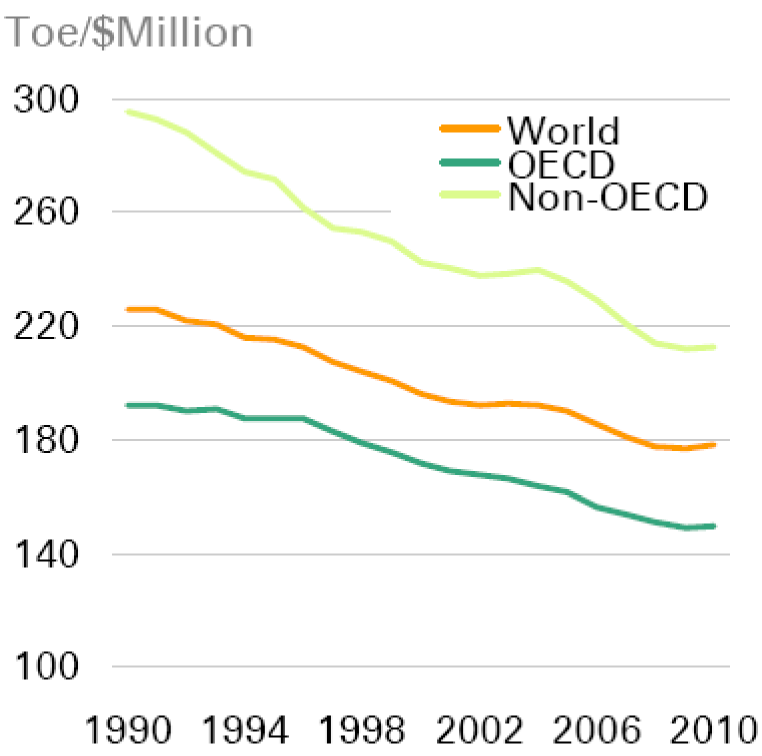
GDP, energy and emissions



Source: IEA, 2017

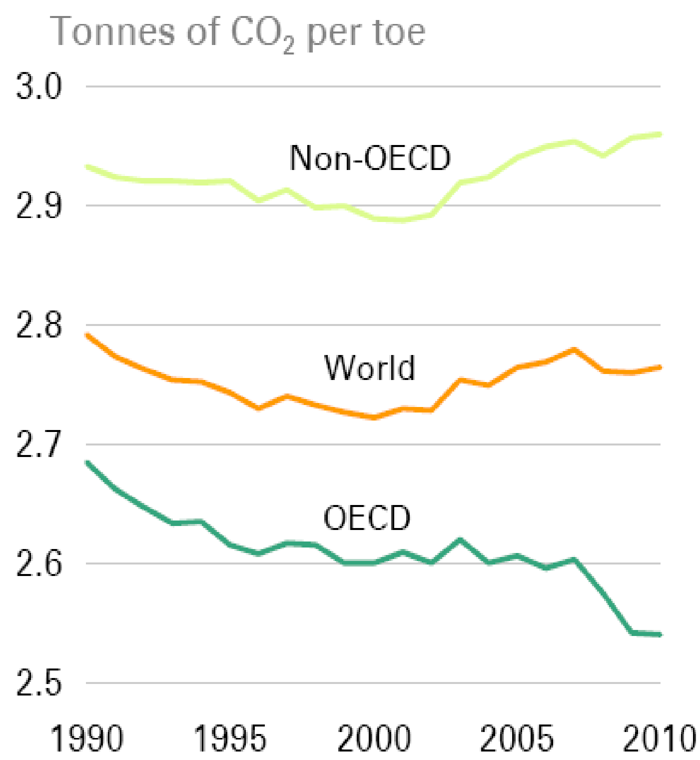
Energy/CO_2 intensity

Energy intensity level



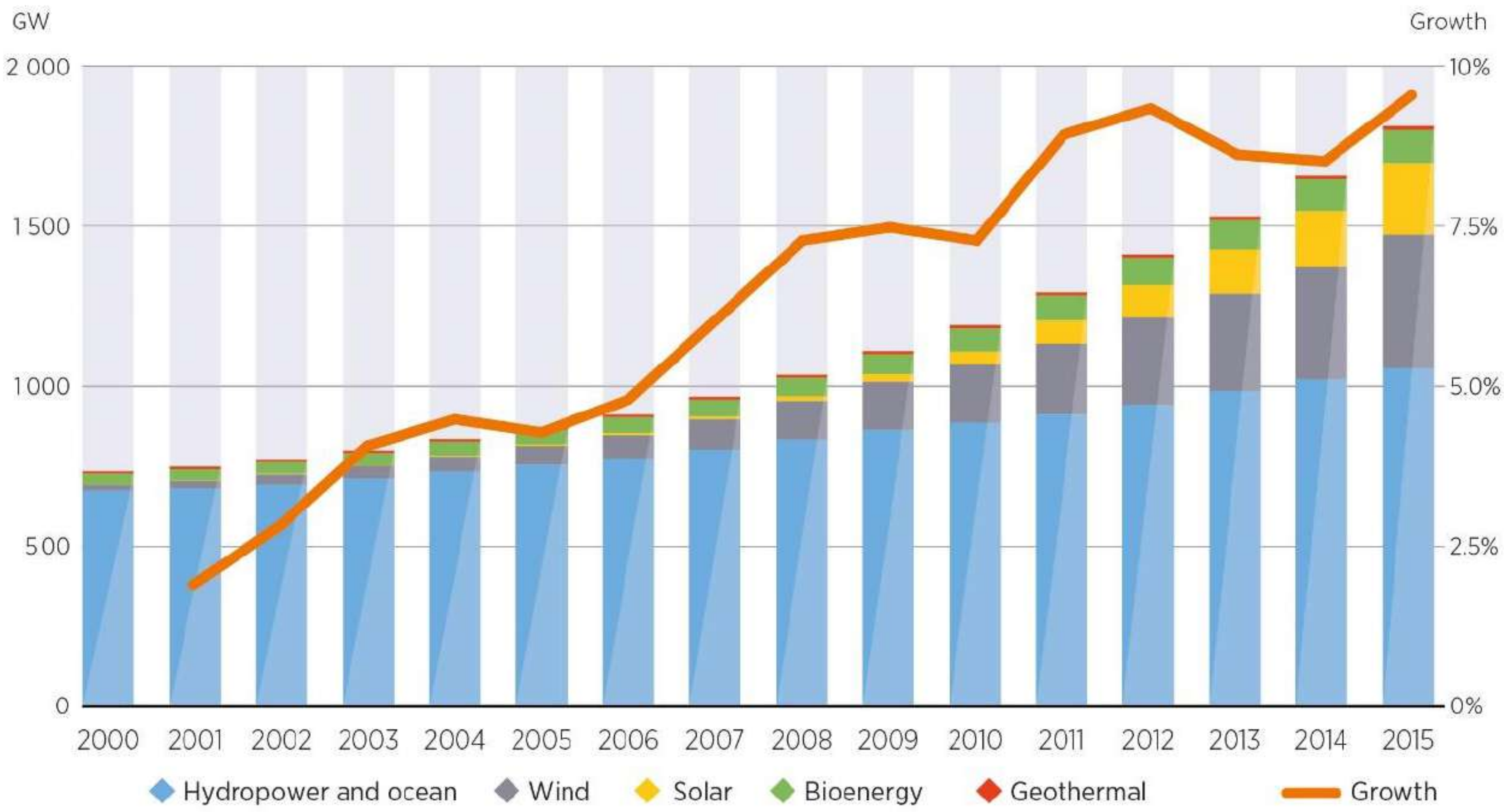
Source: includes data from Oxford Economics.

CO_2 intensity of energy



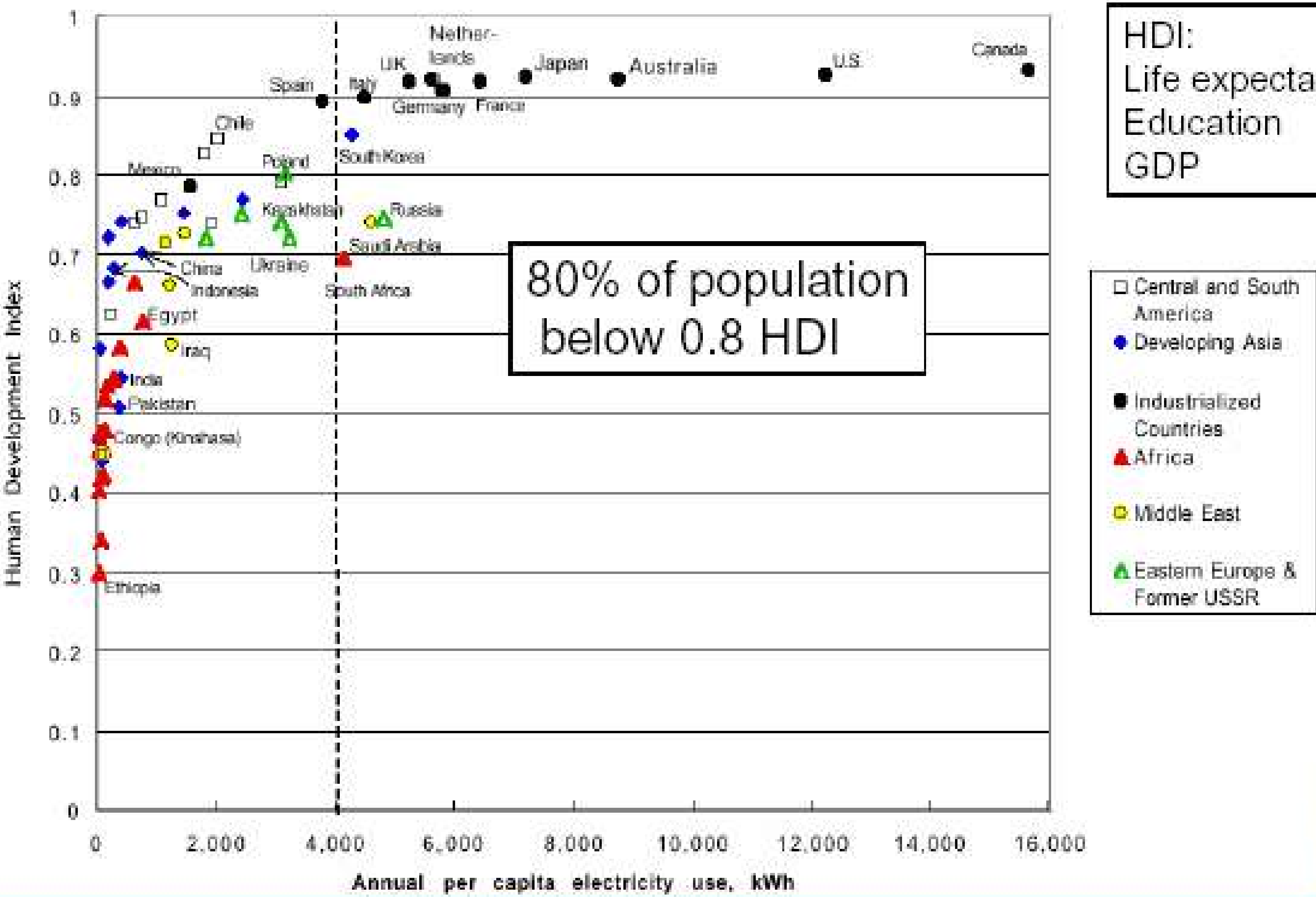
BP Statistical Review of World Energy

Renewable power generation annual growth rate



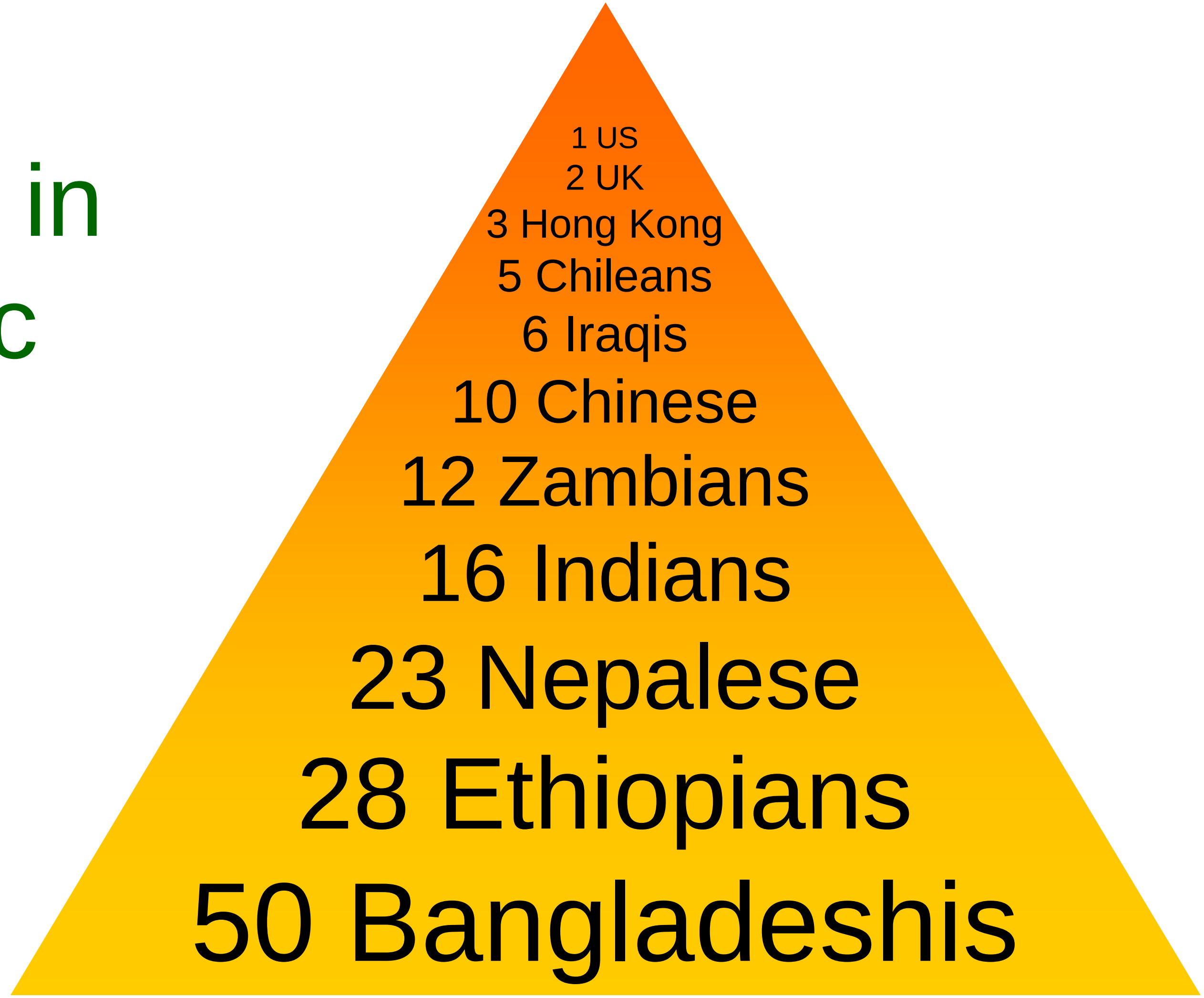
Source: IRENA (2016b).

Prosperity requires Energy



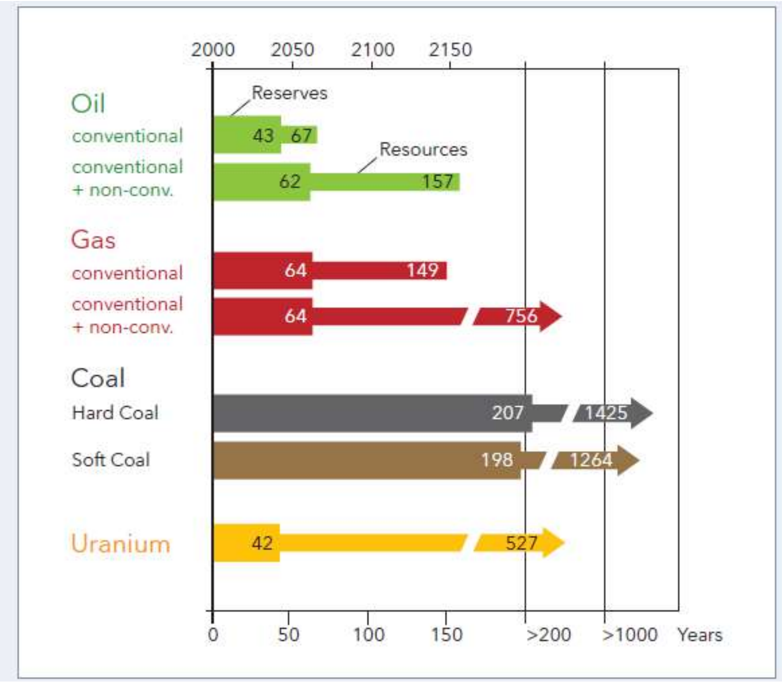
HDI:
Life expectation
Education
GDP

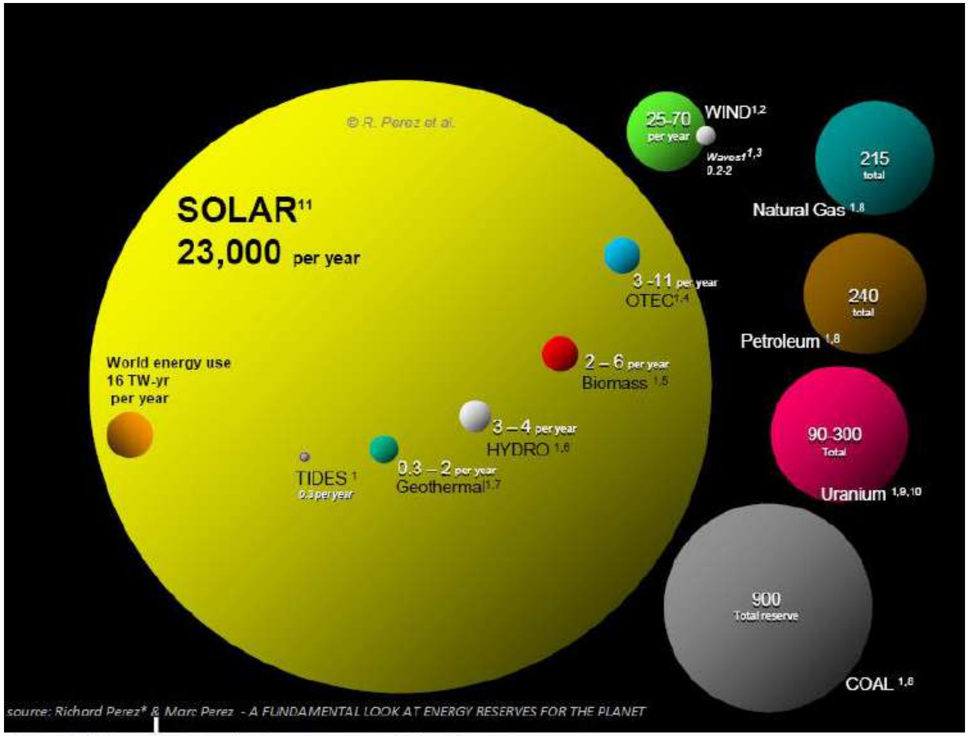
Global inequality in domestic use



Data Source: World Development Indicators, 2001

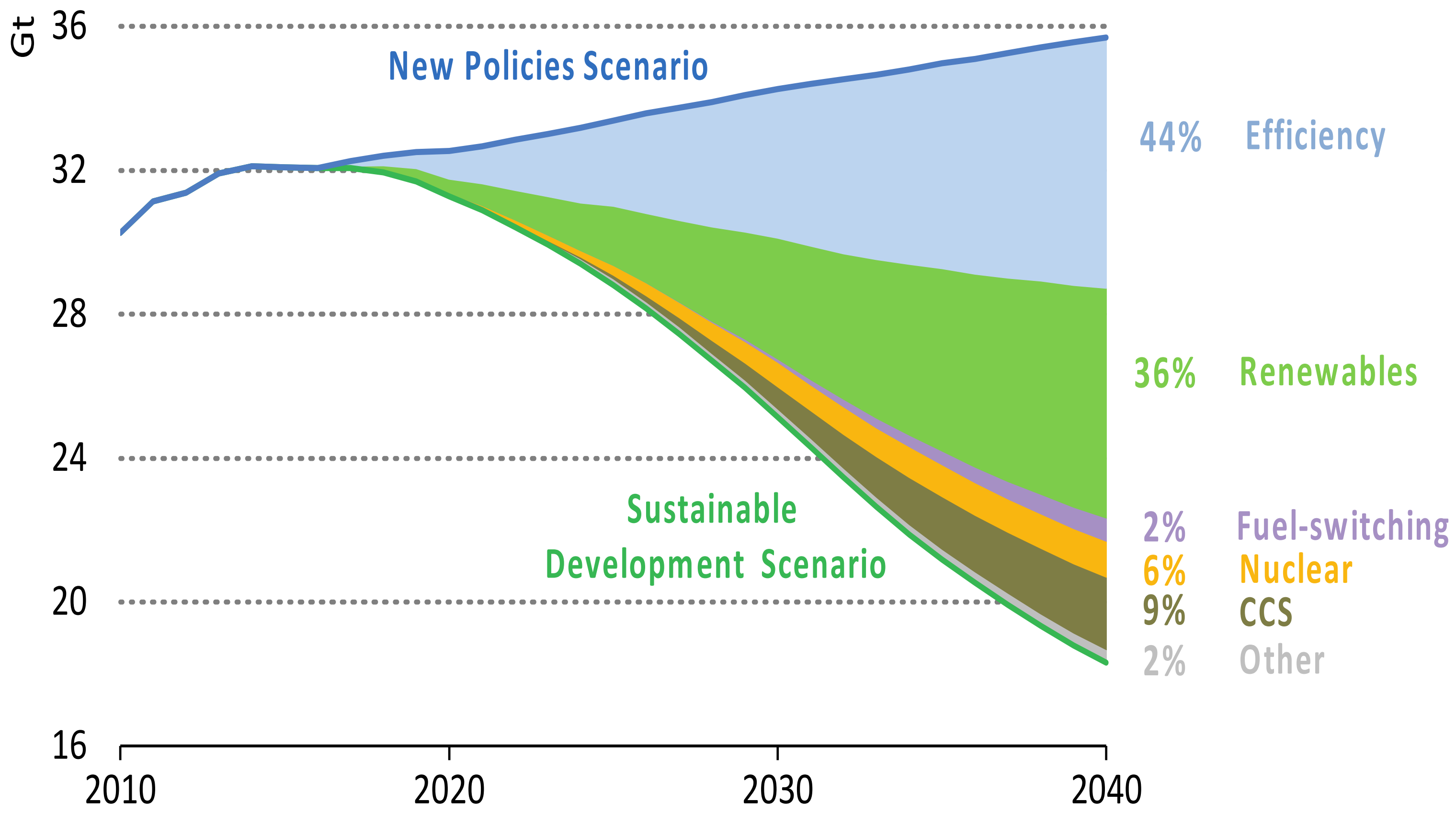
Limited Fossil Reserves on Earth





Comparing finite and renewale planetary energy reserves)Terawatt-years).
Total recoverable reserves are shown for the finate resources.

Energy transition/COP 21



Source: IEA

What is energy transition?

un-sustainable → sustainable

*“**Energy transition** is a long-term strategy for the development of a low-carbon energy system (renewable energies and energy efficiency)”*

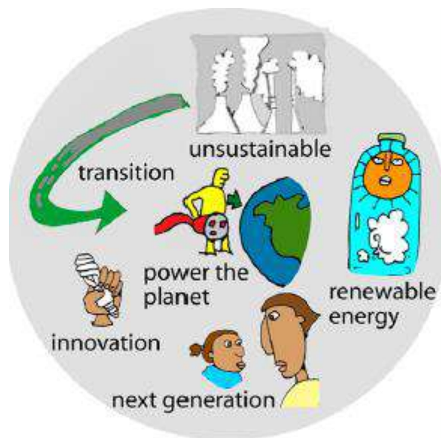


Image credit: Alice Muhlback

*“**Energy transition** is a pathway toward transformation of the global energy sector from fossil-based to net zero-carbon. At its heart is the need to reduce energy-related CO_2 emissions to limit climate change”*

Net Zero Emission (NZE)

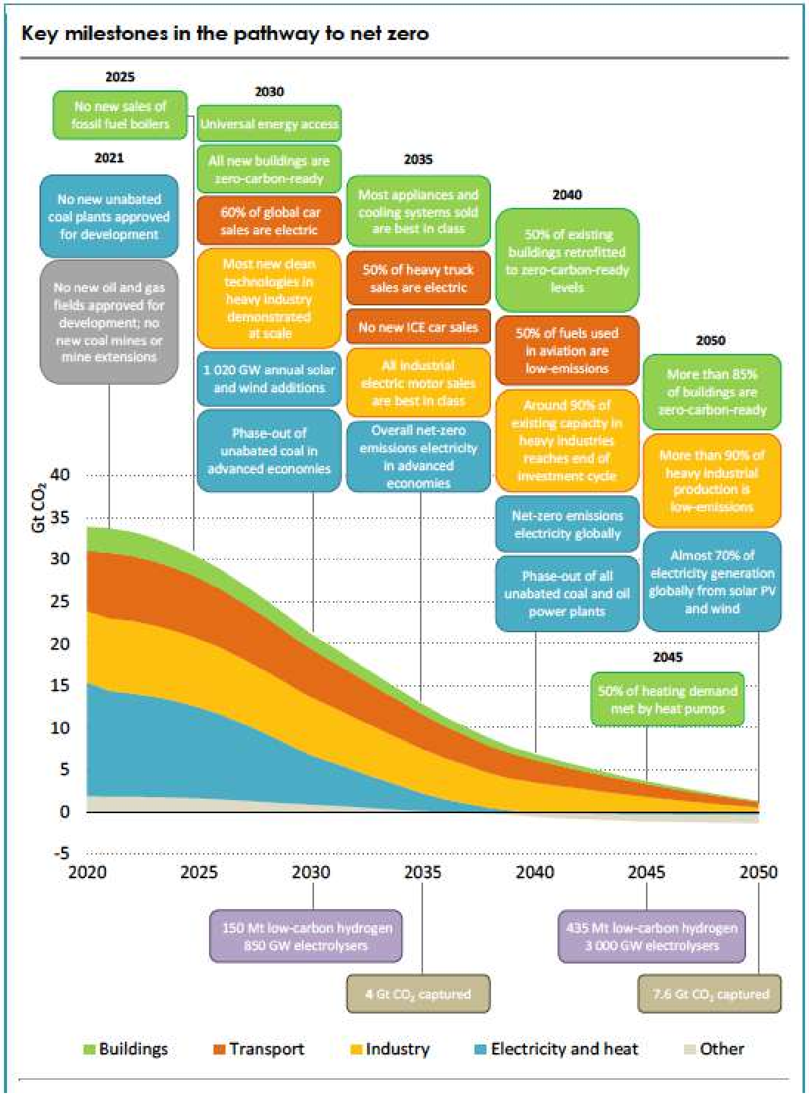
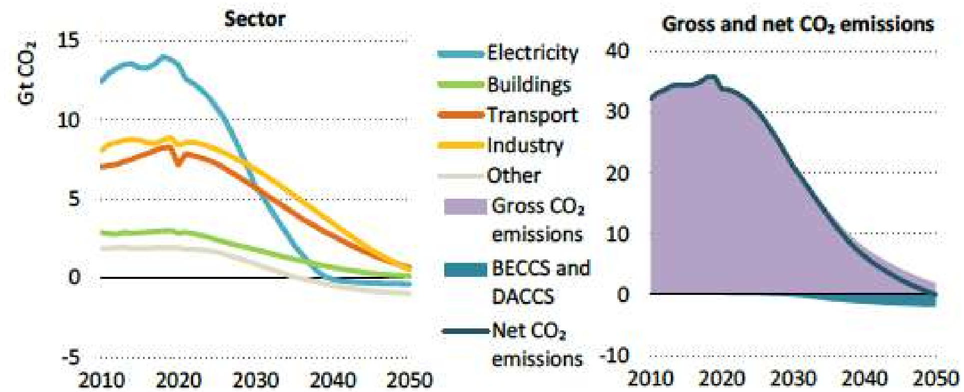


Figure 2.3 ▷ Global net-CO_2 emissions by sector, and gross and net CO_2 emissions in the NZE



Emissions from electricity fall fastest, with declines in industry and transport accelerating in the 2030s. Around 1.9 Gt CO_2 are removed in 2050 via BECCS and DACCS.

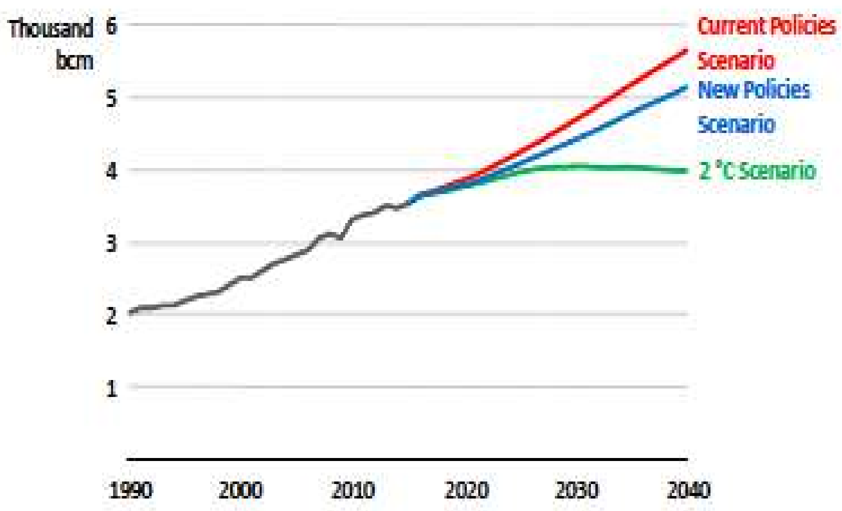
Notes: Other = agriculture, fuel production, transformation and related process emissions, and direct air capture. BECCS = bioenergy with carbon capture and storage; DACCS = direct air capture with carbon capture and storage. BECCS and DACCS includes CO_2 emissions captured and permanently stored.

Soource: IEA, 2021

Consequences of energy transition

- Future affordable, reliable and clean energy requires changes to
  - ✓ Physical system
  - ✓ Consumer behaviour
  - ✓ Market rules,
- Moving from an energy system of scarcity to one of potential abundance for almost every country,
- The country that have benefitted from fossil fuel production, it could geopolitical changes and potentially disrupt,
- The greatest challenges for fossil fuel-producing countries to adopt a new, diversified, economic model.

Main possible consequences of energy transition on O&G

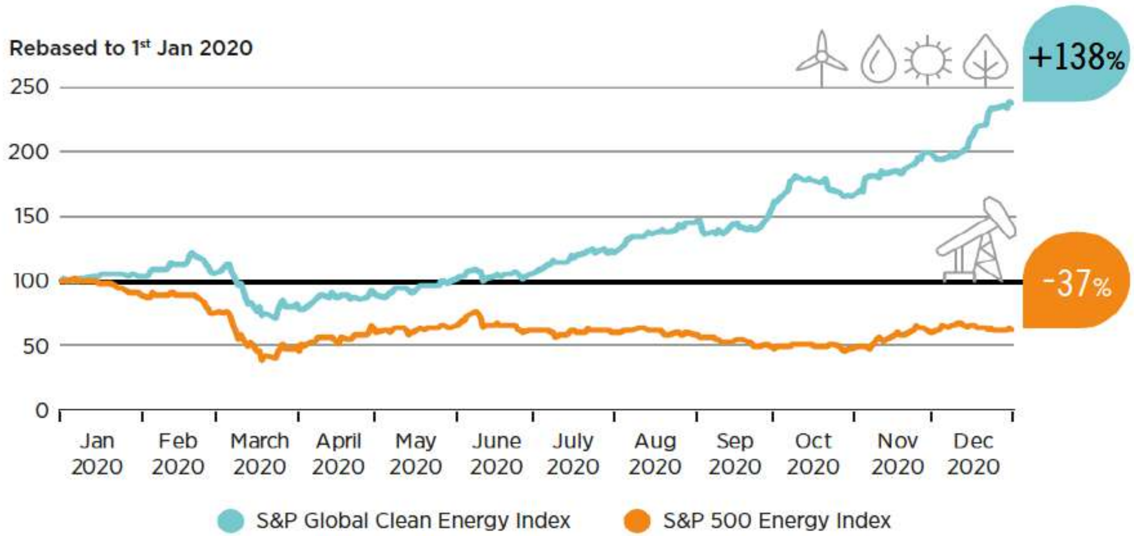


Global gas demand is projected to plateau from the late-2020s in the 2 °C Scenario

Slide Source IEA WEO 2016 Slide Deck

- ✓ Exploration would significantly reduce
- ✓ Many upstream assets would become stranded, with a higher proportion for gas than for oil
- ✓ Stranded assets could disproportionately affect producing countries

Financial markets are shifting towards new energy technologies



Source: Bloomberg.

Investors and financial markets are anticipating the energy transition and already allocating capital away from fossil fuels and towards energy transition technologies, such as renewables. For example, in 2020, the S&P Clean Energy Index of clean energy stocks was up by 138%, as compared to the fossil fuel-heavy S&P Energy Index which was down by 37%.

Source: IRENA, 2021

The major issues in Indonesia

Net oil importer country: -60%
Net gas importer country in 2020, -70% LPG

Enjoy strong and stable economic growth 5.3% (2011-2016)

Positive appetite from investors: FDI 5.8%

Energy supply mix is largely met by fossil fuels (93.3%)

Regulated price, energy subsidies ~ 100 trilion IDR

Archepelago – inter-regional disparities and complex logistics

Immense RE resources but not been used widely (RE ~7.7%)

Indonesia has ambitious RE targets 23% by 2025 and 31% by 2050

Most of energy planning objective is least cost without consider environmental external.

Low electrification ratio compared to ASEAN countries

Low energy productivity of most sectors

Policy objectives – *unclear*

Value Chain: Exploration & production → Wholesale trade → Transmission → Distribution & Marketing

Activities




Key players: Pertamina, IOCs | Private companies holding trading licenses | PGN, Pertagas | PGN, Pertagas

etc

Regulators: MEMR/ SKK Migas | BPH Migas

New law?: BUMN-K | BUP

Policy - multi objectives

?

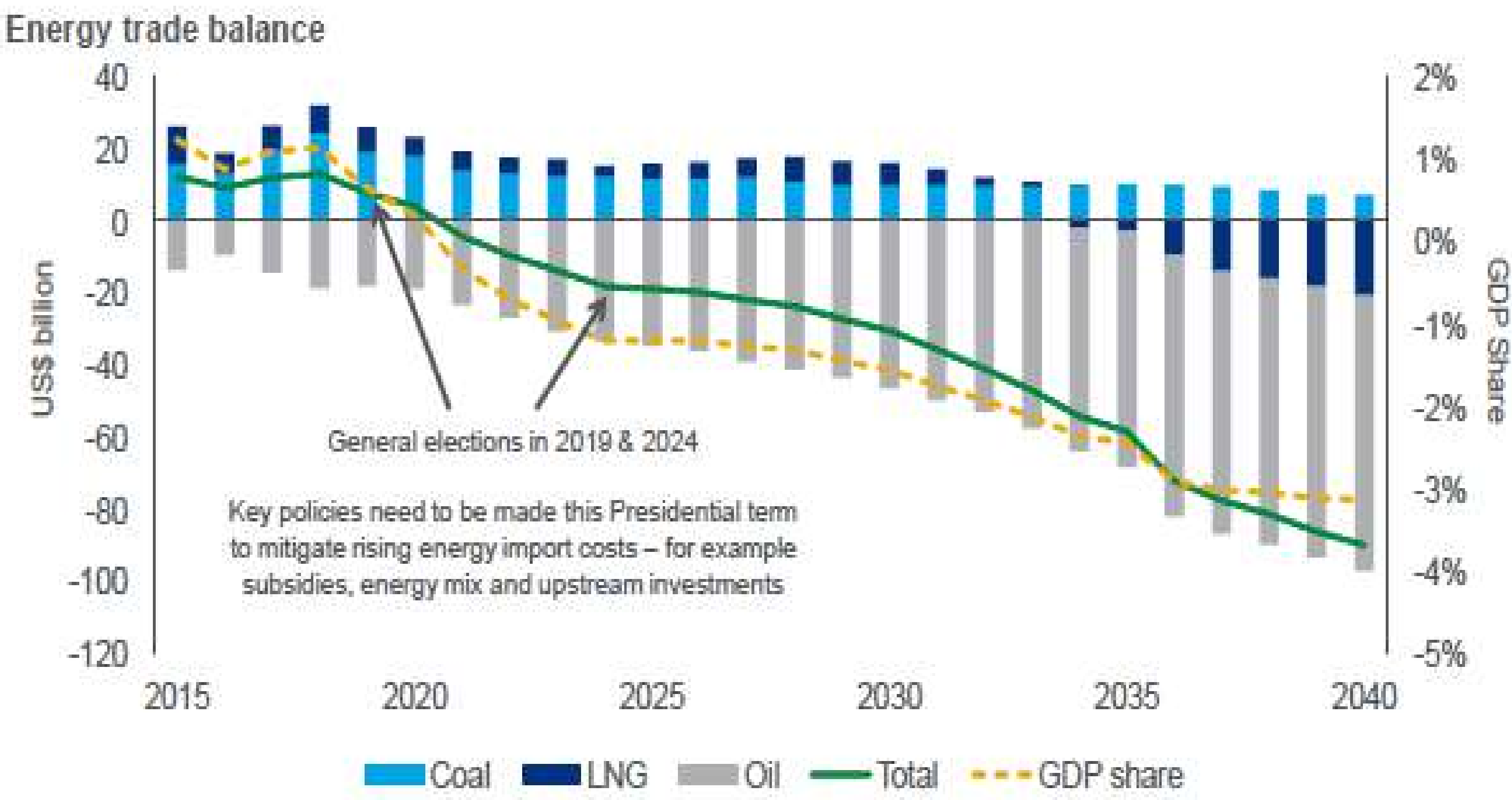
Lack of integration

Max Netback Gas ↔ Max Social Welfare

Balancing

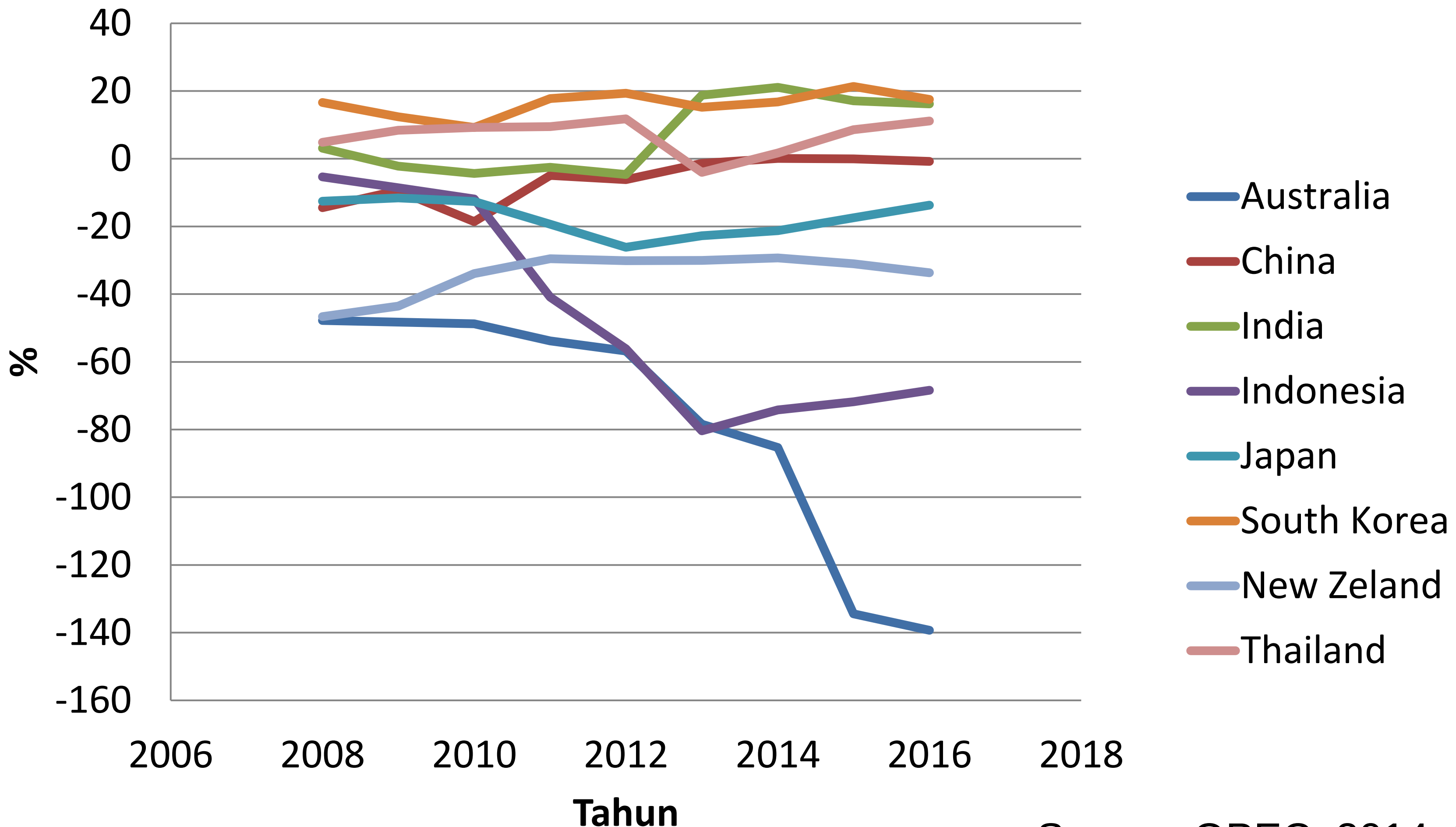
Source: WB, Modified

Rising energy import cost & net gas importer



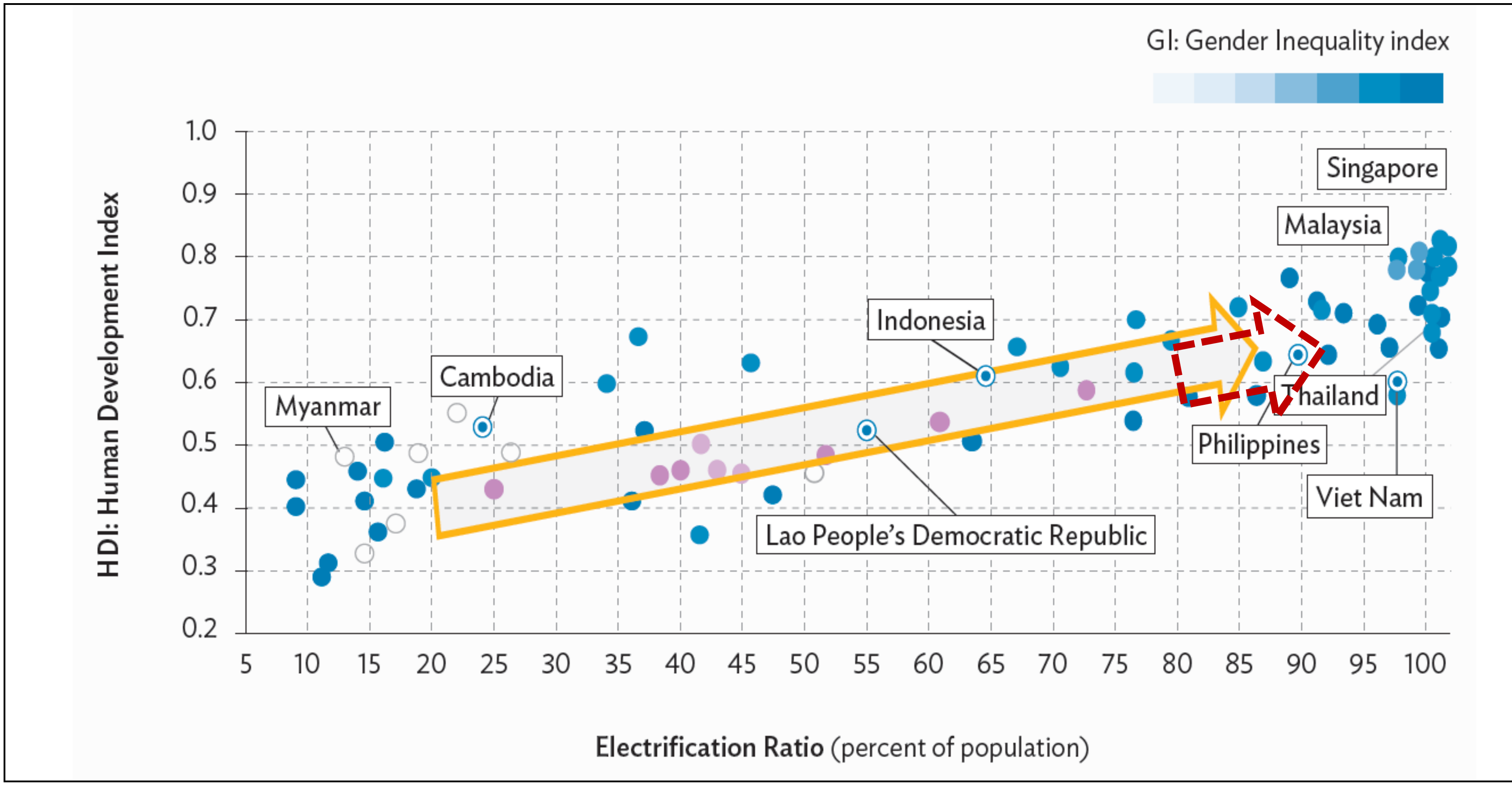
Source: Wood Mackenzie

Import dependency of petroleum fuels



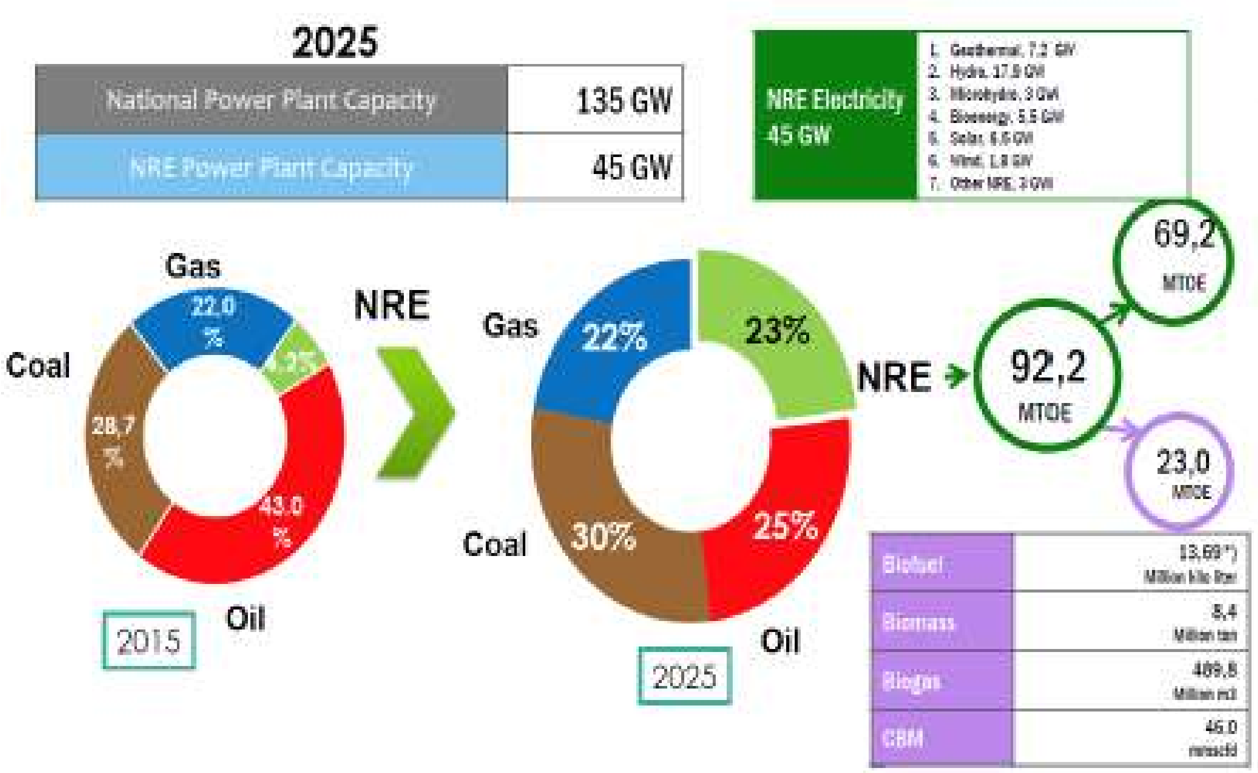
Source: OPEC, 2014, 2017

HDI & GI and Electrification ratio



Source: ADB, 2016

Limited RE adoption



Electricity
11,7 % RE share
13,6% (incl. Biomass)

achievement: 7.7% RE share of total energy supply

Source: MEMR

Stockholding of petreleum fuels

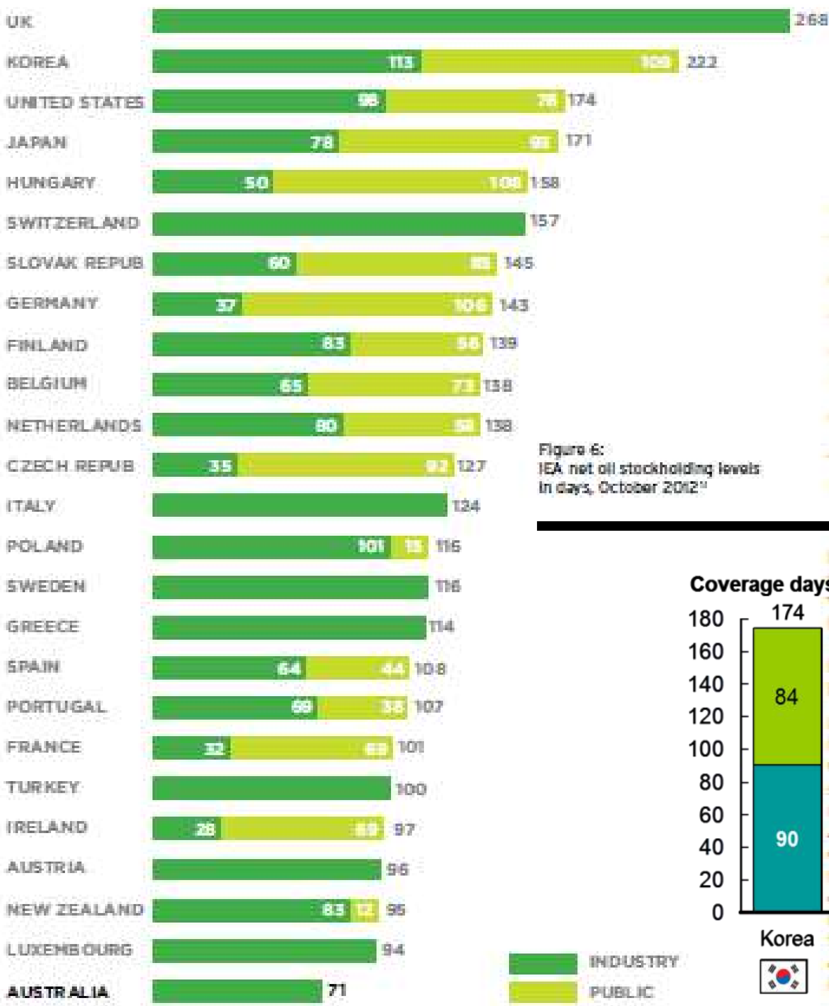
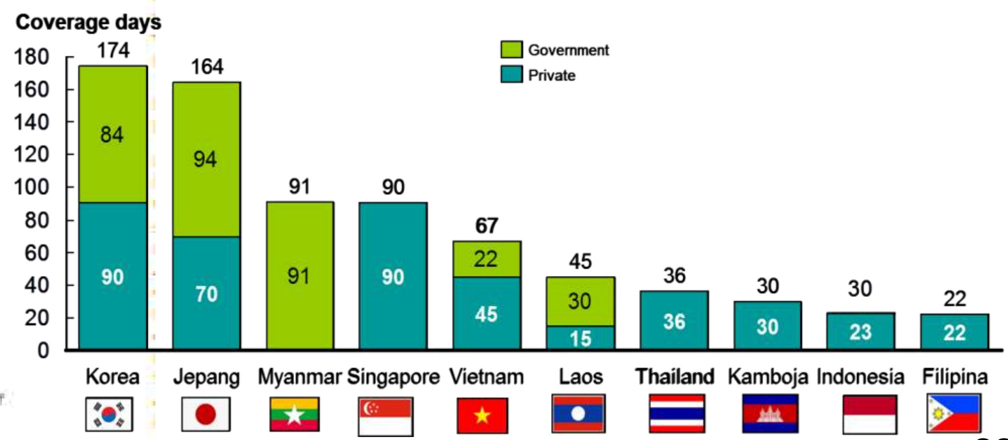


Figure 6:
IEA net oil stockholding levels in days, October 2012

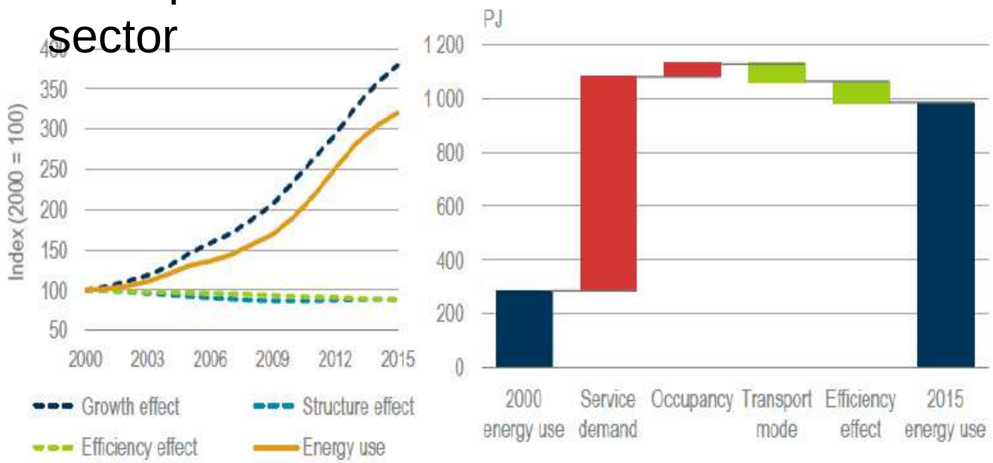


APEC: Minimum holding of 30 days of net import level
IEA: Minimum holding of 90 days of net import level

Indonesia 21 hari dari konsumsi ?

Productivity/efficiency

Transportation sector



Source: Adapted from IEA (2017a), *Energy Efficiency Indicators* (database), www.iea.org/statistics/topics/energyefficiency/.

Source: IRENA, 2017

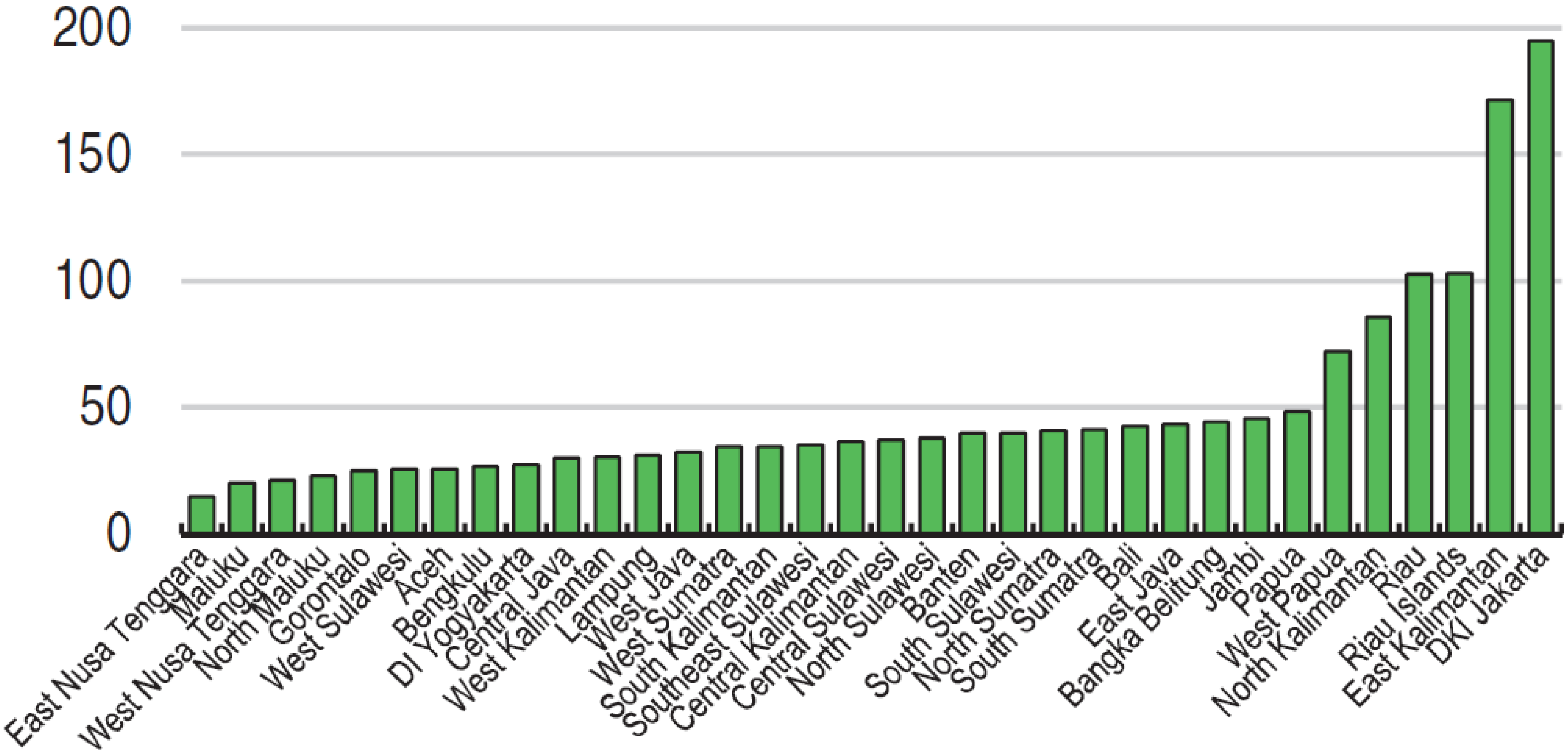
Table 1. Specific energy consumption of the selected industry groups.

Industry group	SEC (BOE/ Tonne)	SEC reference (BOE/Tonne)	References
Pulp	1.21–2.74	1.13–3.16	[16]
Paper	1.63–2.14	1.23–1.79	
Alcohol	1.11	0.78	[17]
Cement	0.67	0.57	[18]
Spinning	1.48–3.65	0.57–0.59	
Weaving	0.83–8.6	0.82–7.03	
Finishing	8.35	7.8	
Basic Metal and Steel	0.67–0.86	0.46–0.50	
Sugar processing	5.98	4.75	[19]

Source: Vivadinar et al, *Energy Sci and Eng*, 2016

Inequality across region is large

% of national GDP per capita, 2014



Source: Statistics Indonesia.

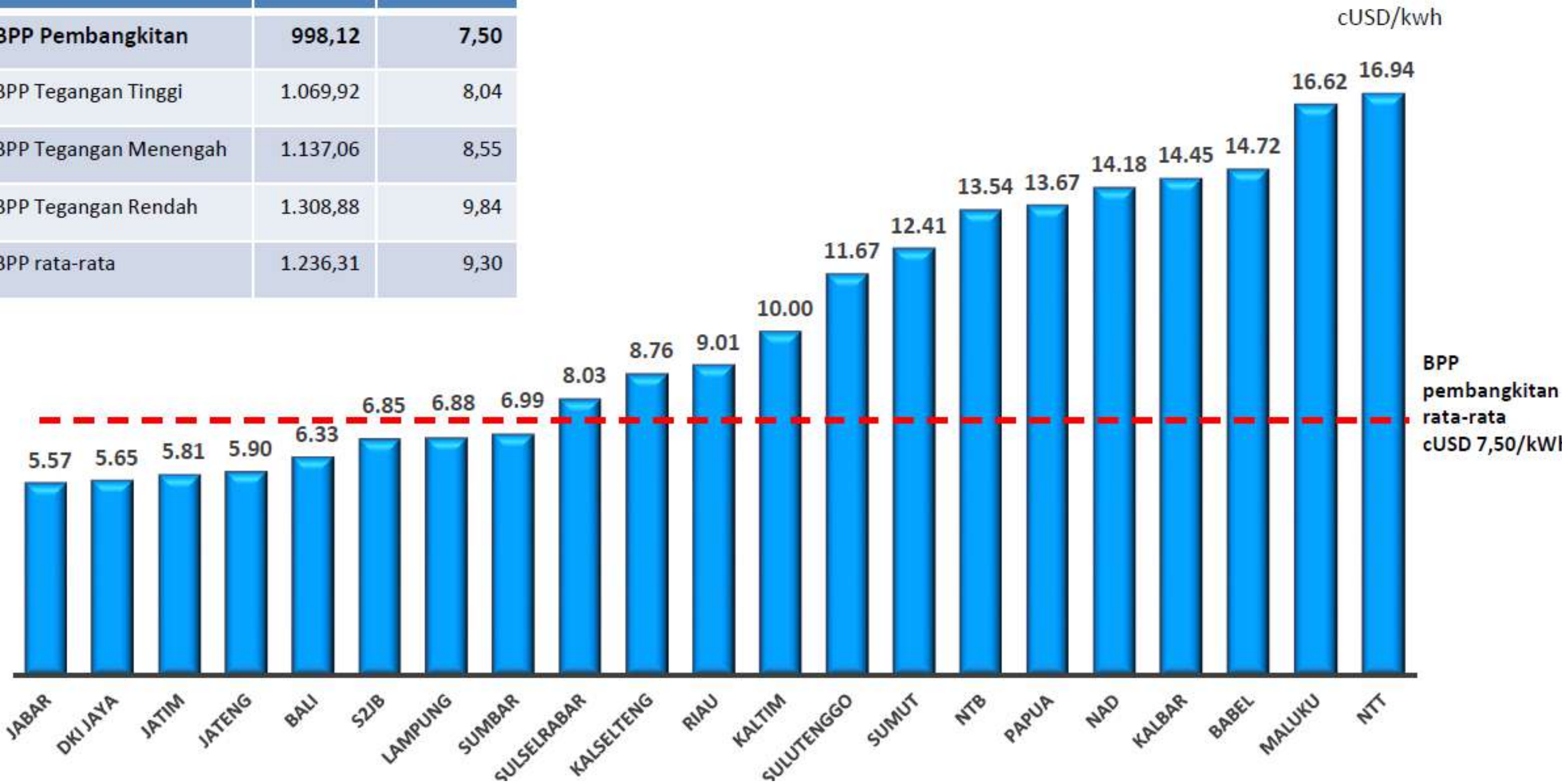
Source: OECD, 2016

Inequality across regions is large

Generation cost of electricity

BPP Tenaga Listrik 2015 (Audited)

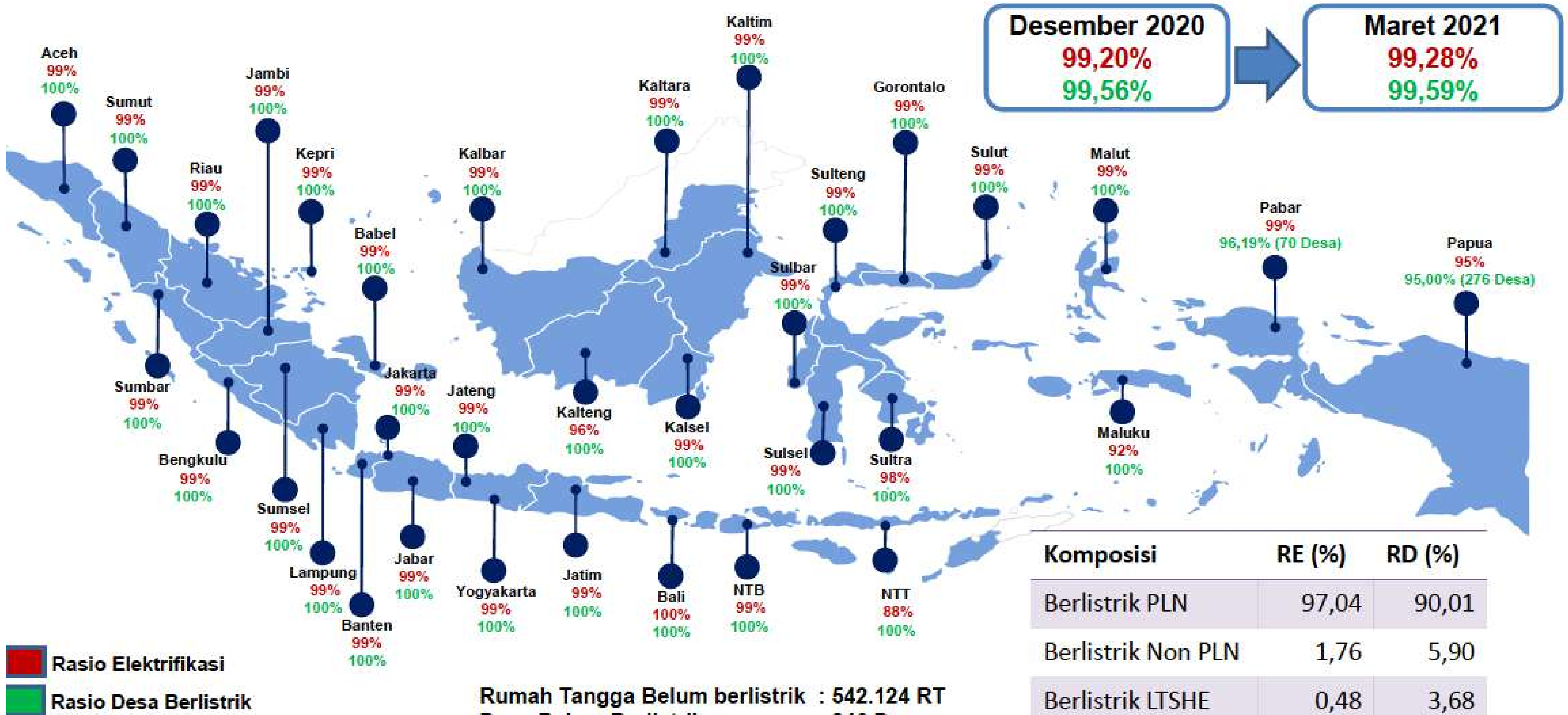
No.	Uraian	Rp/kWh	cUSD/kwh
1	**BPP Pembangkitan**	**998,12**	**7,50**
2	BPP Tegangan Tinggi	1.069,92	8,04
3	BPP Tegangan Menengah	1.137,06	8,55
4	BPP Tegangan Rendah	1.308,88	9,84
5	BPP rata-rata	1.236,31	9,30



Source: MEMR, 2017

Inequality across regions is large

Electrification ratio



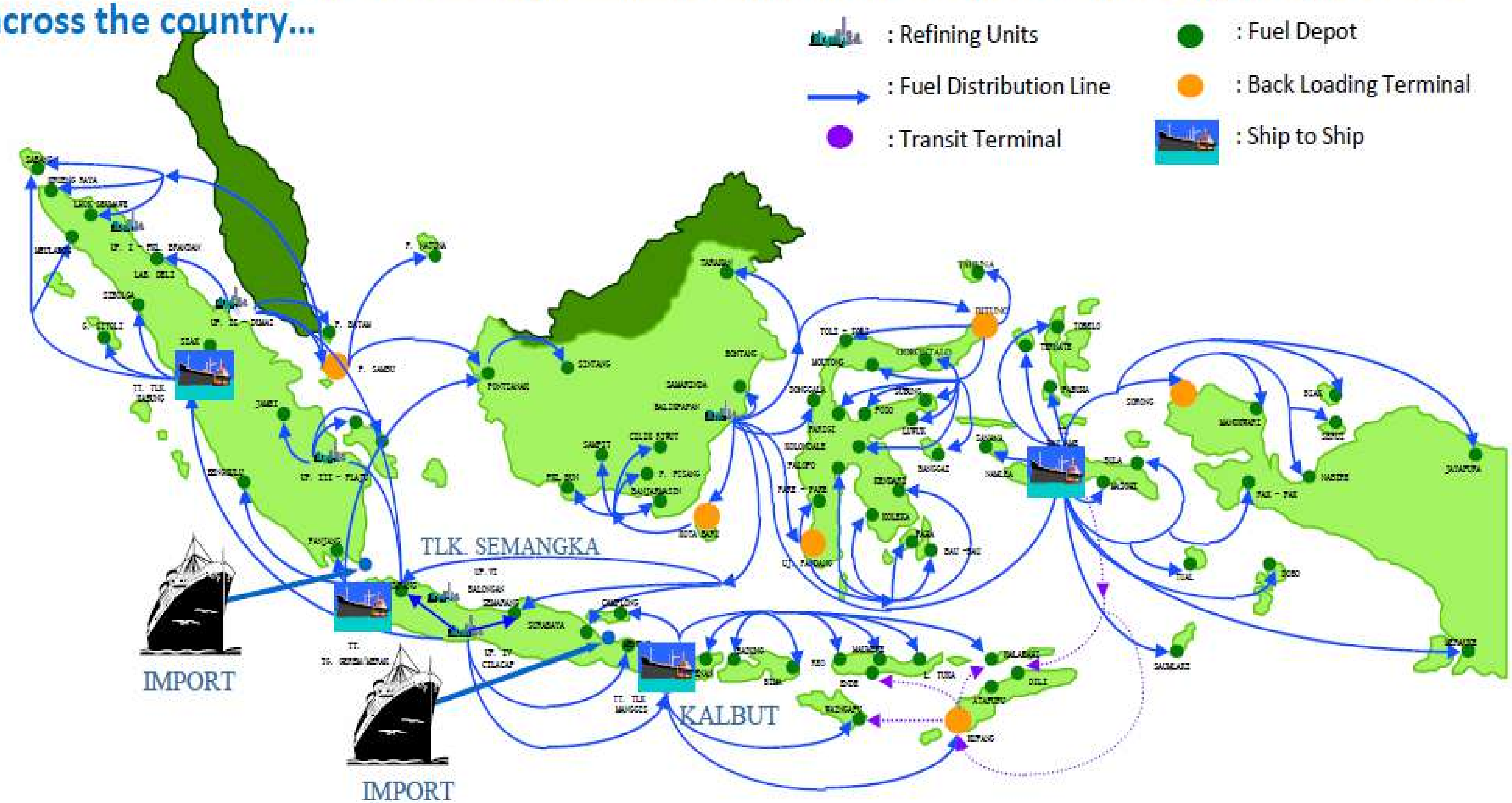
Rumah Tangga Belum berlistrik : 542.124 RT
Desa Belum Berlistrik : 346 Desa

Komposisi	RE (%)	RD (%)
Berlistrik PLN	97,04	90,01
Berlistrik Non PLN	1,76	5,90
Berlistrik LTSHE	0,48	3,68
Belum Berlistrik	0,72	0,41

Source: MEMR

Complex fuel product logistics

Pertamina handles the most complex distribution in the world in delivering fuel products across the country...

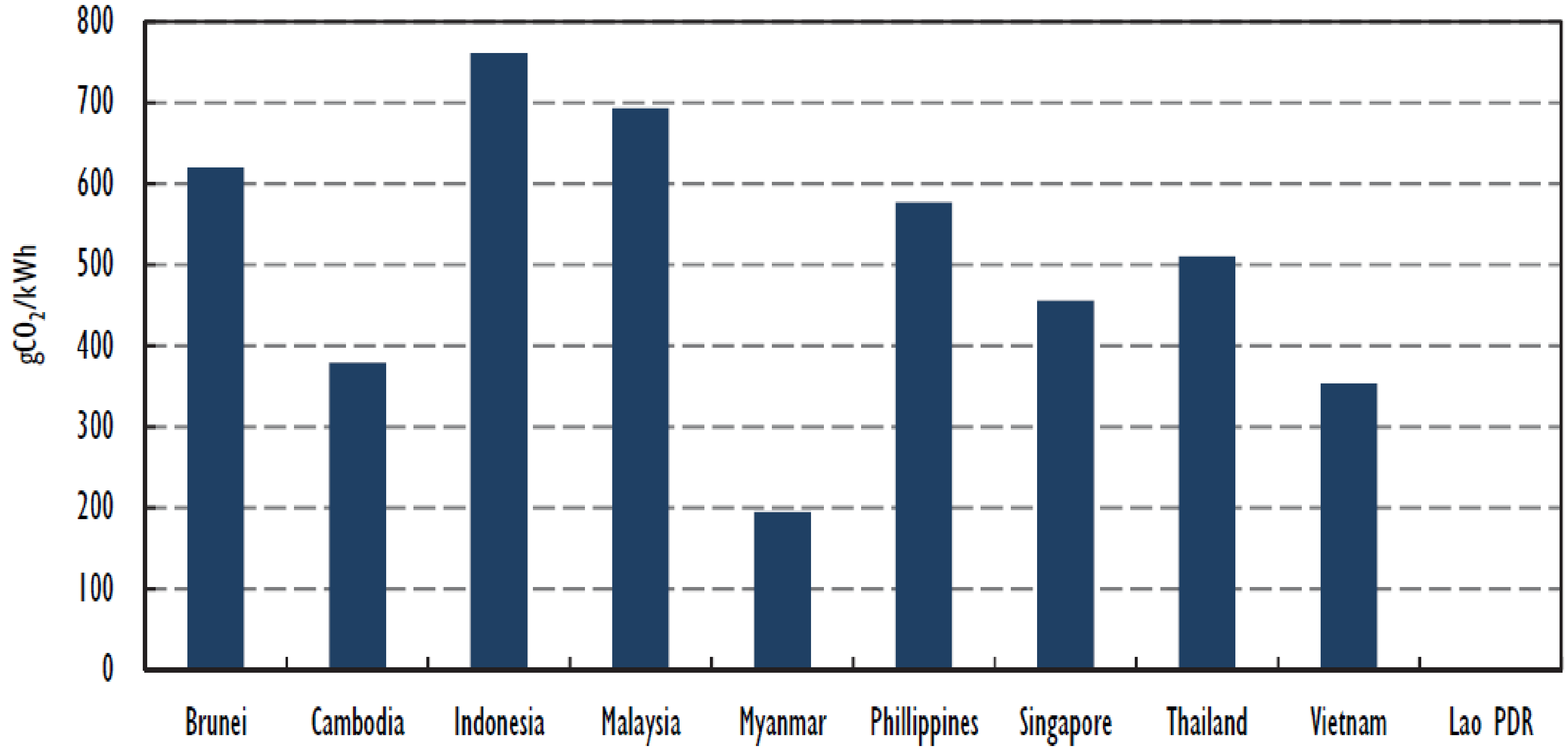


- 5,161 unit Gas Stations, 603 APMS, 260 SPDN, 50 SPBN

...but still lags behind especially gas and electricity logistic infrastructure systems

Source: Pertamina

High CO_2 intensity of electricity



Source: IEA (2015h), *CO_2 Emissions from Fuel Combustion*, www.iea.org/statistics.

Source: IEA, 2016

What is energy systems?

What is energy?

The ability of matter or radiation to do work'

People don't demand *energy* - they ask for these *services:*

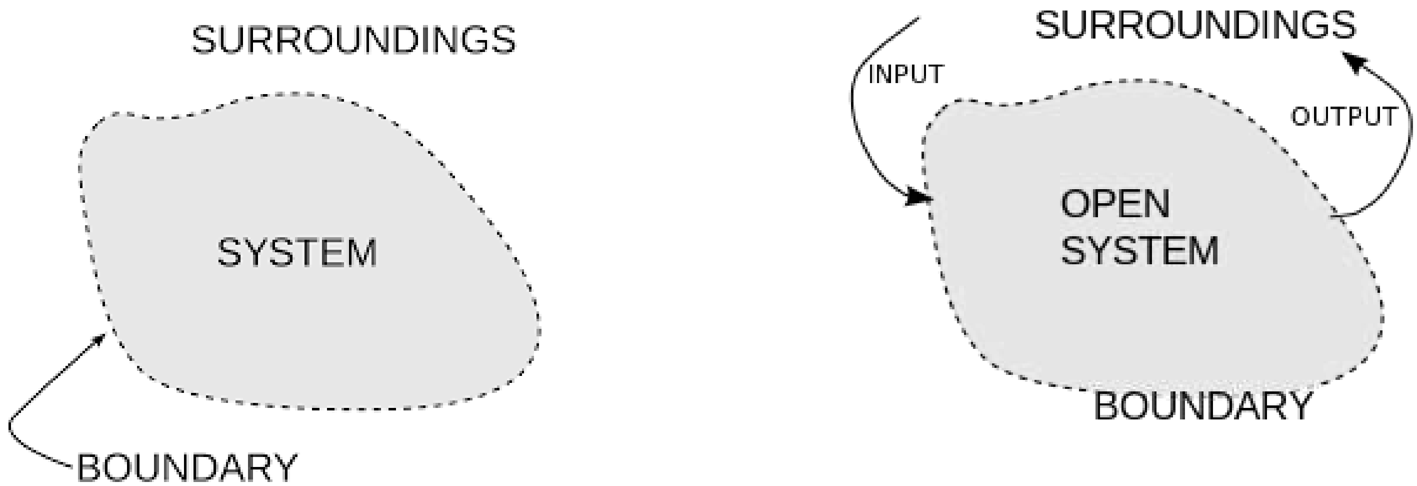
- heating / cooling / lighting - buildings
- mobility / carrying capacity - transport
- 'making things' power - industry
- IT/ communication / entertainment - all

Role of Energy

- Energy is a vital input for economic and social development of any nation;

- The significant energy use is related to the nature of energy services in different sectors in the economy, environmental constraint as well as the economic situation.

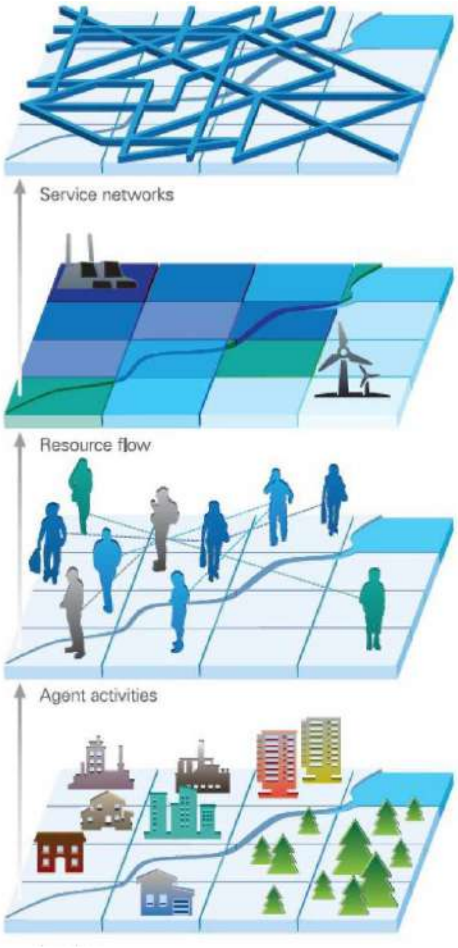
What is system & system engineering

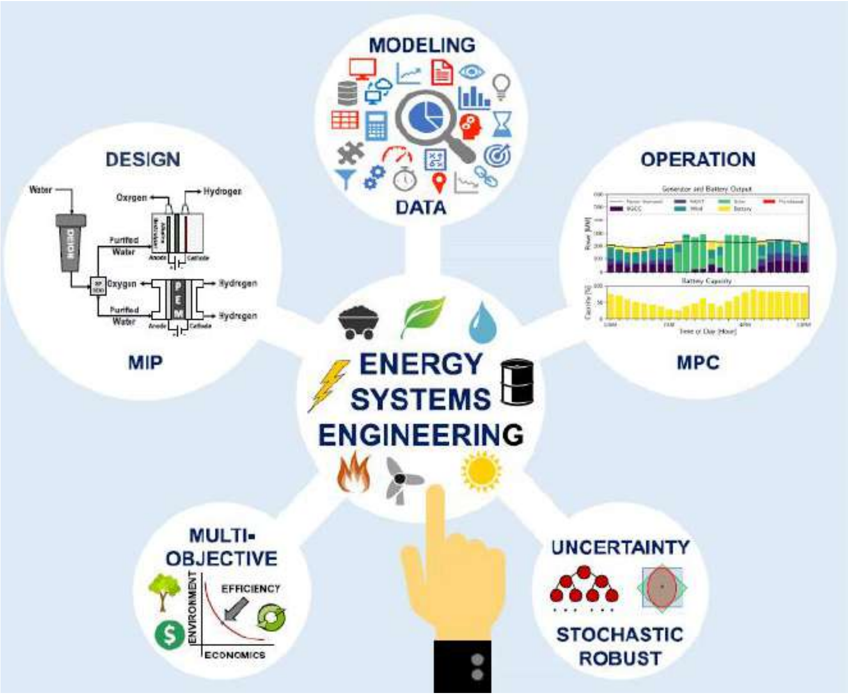


A system is a group of interacting or interrelated entities that form a unified whole

Systems engineering is an interdisciplinary field of engineering and engineering management that focuses on how to design and manage complex systems over their life cycles.

Energy system engineering



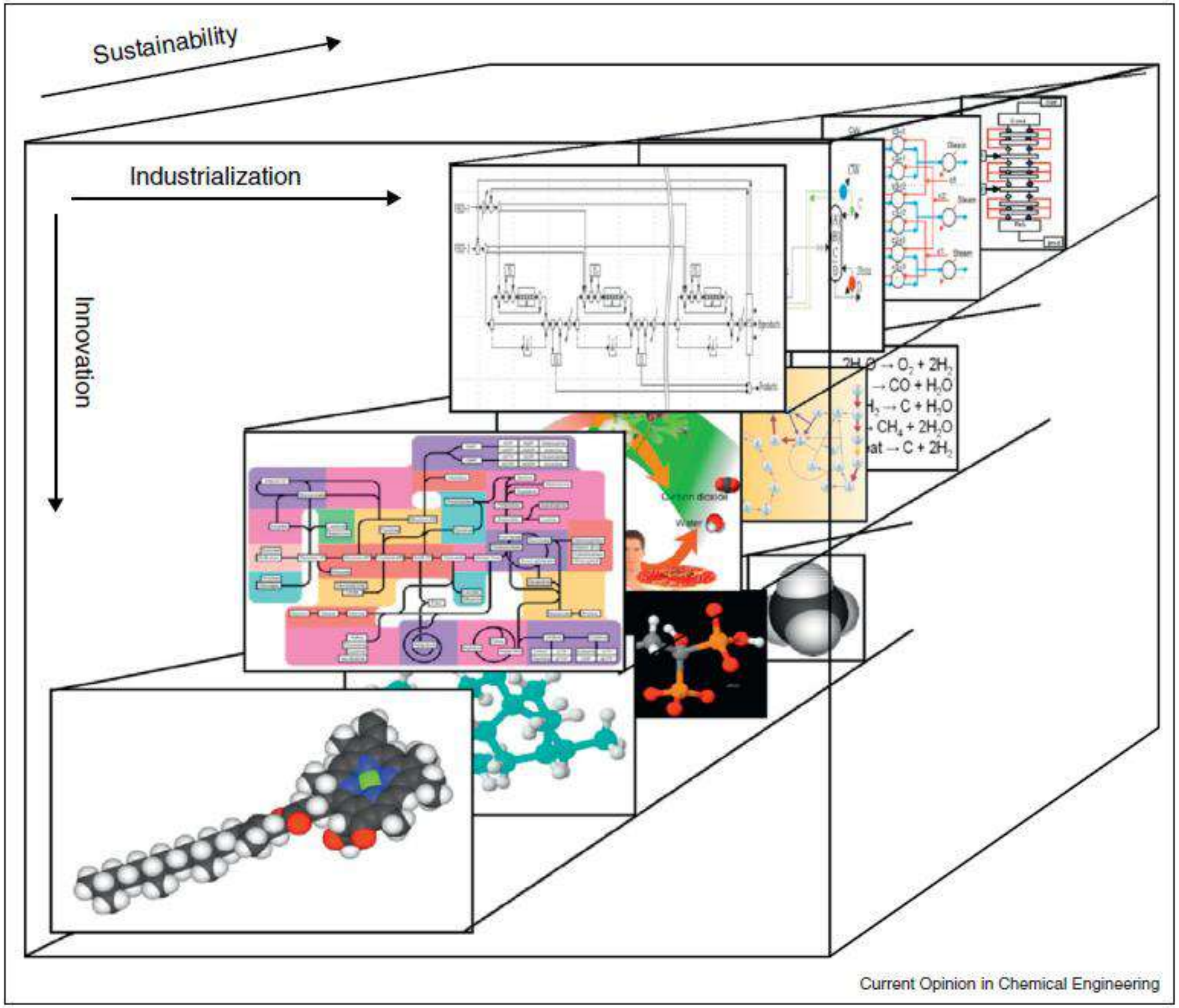


Energy systems engineering provides a methodological scientific framework to arrive at realistic integrated solutions to complex energy problems, by adopting a holistic, systems-based approach.

Source: ICL, Demirhan

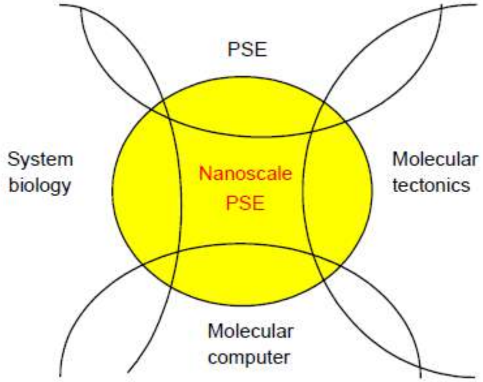
Multi-scale

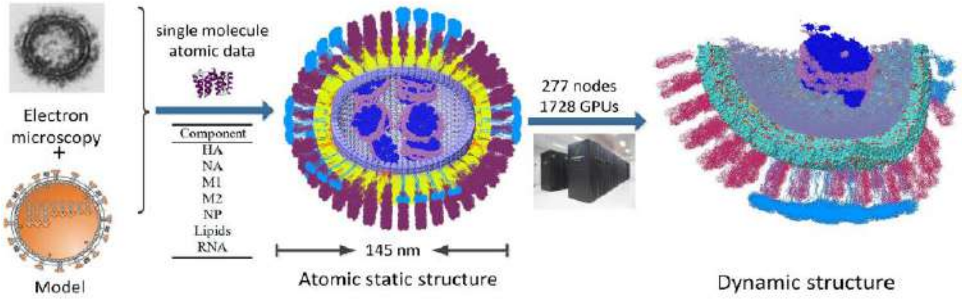
Multi-scale energy system

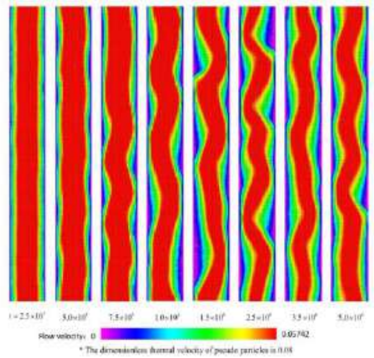


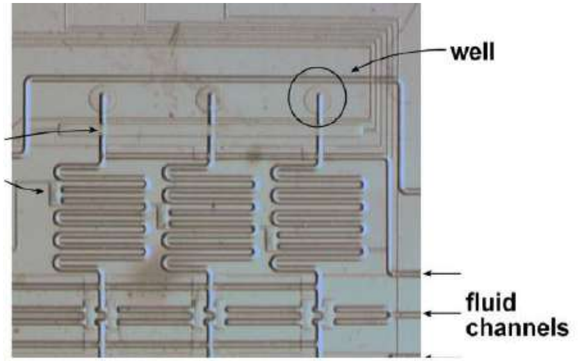
Source: Kravanja, 2012

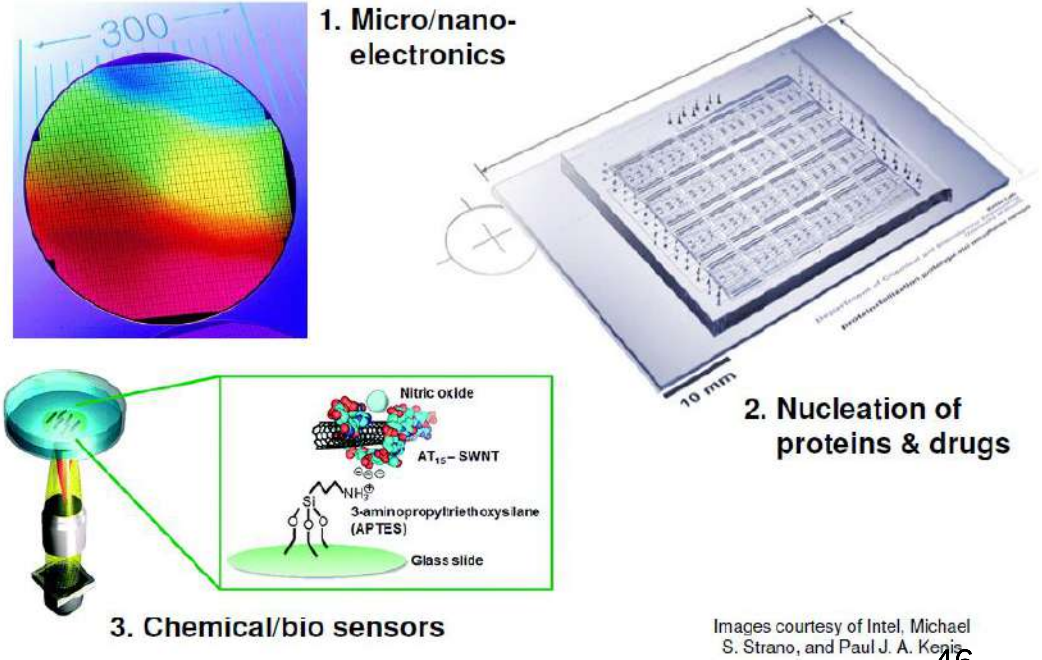
Micro/nano scale system





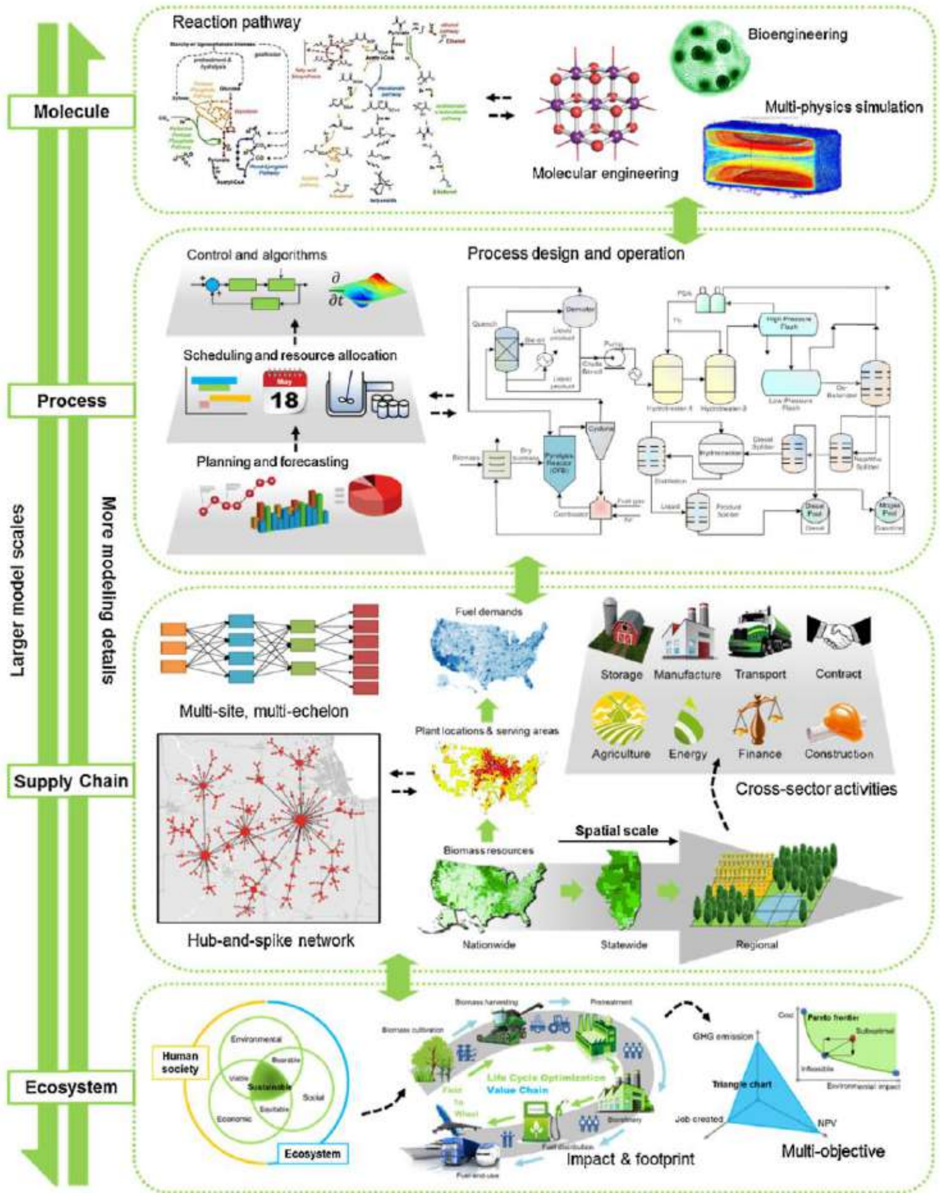






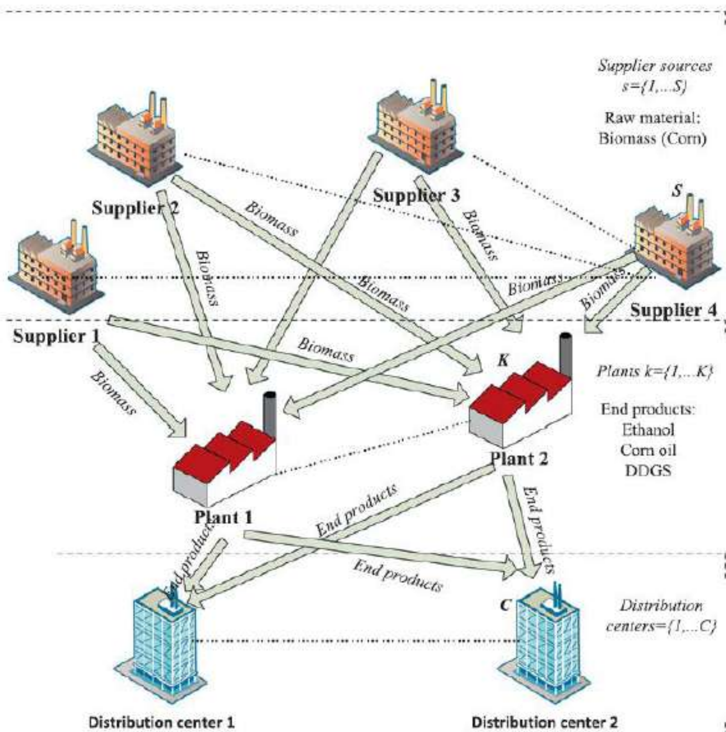
Source: Yang, 2008, Braatz-MIT, Xu et al. *Chem Eng Sci*, 2015

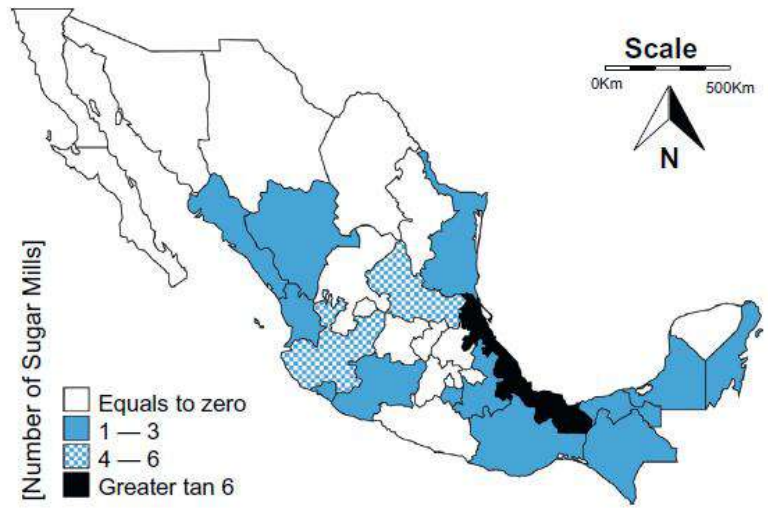
Multi-scale (molecular to ecosystem) of biofuels

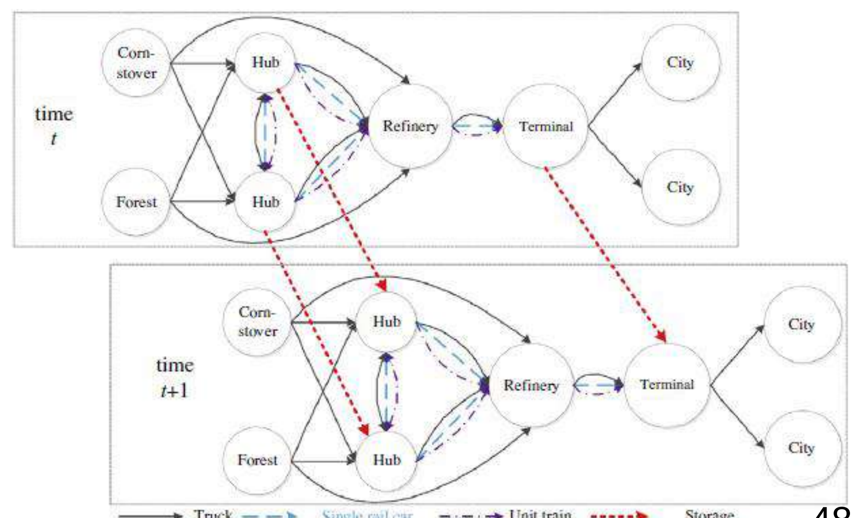


Source: Yue et al, 2014

Macro scale and multi-region: optimal design of supply chain

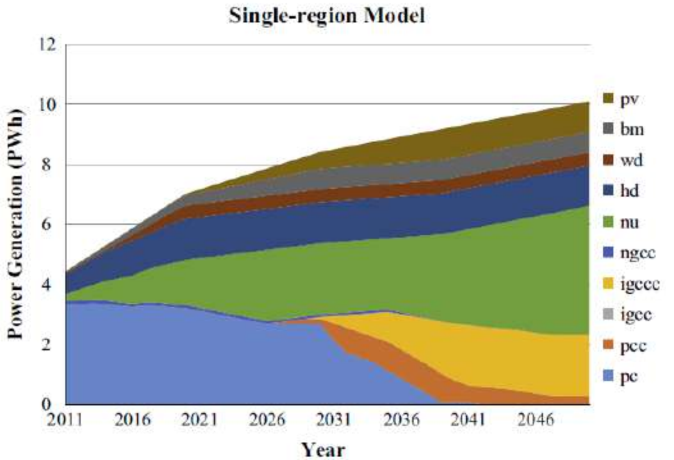


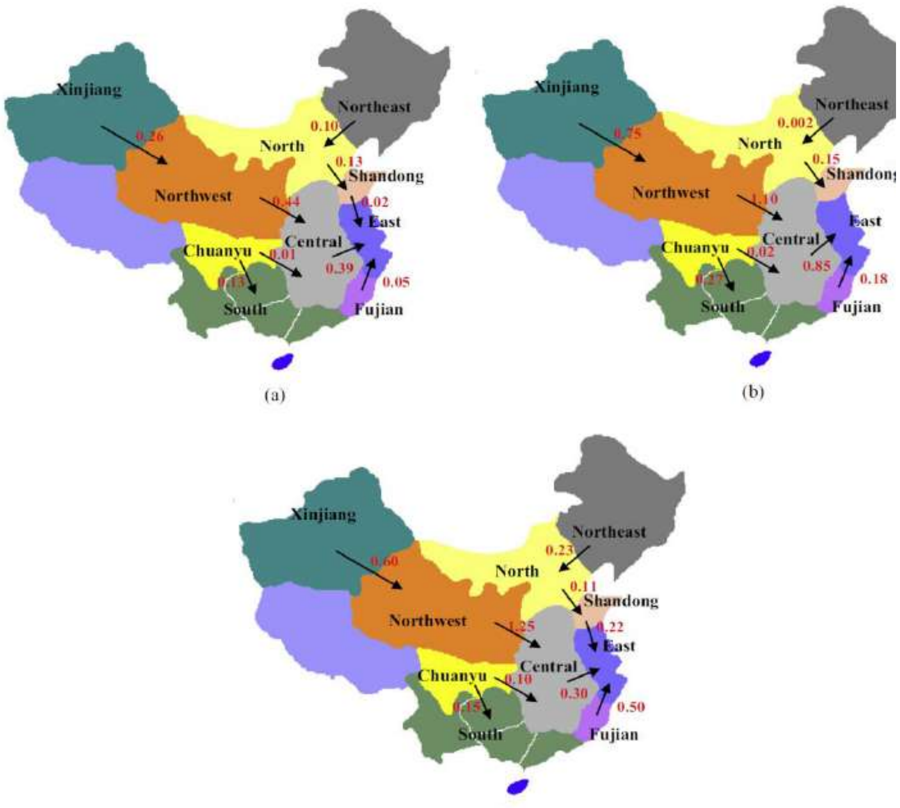




Source: Awudu & Zhang. *Appl Energy,* 2013; Xie et al. *Bioresour Technol*,

Multi-region system

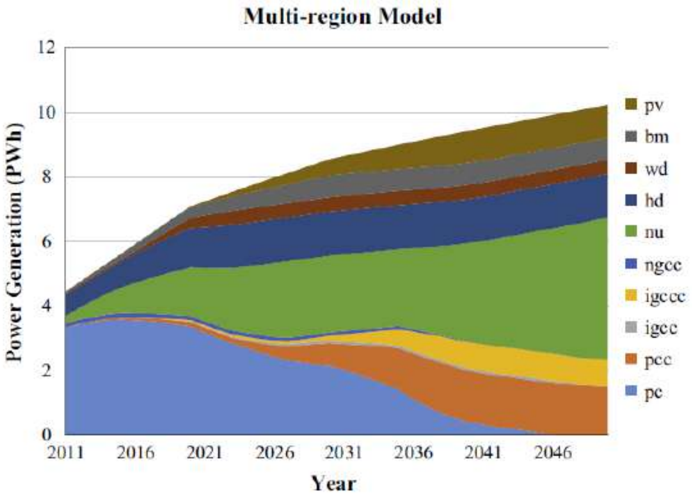




(a)

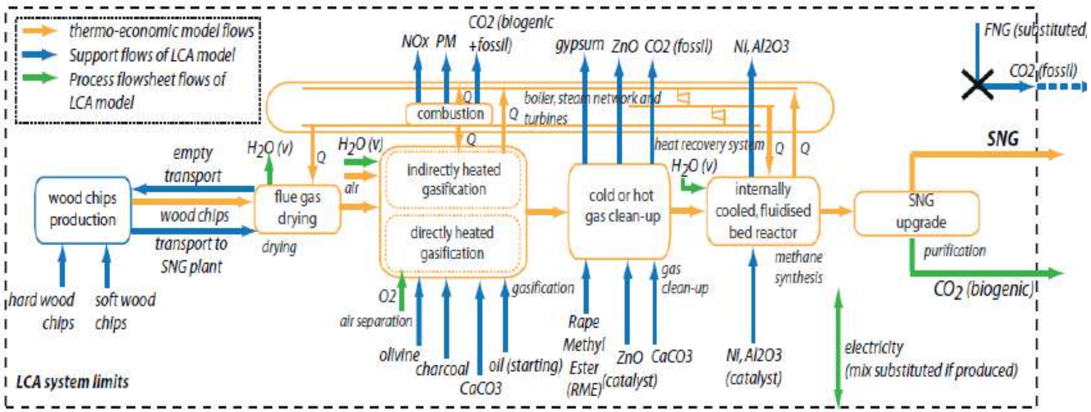
(b)

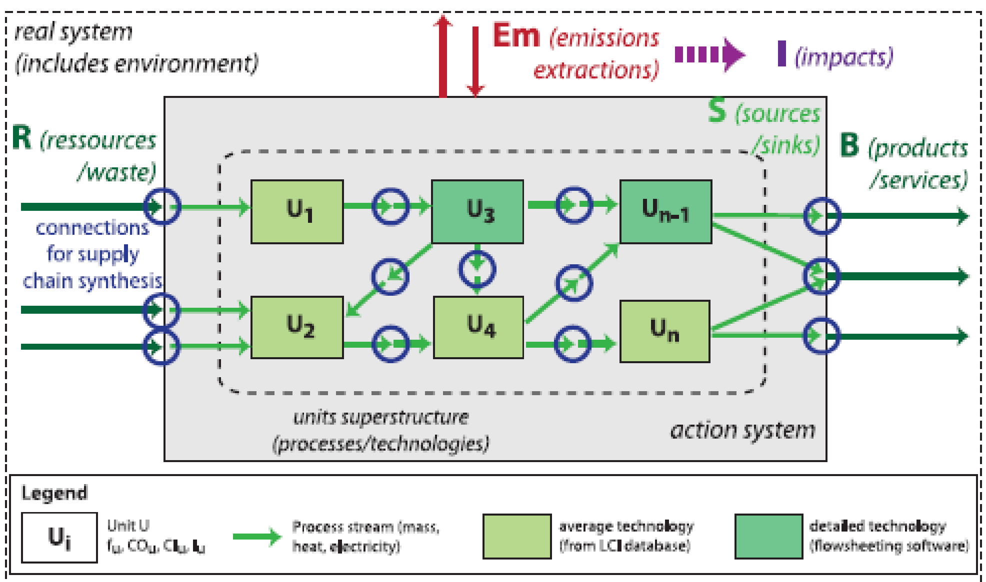
(c)

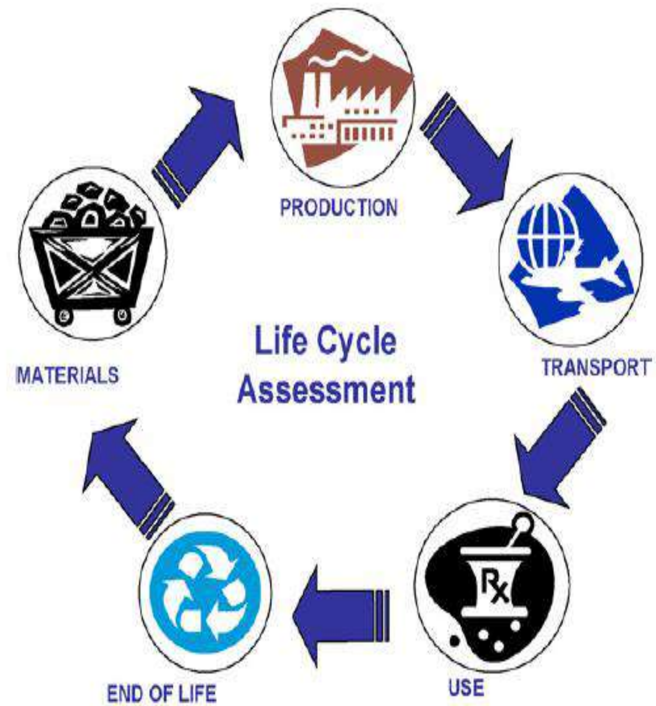


Source: Cheng et al, 2015

Ecosystem/LCA



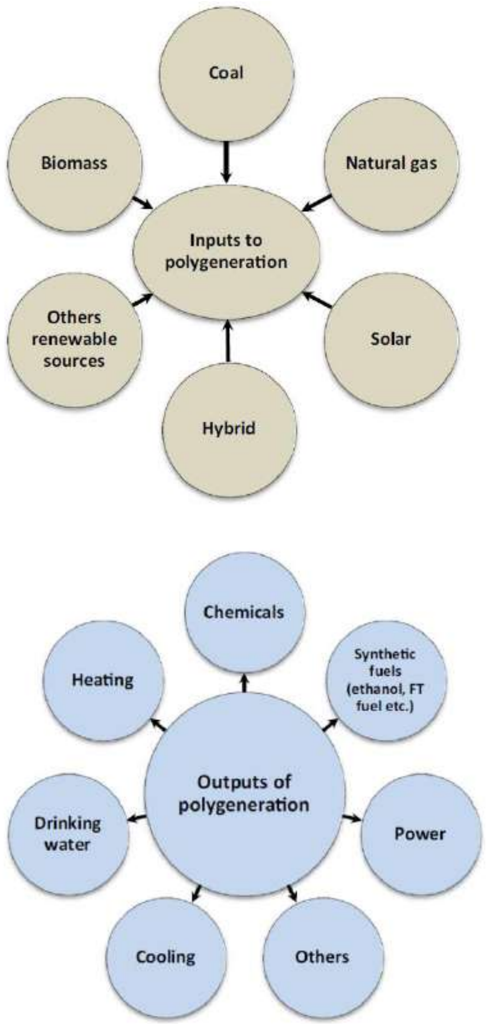


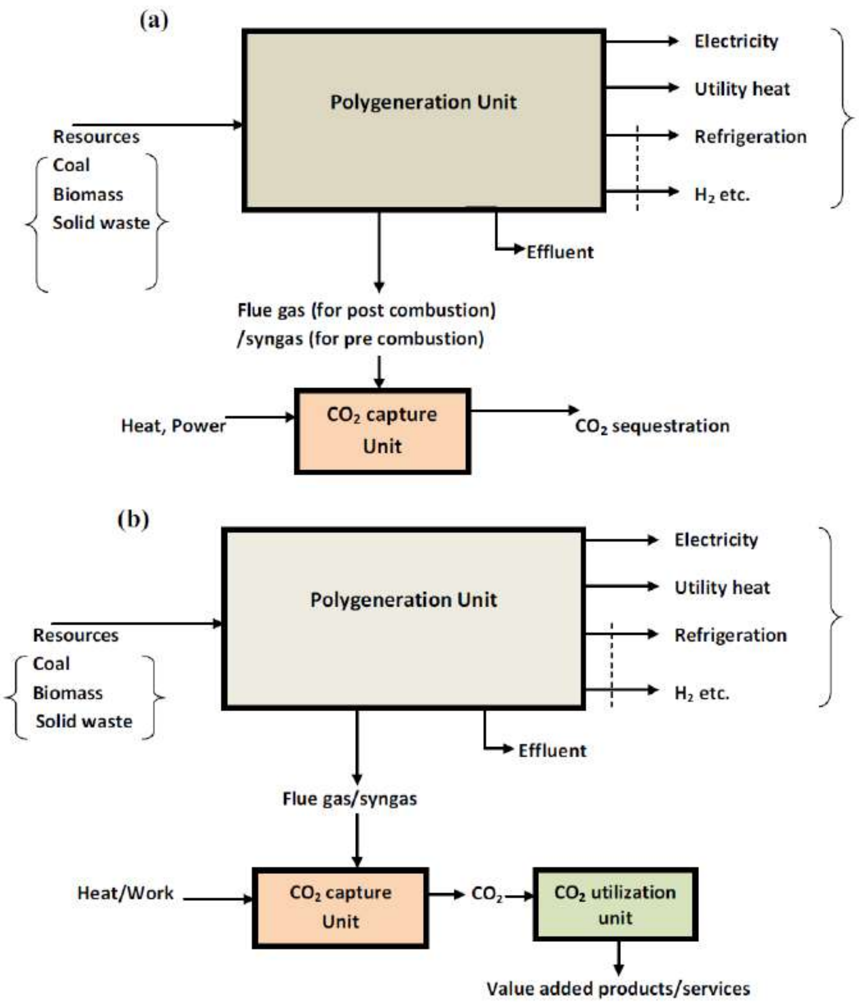


Gerber et al. *Comput Chem Eng*, 2011, 2013

Integration/polygeneration

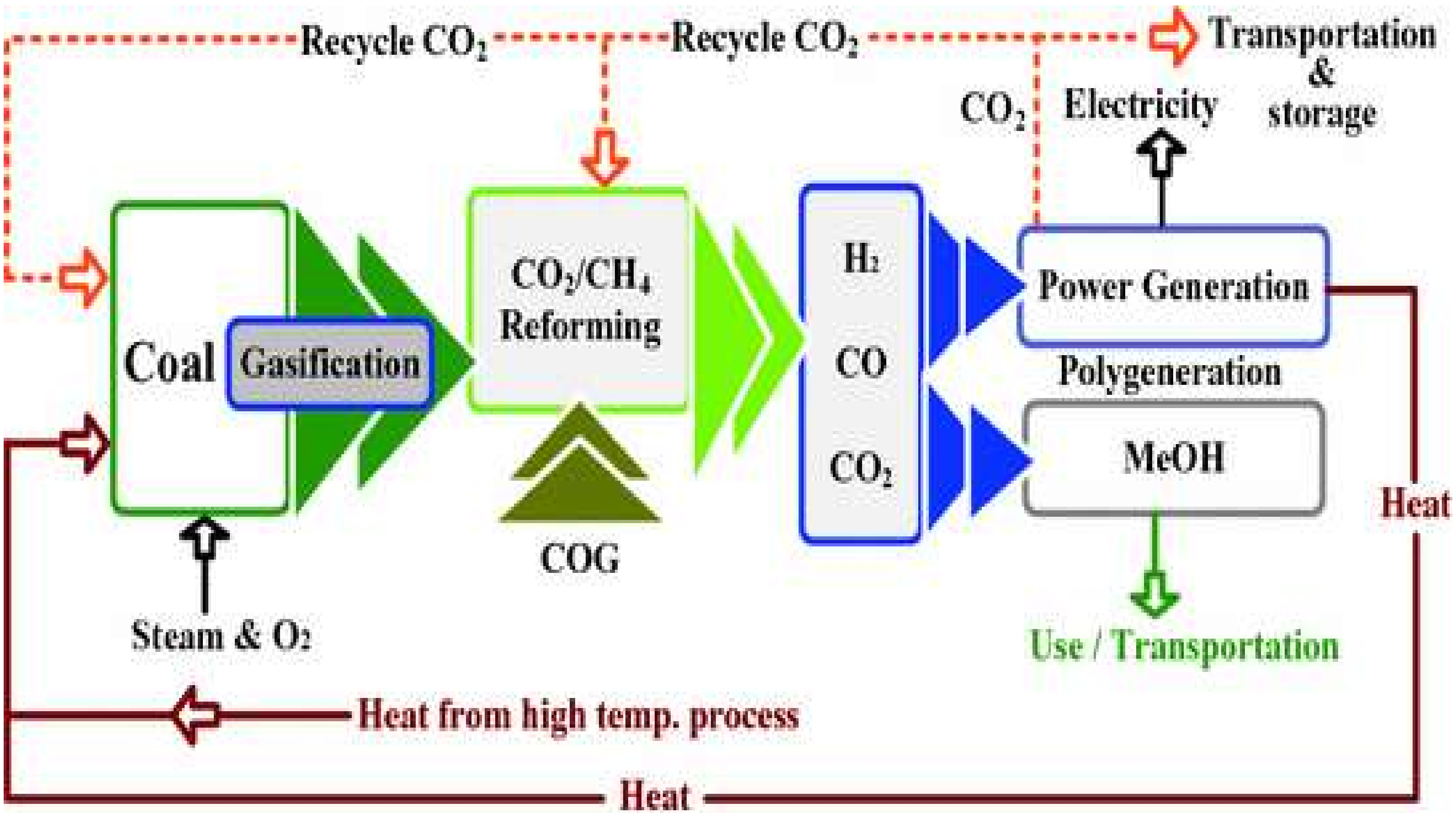
Polygenerations/Multi feed-Coproduction



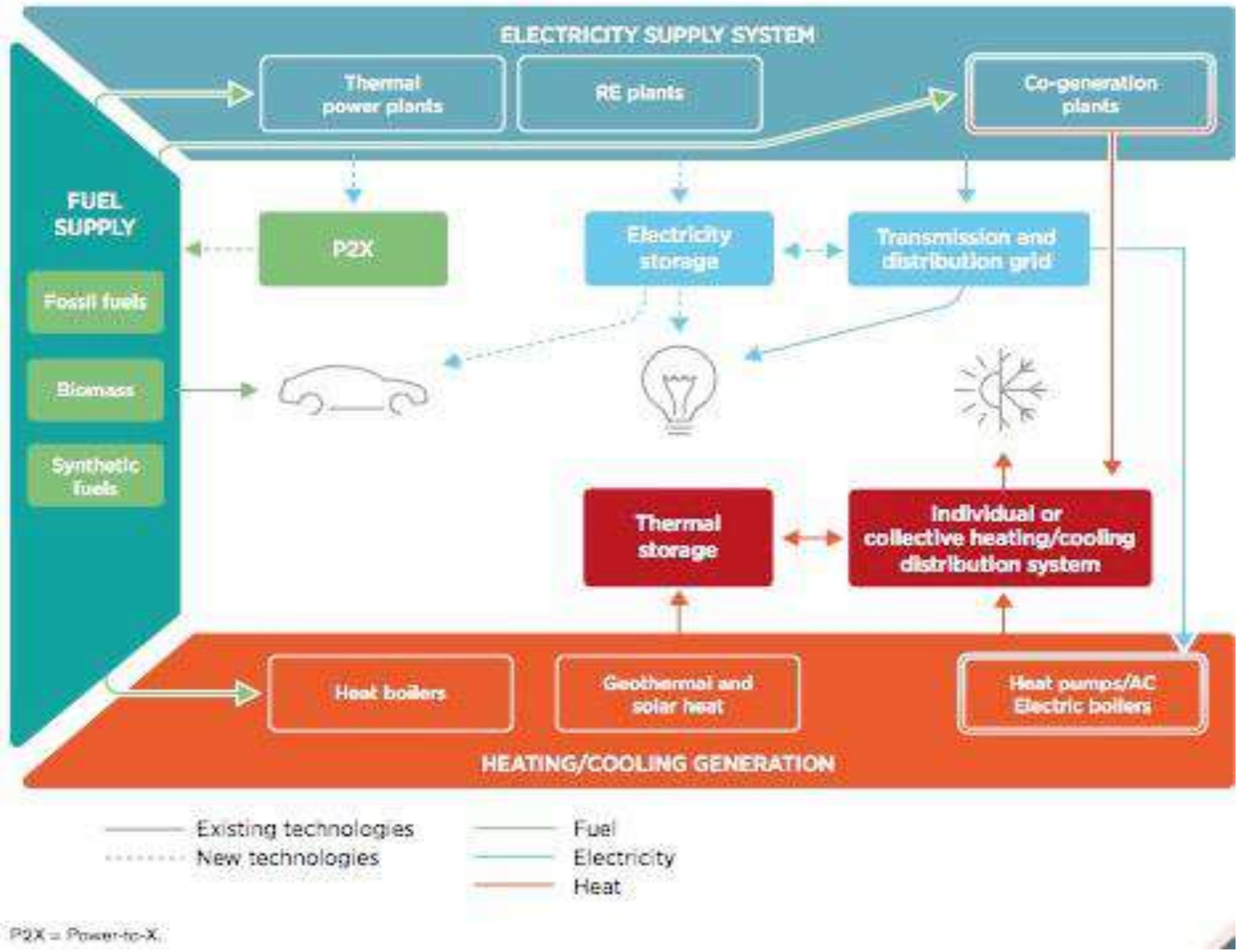


Source: Jana et al, 2017

Coal-based polygeneration

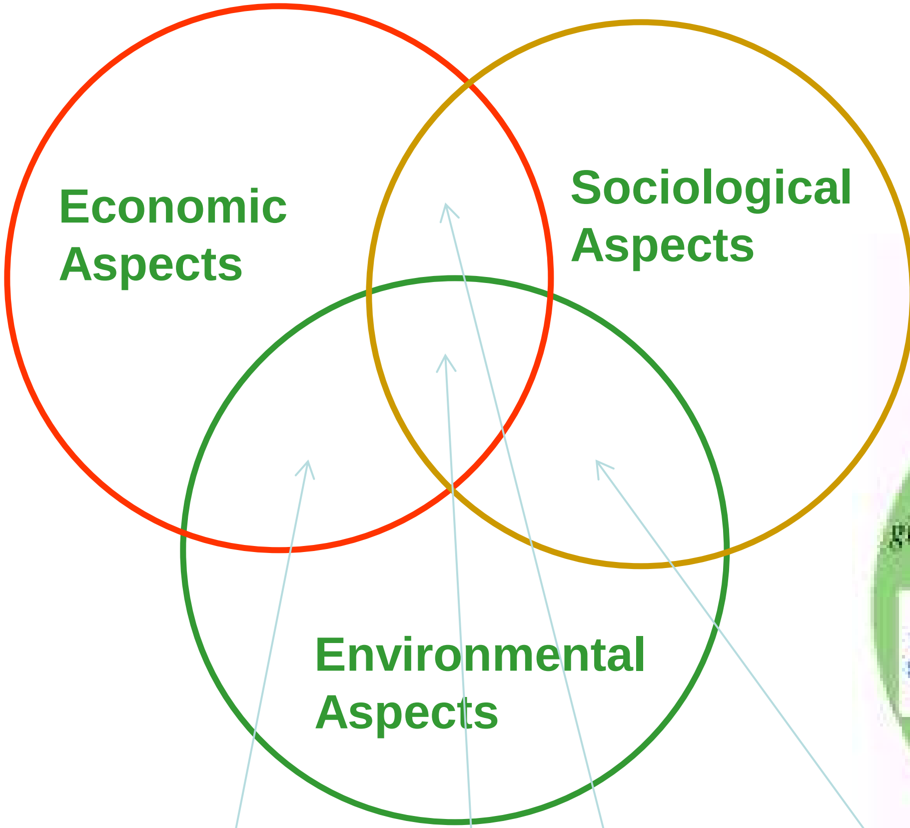


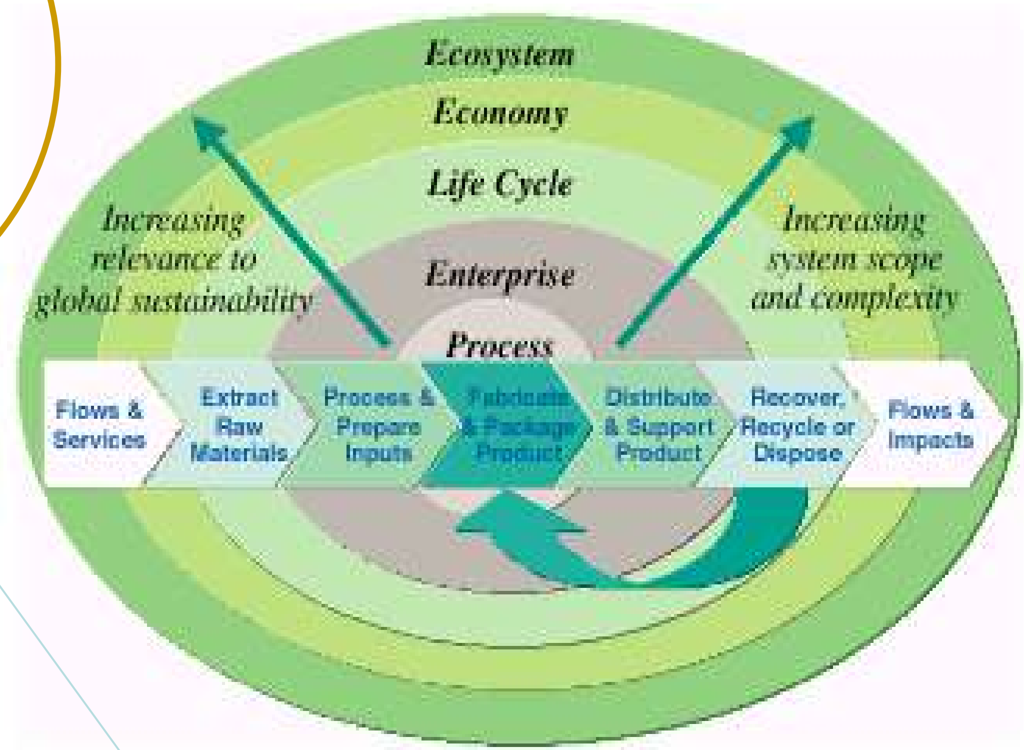
Sector coupling



Multi-dimension (sectors)

SD and Sustainable system

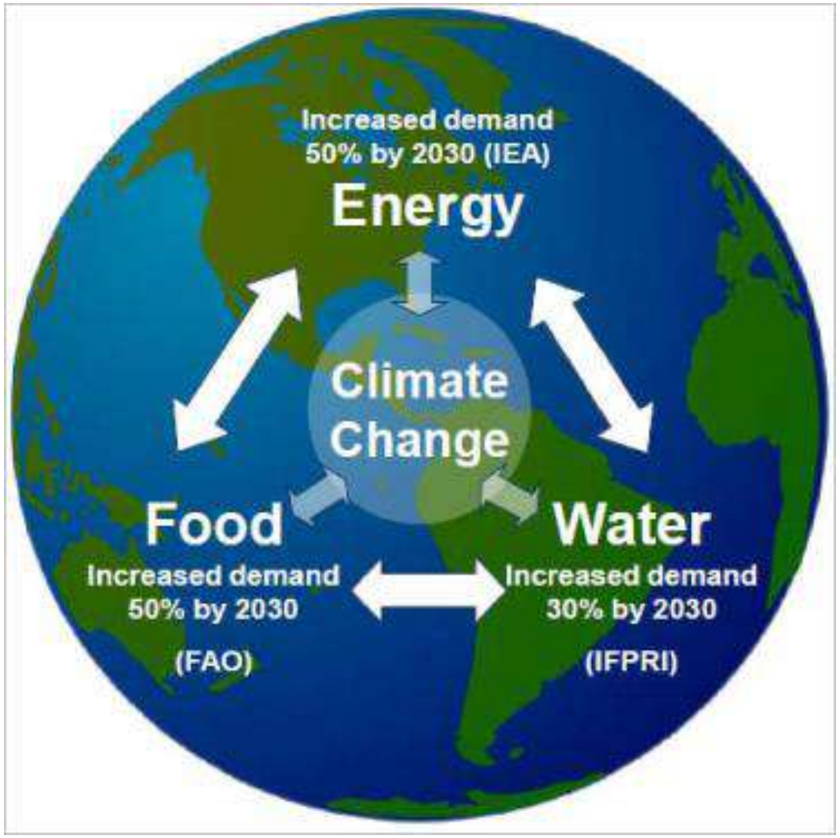


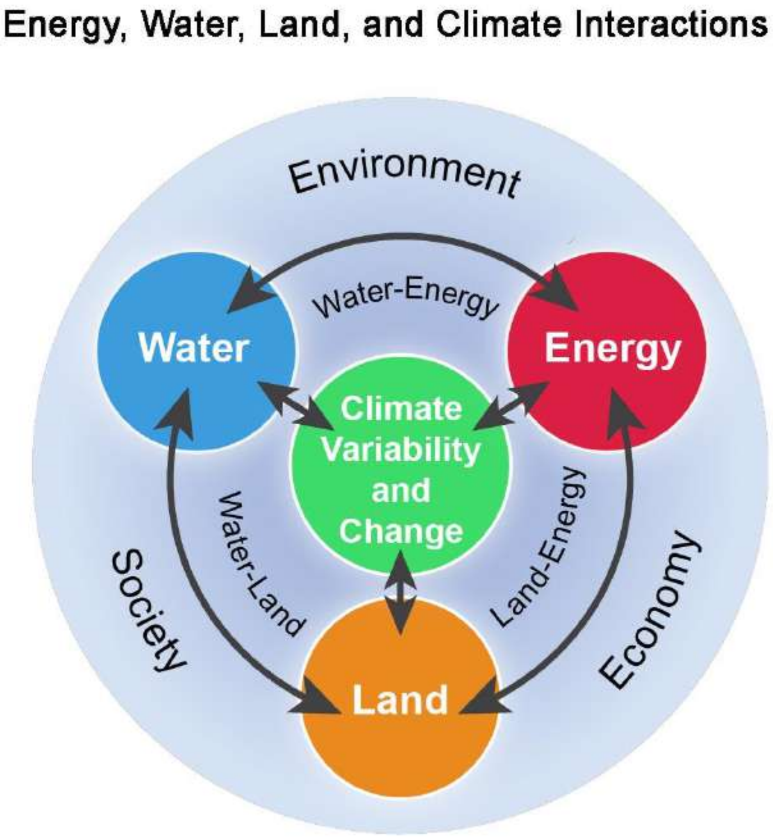


1-D : Economic, Sociology, Environmental
2-D : Eco-efficiency, Socio-economic, Socio-ecological
3-D : Sustainability

Bakshi, *CEP* 2003

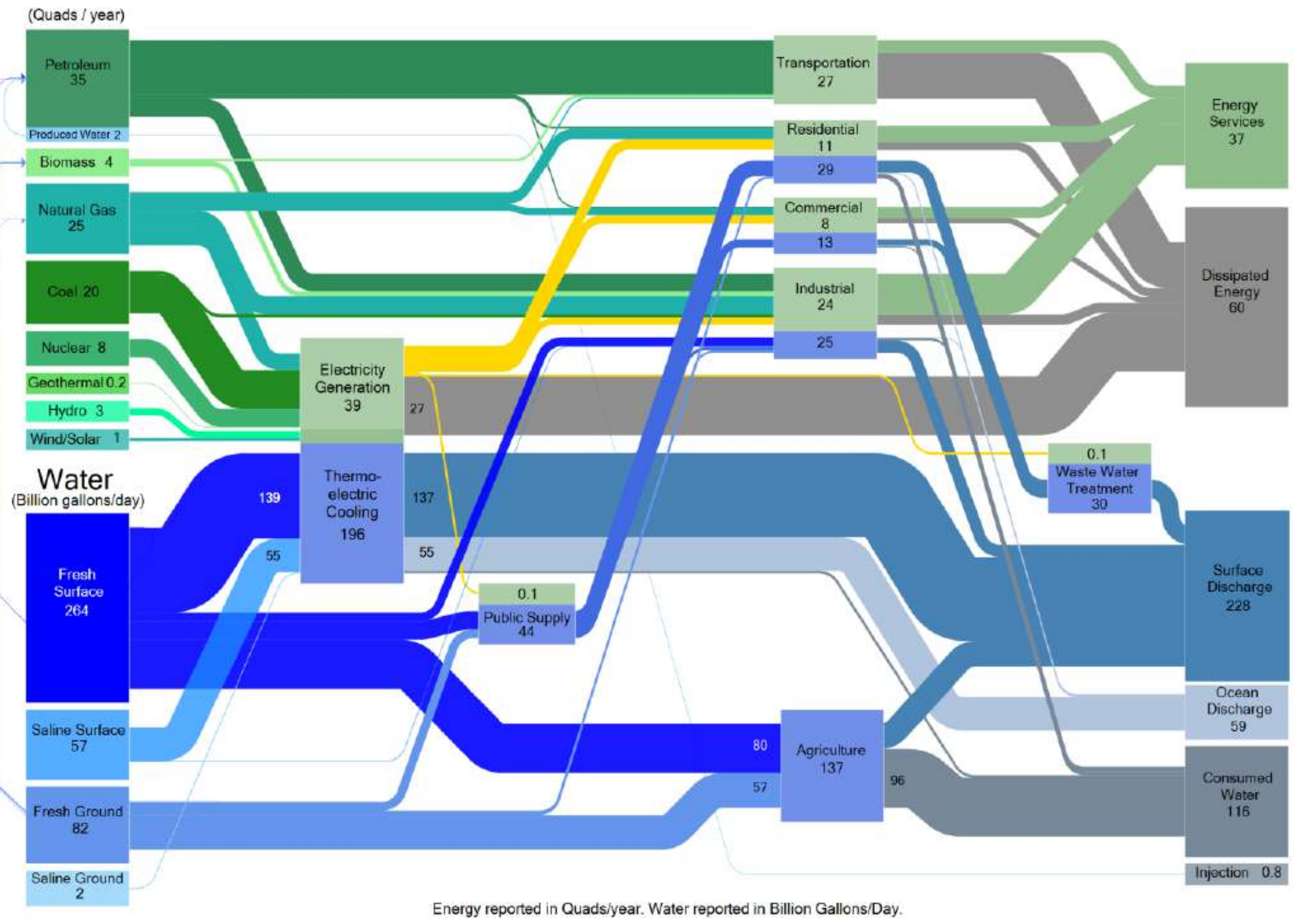
Water-Energy-Food Nexus





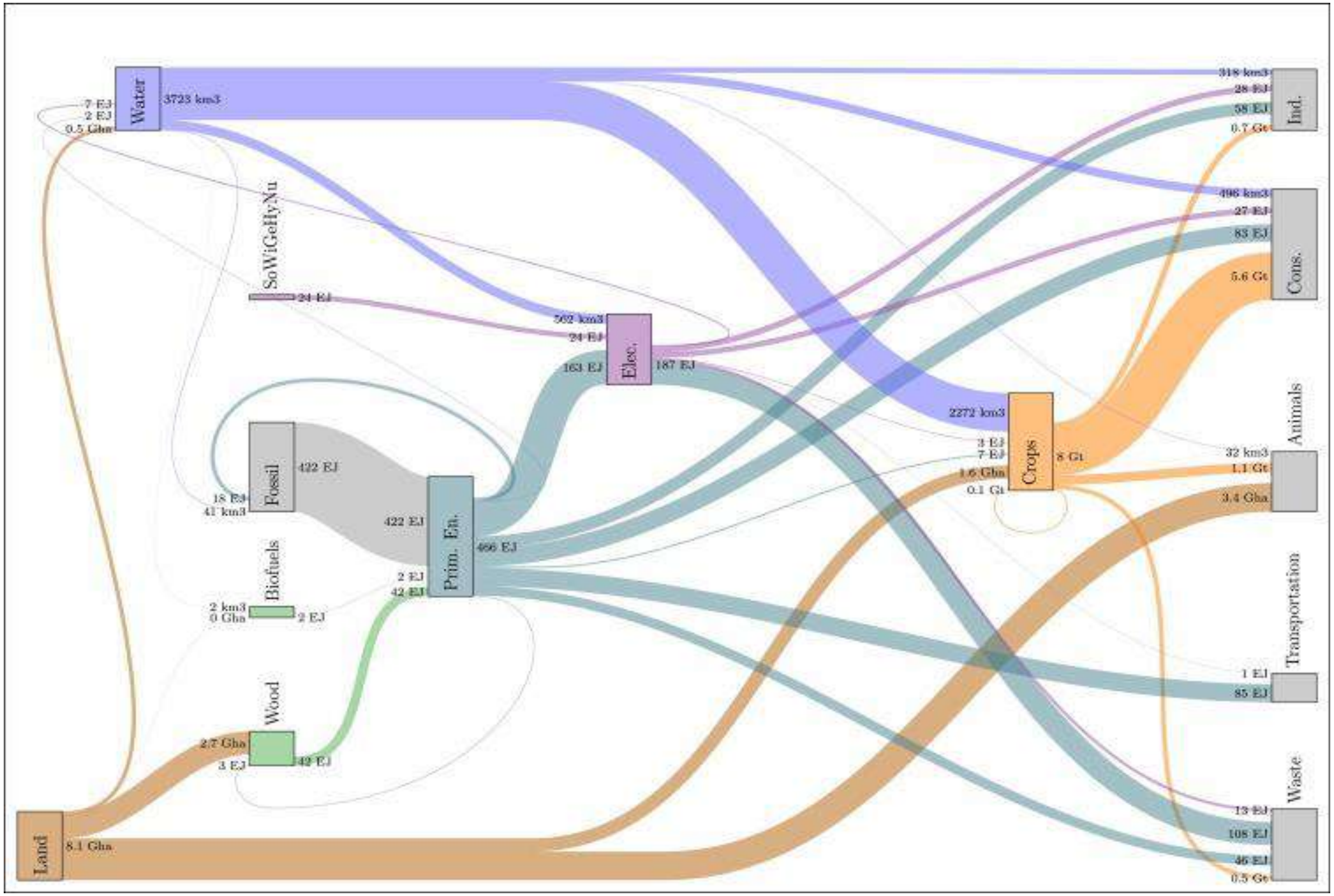
Source: GlobalChange.gov

Energy-water flows



Source: DOE

Nexus resource flows



Source: Bijl et al, 2018

Smart & Variable System

Smart Energy System

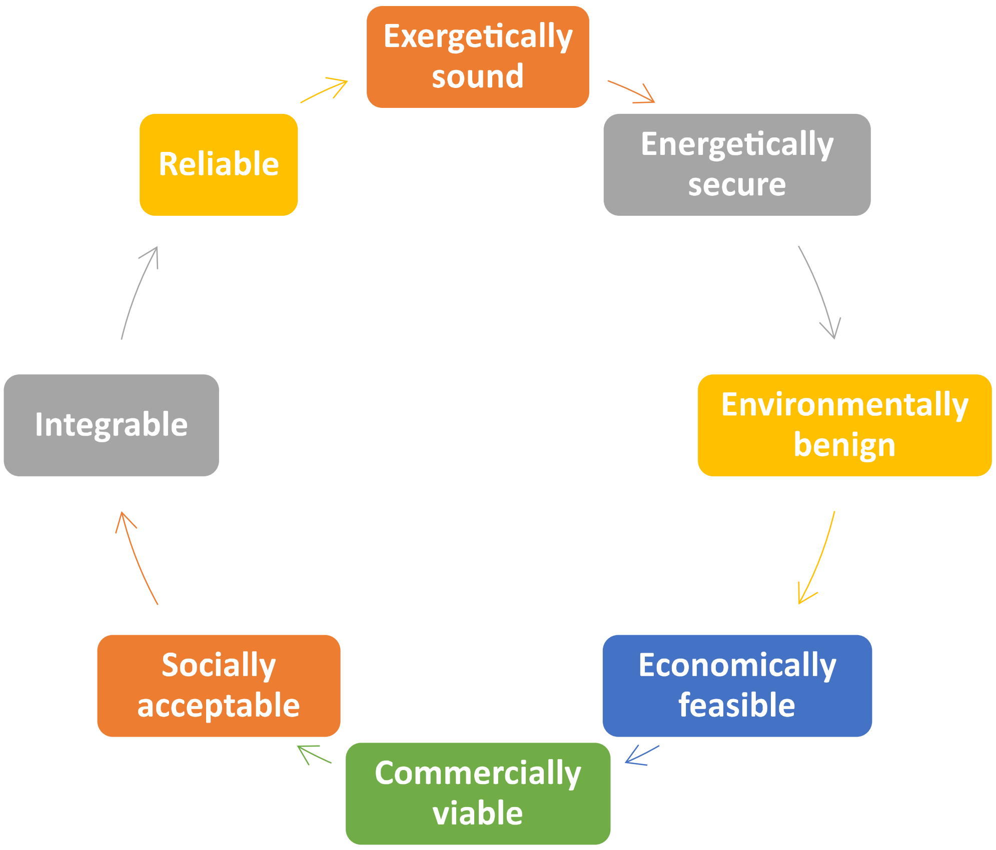
A **Smart Energy System** is defined as an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system [5,6].

The smart energy system is built around three grid infrastructures:

- ✓ ***Smart Electricity Grids*** to connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources such as wind and solar power.
- ✓ ***Smart Thermal Grids*** (District Heating and Cooling) to connect the electricity and heating sectors. This enables the utilisation of thermal storage for creating additional flexibility and the recycling of heat losses in the energy system.
- ✓ ***Smart Gas Grids*** to connect the electricity, heating, and transport sectors. This enables the utilisation of gas storage for creating additional flexibility. If the gas is refined to a liquid fuel, then liquid fuel storages can also be utilised.

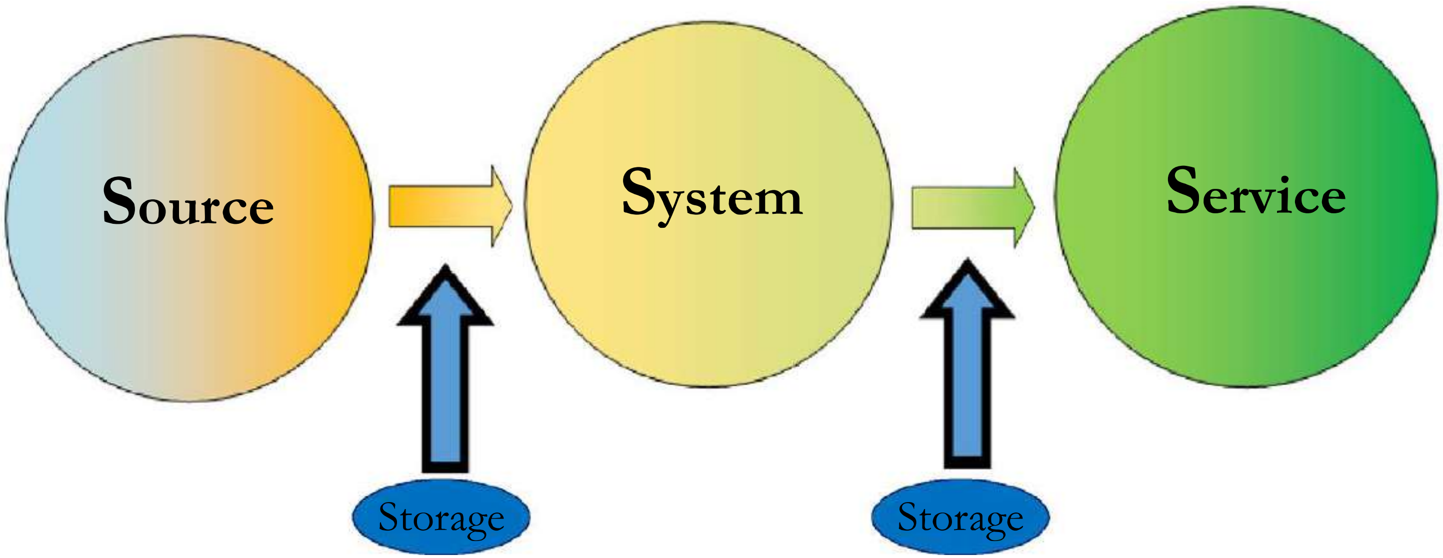
Source: Lund: 2017

Major expectations from smart energy systems



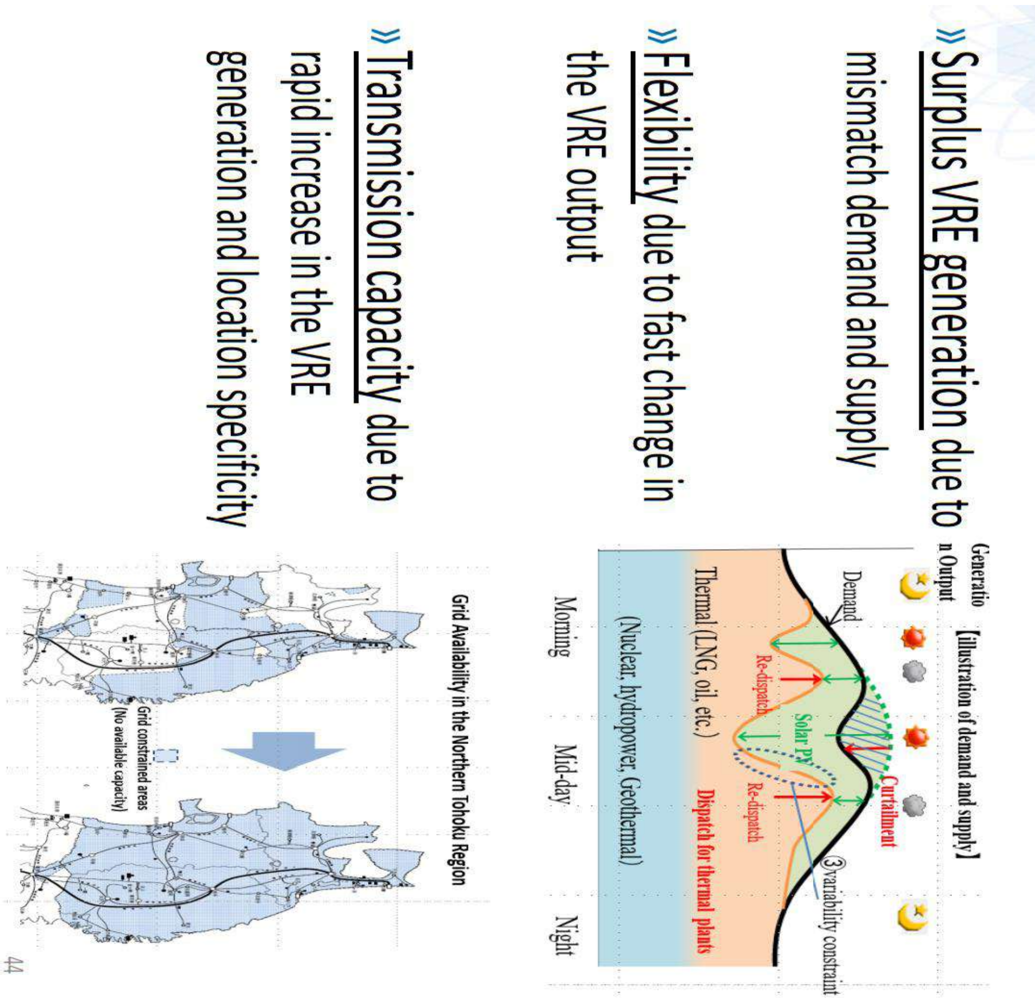
Source: Dincer, 2017

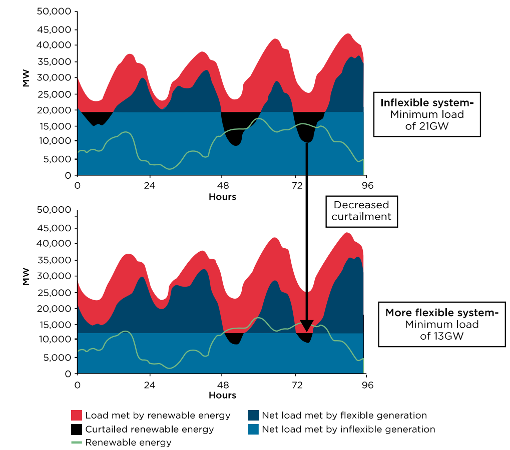
Smart targets for smart energy systems from 3S approach



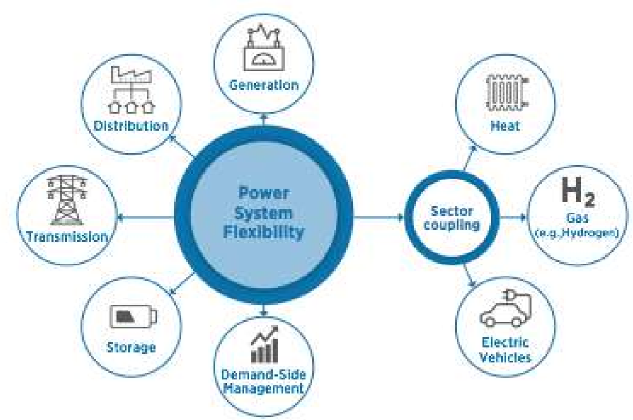
Source: Dincer, 2017

VRE integration system



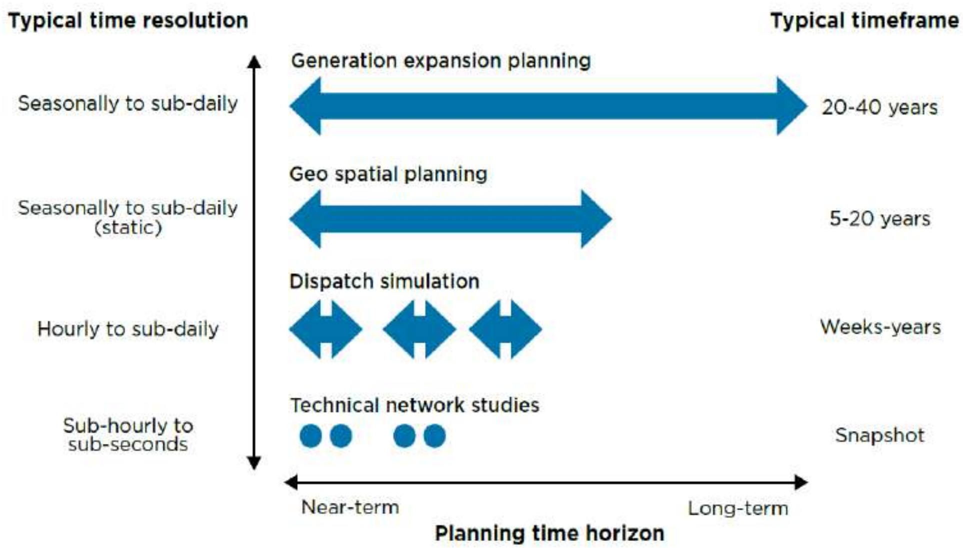


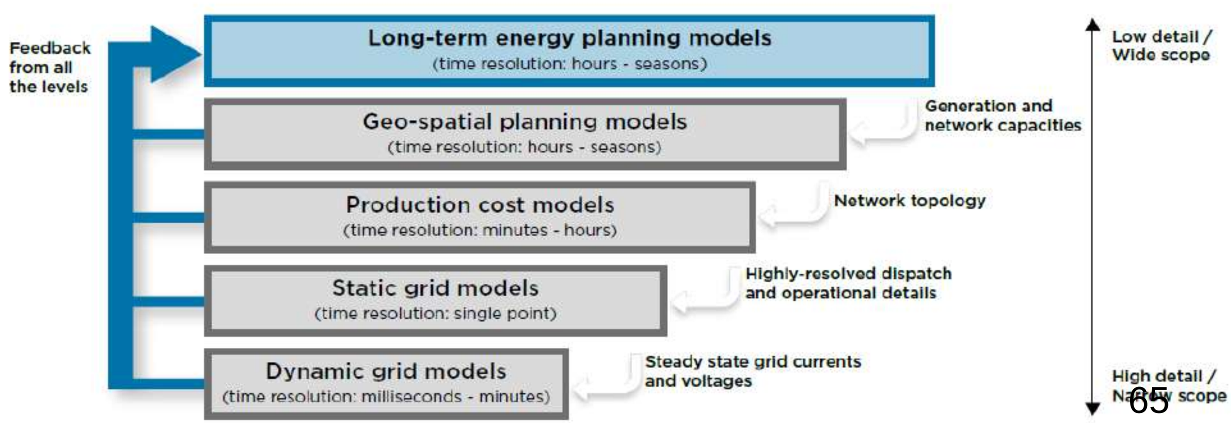
Source: Denholm and Hand, 2011



Source: IRENA

Transition planning components and time horizon





System engineering for DMP

Energy services
Resources
Context & Constraints

System Boundaries

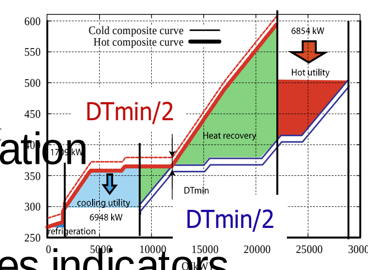
Technology options

Models

Technologies Thermodynamics Economics Environmental impact

Process Superstructure

Heat &
Mass integration



System performances indicators

- Economic
- Thermodynamic
- Life cycle environmental impact

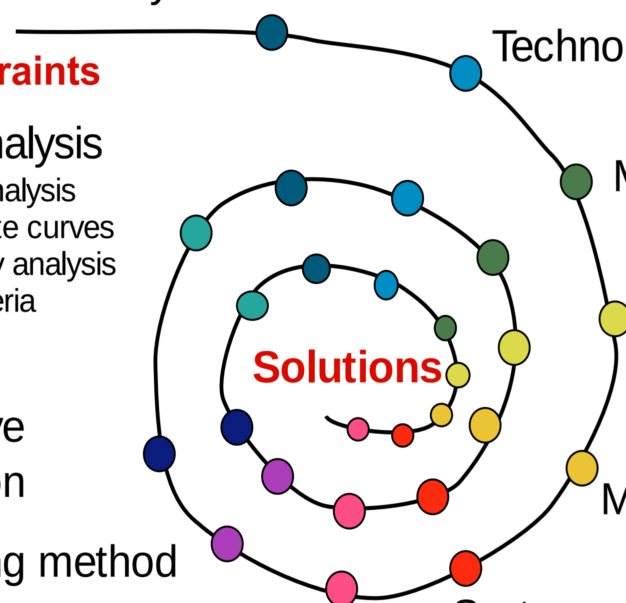
Decision variables

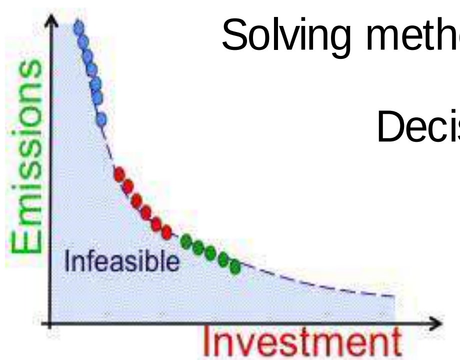
Solving method

Multi-objective
Optimization

Results analysis

- Exergy analysis
- Composite curves
- Sensitivity analysis
- Multi-criteria



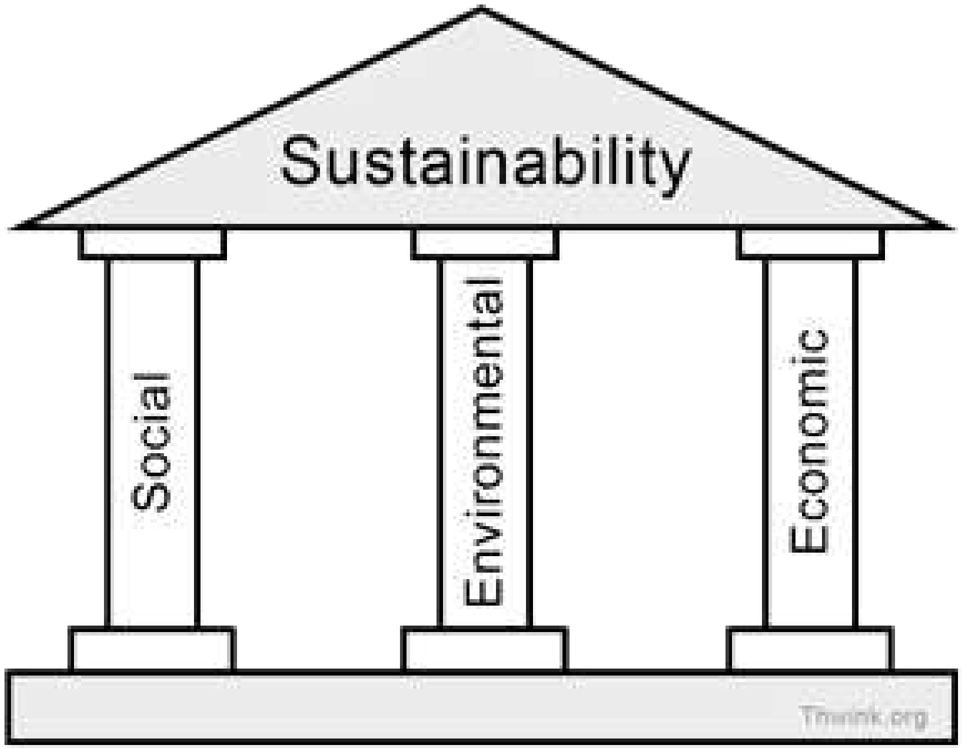


Thermo-economic Pareto

Source: EPFL

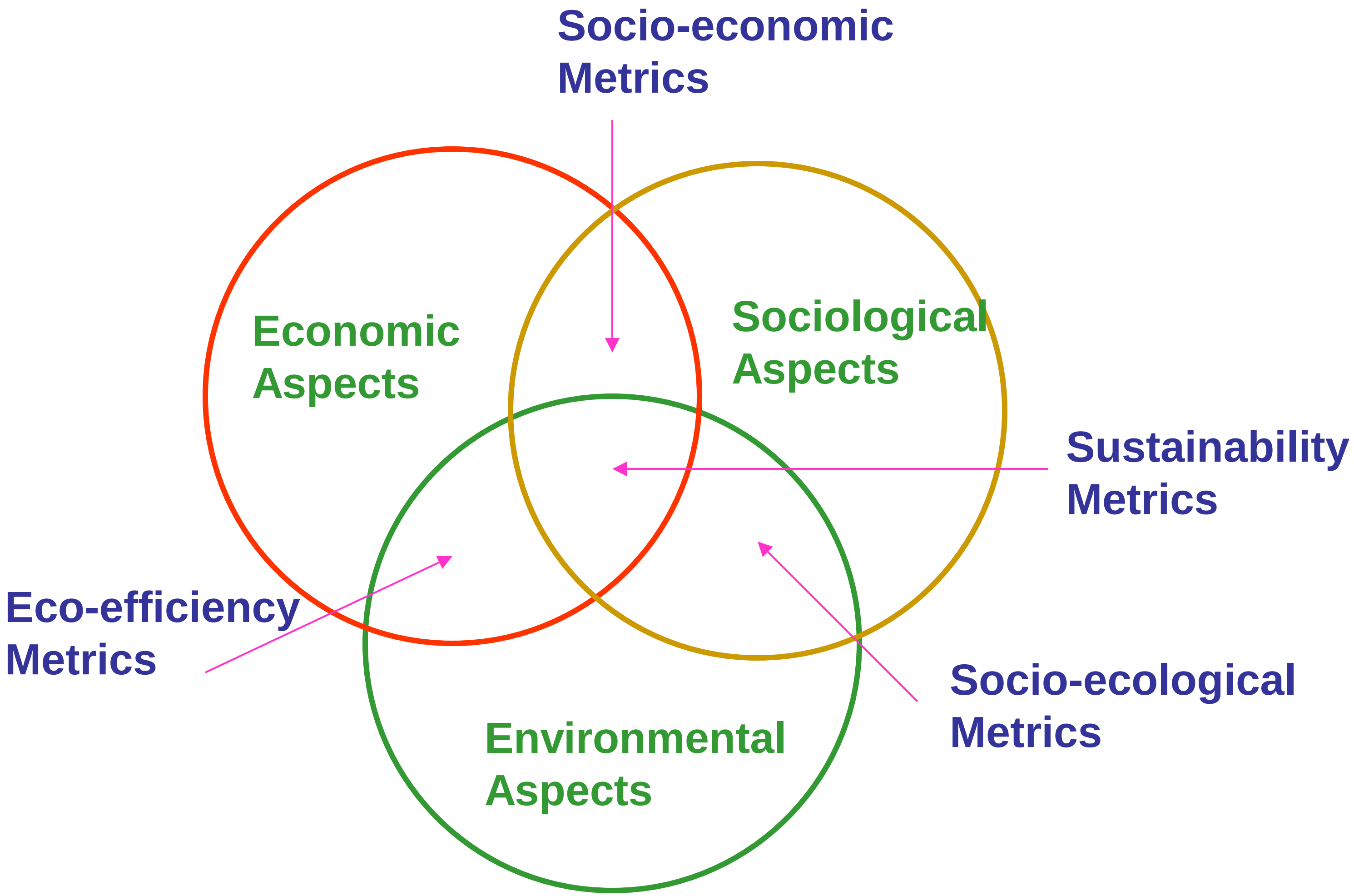
Concept of Sustainability

The Three Pillars of Sustainability



Sustainability focuses on meeting the needs of the present without compromising the ability of future generations to meet their needs

Metric for Sustainability



1-D : Economic, Sociology, Environmental
2-D : Eco-efficiency, Socio-economic, Socio-ecological
3-D : Sustainability

(Sikdar, 2003)

Types of Sustainability Systems

Type I: Global concerns:
global warming, genetically modified crops

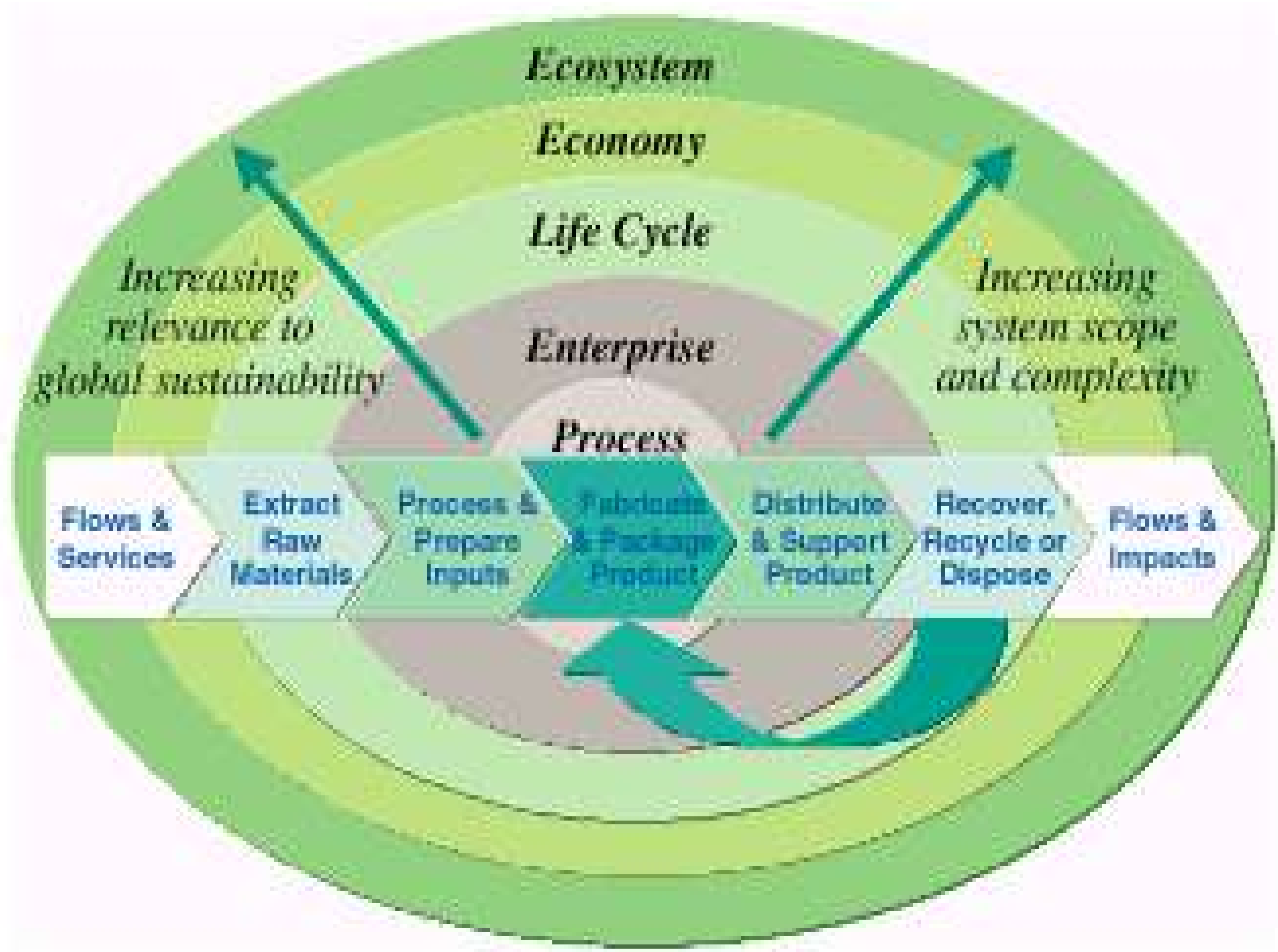
Type II: Geographical boundaries systems:
country, Cities, villages

Type III: Businesses/Corporate: *industrial ecology*

Type IV: Sustainable technologies: *process and product designs, manufacturing methods*

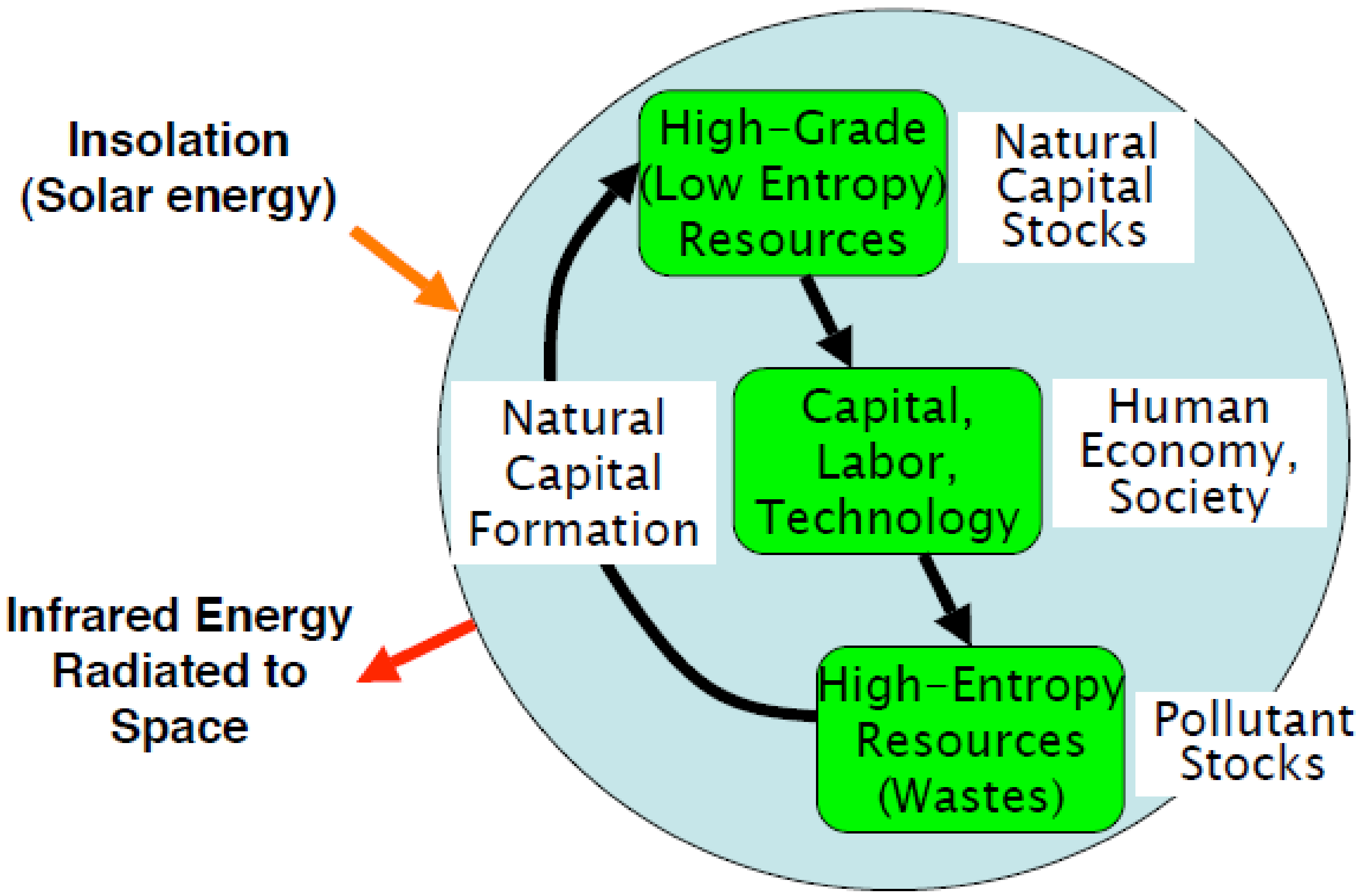
(Sikdar, 2003)

Hierarchy of sustainable systems



(Bakshi, 2003)

A Finite Planet



Sustainability Frameworks

Natural Capitalism:

(Eco-efficiency)

- **Natural Capital:** materials, energy, stability, diversity
- **Human Capital:** people & society
- **Manufactured Capital:** materials, energy, and IP
- **Financial Capital:** money

Necessary Conditions for a Sustainable World

1. **Renewable resources**

   can be used no faster than the rate at which they regenerate.

2. **Pollution and wastes**

   can be emitted no faster than natural systems can absorb them, recycle them, or render them harmless.

3. **Nonrenewable resources**

   can be used no faster than renewable substitutes for them can be introduced.

Source: Herman Daly

The ‘IPAT’ equation

I = P x A x T

I = *Global environmental* ***impact***

P = ***Population***

A = *Affluence (Level of* ***services used)***

T = *Technology used (resource or waste assimilation* ***efficiency****)*

IPAT

Impact = Population * Affluence * Technology

Example:

$$\text{CO2 Emissions} = \text{Population} * \frac{\text{Income}}{\text{Capita}} * \frac{\text{Emissions}}{\text{Dollar}}$$

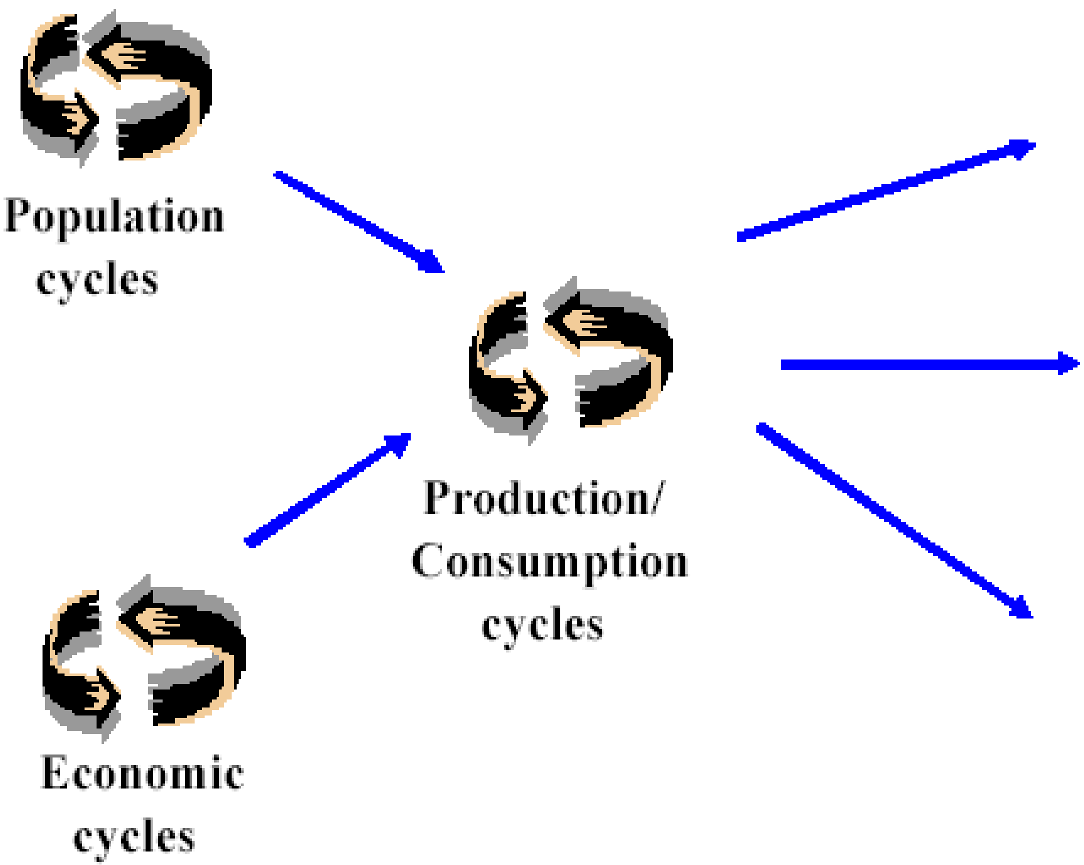
$$\frac{\text{Tons}}{\text{year}} = \text{People} * \frac{\text{\$/Year}}{\text{Person}} * \frac{\text{Tons}}{\text{\$}}$$

How will we achieve sustainability?

- Better Technology?
- Lower Consumption?
- Lower Population?

- Huge technical, economic, political, social and ethical issues for each
- All options linked by intricate feedbacks

Engines of "More"



ULTIMATE RISKS

GROSS INEQUITY: Poverty, Wars, Mass migration

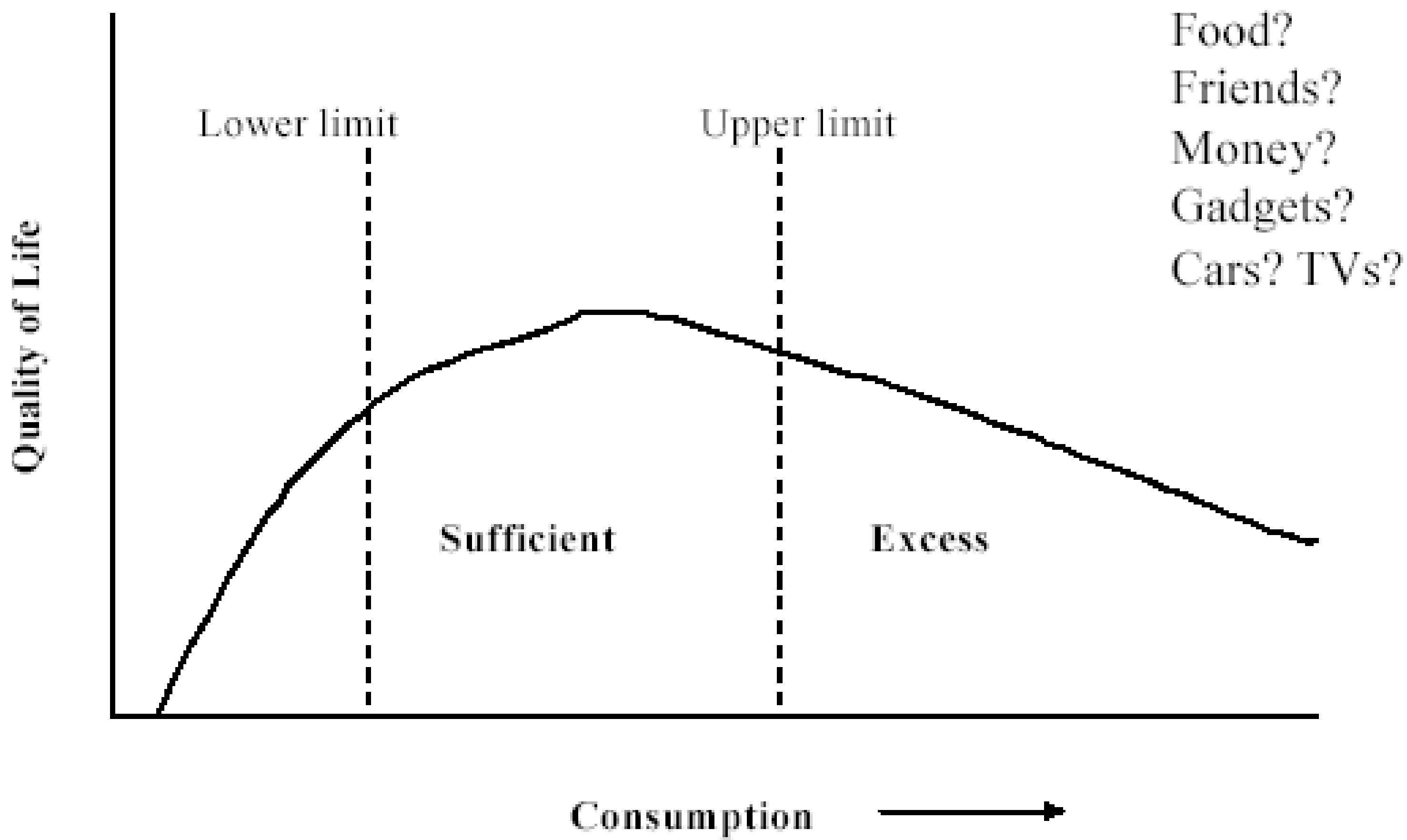
ENVIRONMENTAL DAMAGE: Climate Change, Pollution, Habitat/Species loss, Ecosystem disruption

INSTITUTIONAL COLLAPSE: Govts. and Businesses

RESOURCE DEPLETION: Water, Materials. and Non-renewable Energy

HUMAN HEALTH IMPAIRMENT

Thring's model



White's Law

"Culture advances as the quantity and quality of energy used increases. This relationship can be captured formally as an equation."

$$C = k \times E \times T$$

Leslie White, 1973

C = culture

E = energy

T = technology

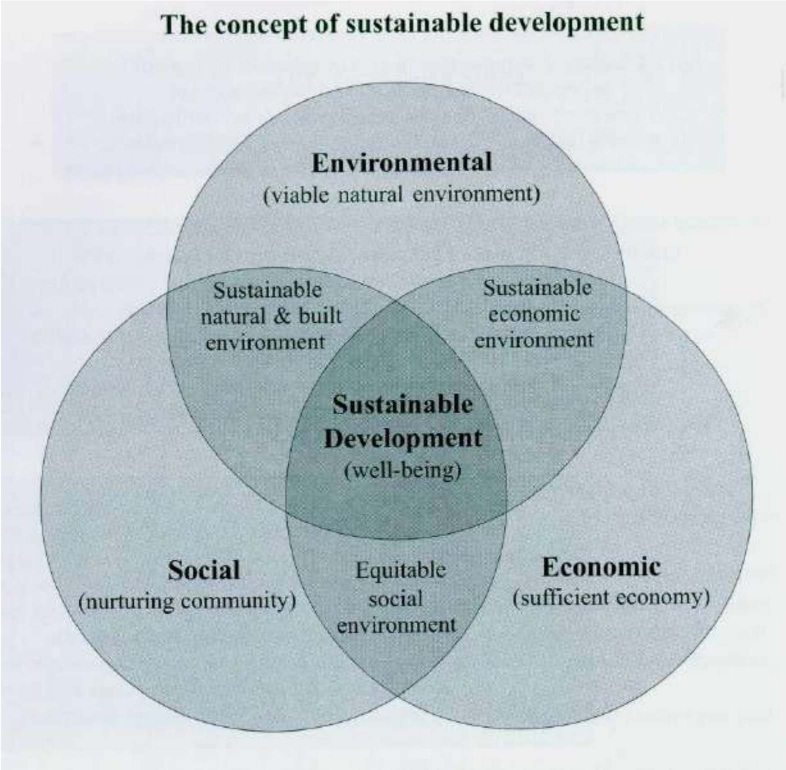
k = scaling (efficiency) constant

What is sustainable energy?

What is Sustainable Development

"development that which satisfies present needs without compromising the possibility for future generations to satisfy theirs own needs" (The Brundtland Report, Our Common Future)

Sustainable development
aims to balance three elements



- **Economic:** what things cost - and how to make a business out of providing infrastructure, goods or services
- **Environmental:** what impact those things have on nature and the earth's support systems - which are finite
- **Social:** how those things serve the needs and quality of life of people and their communities

What is Sustainable Energy

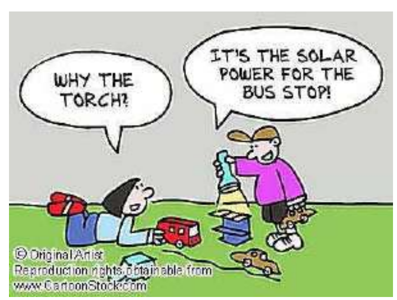
- *“Sustainable Energy is a dynamic harmony between equitable availability of energy-intensive goods and services to all people and perservation of the earth for future generation” (Tester, MIT)*

- *“Sustainable Energy’ is energy systems, technologies, and resources that are not only capable of supporting long-term economic and human development needs, but that do so in a manner compatible with (1) preserving the underlying integrity of essential natural systems, including averting catastrophic climate change; (2) extending basic energy services to the more than 2 billion people worldwide who currently lack access to modern forms of energy; and (3) reducing the security risks and potential for geopolitical conflict that could otherwise arise from an escalating competition for unevenly distributed oil and natural gas resources. In other words, the term ‘sustainable’ in this context encompasses a host of policy objectives beyond mere supply adequacy.”. (InterAcademy Council)*

What is the difference between sustainable and renewable energy?

- People often use the terms “sustainable” and “renewable” interchangeably.
- Sustainable energy is derived from resources that can maintain current operations without jeopardizing the energy needs or climate of future generations. The most popular sources of sustainable energy, including wind, solar and hydropower, low carbon, are also renewable.
- On the other hand, renewable energy is defined by the time it takes to replenish the primary energy resource, compared to the rate at which energy is used.

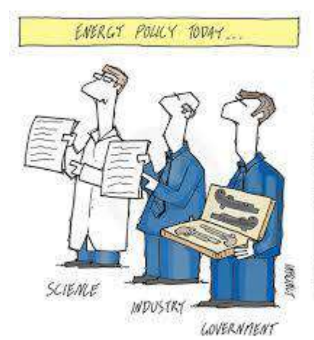
The energy hierarchy



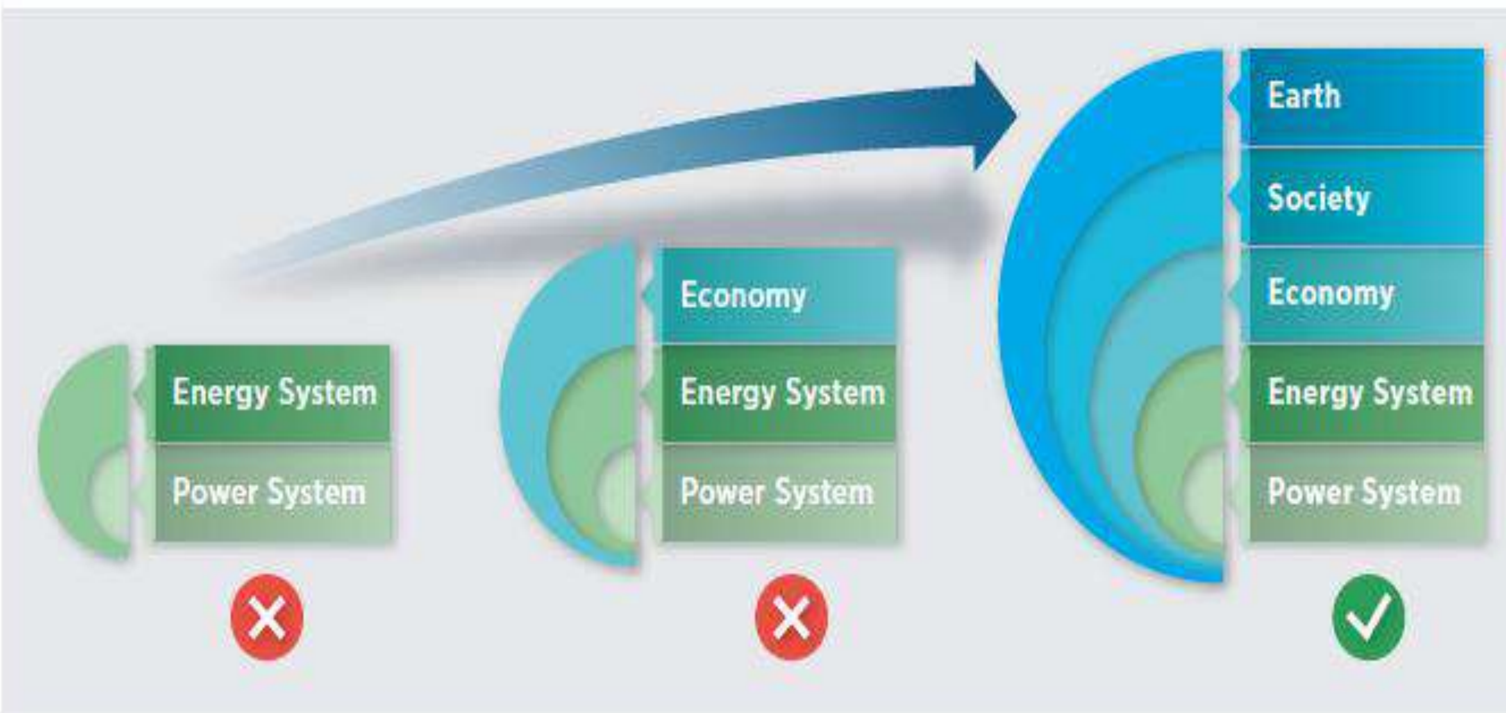
Reference energy system

Primary Energy Supply	Conversion Technologies	End-Use Technologies	Demand for Energy Service
Renewables e.g. -Biomass -Hydro	Fuel processing plants e.g. -Oil refineries -Hydrogen plant -Ethanol plants	Industry, e.g. -Steam boilers -Machinery	Industry, e.g. -Process steam -Motive power
Mining e.g. -Crude oil -Natural gas -Coal	Power plants e.g. -Solar -Wind -Nuclear -CCGT -Fuel Cells	Services, e.g. -Air conditioners -Light bulbs	Services, e.g. -Cooling -Lighting
Imports e.g. -oil products		Households, e.g. -Space heaters -Refrigerators	Households, e.g. -Space heat -Refrigeration
Exports		Agriculture, e.g. -Irrigation pumps	Agriculture, e.g. -Water supply
Stock changes		Transport, e.g. -Gasoline Car -Fuel Cell Bus	Transport, e.g. -Person-km

Energy-economic-environment-social relationships



The embedded nature of the energy system



Source: IRENA (2019b)

UN Sustainable Development Goals (SDG7)

We need cleaner, affordable, local and abundant sources of energy

Source: IRENA, 2017

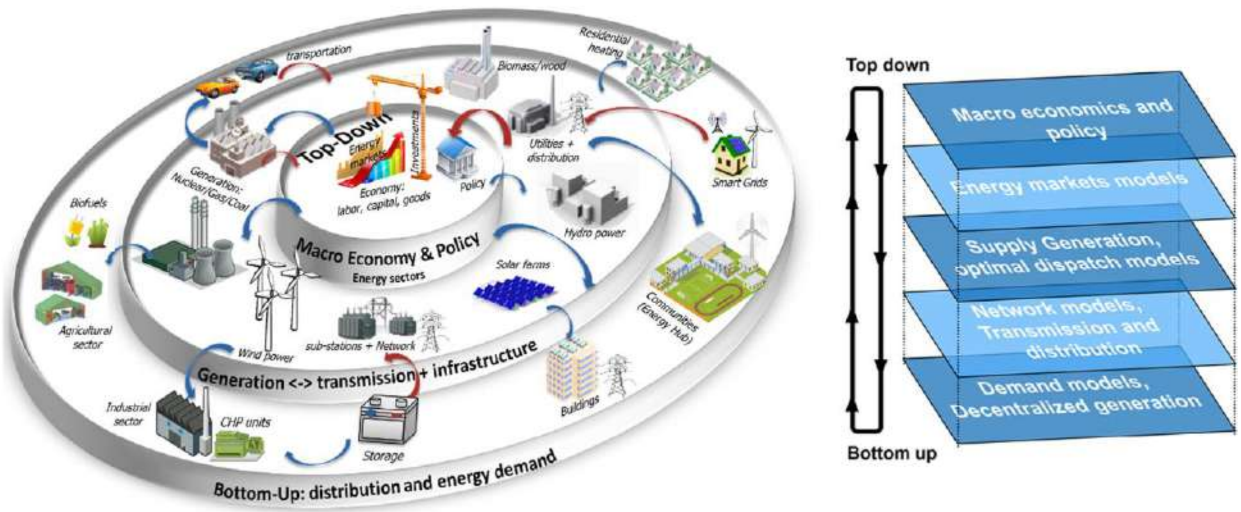
What is the relationship between energy use and environmental damage?

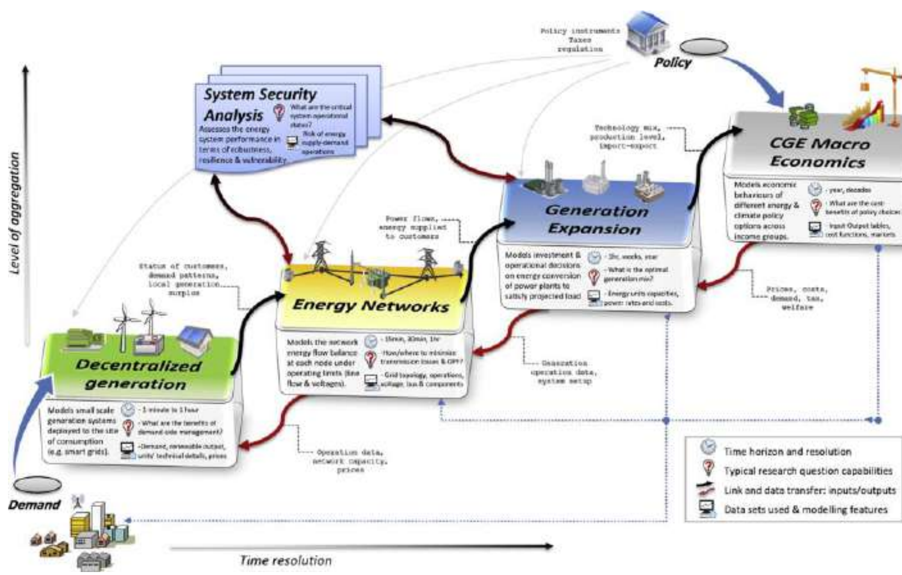
- Which energy resources are the most environmentally destructive?
- Which energy resources are the most environmentally benign?
- Is our current consumption of energy sustainable?
- Which energy resources are sustainable?
- What are the negative consequences, if any, of switching from fossil fuels to other forms of energy?

What is the relationship between energy use and development?

- Does increasing energy consumption cause wealth or is it a result of wealth?
- Must per capital energy consumption increase to improve our standard of living?
- What link, if any, exists between our culture and energy consumption?
- How is economic development measured?

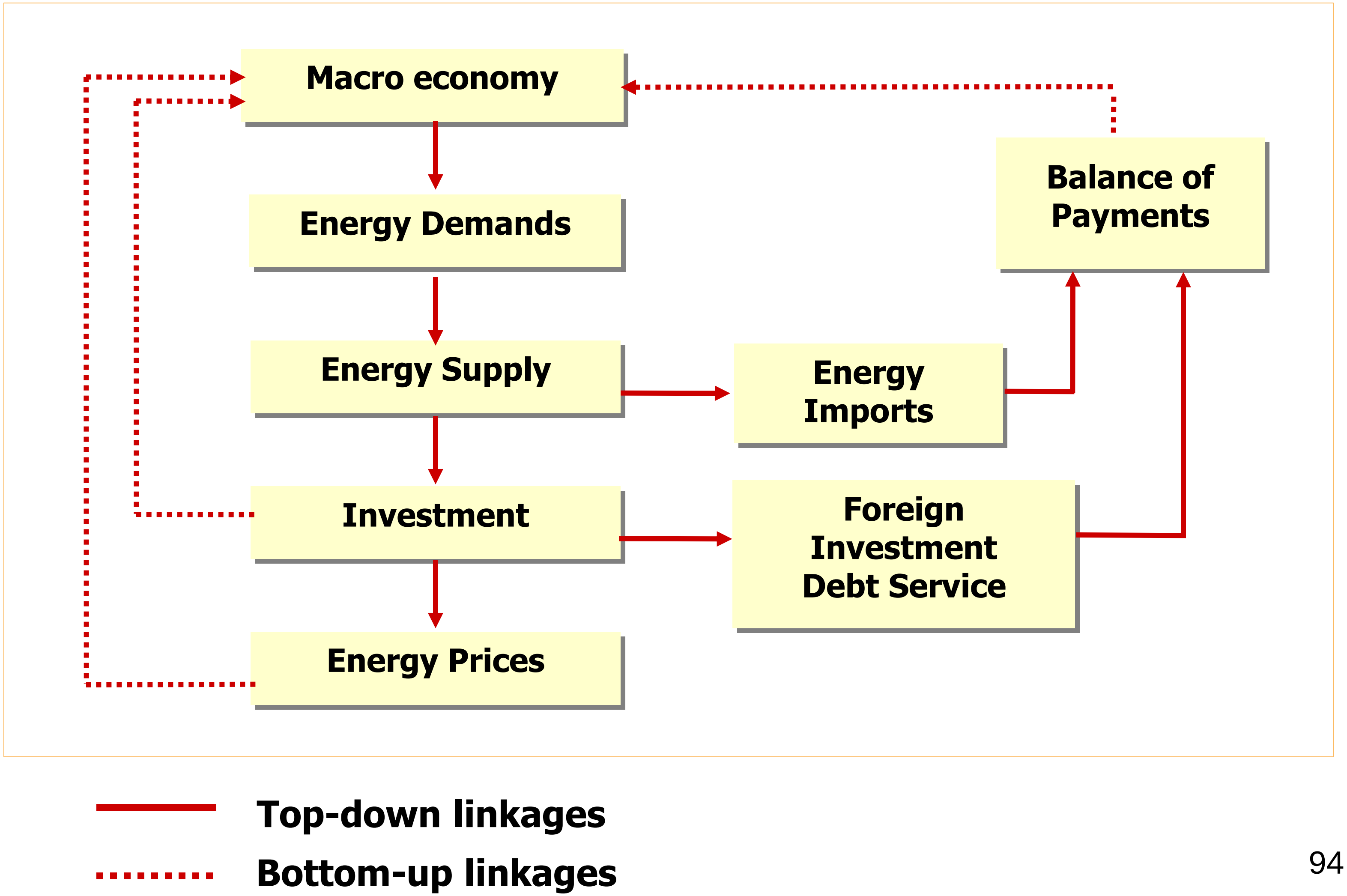
Energy-economic system





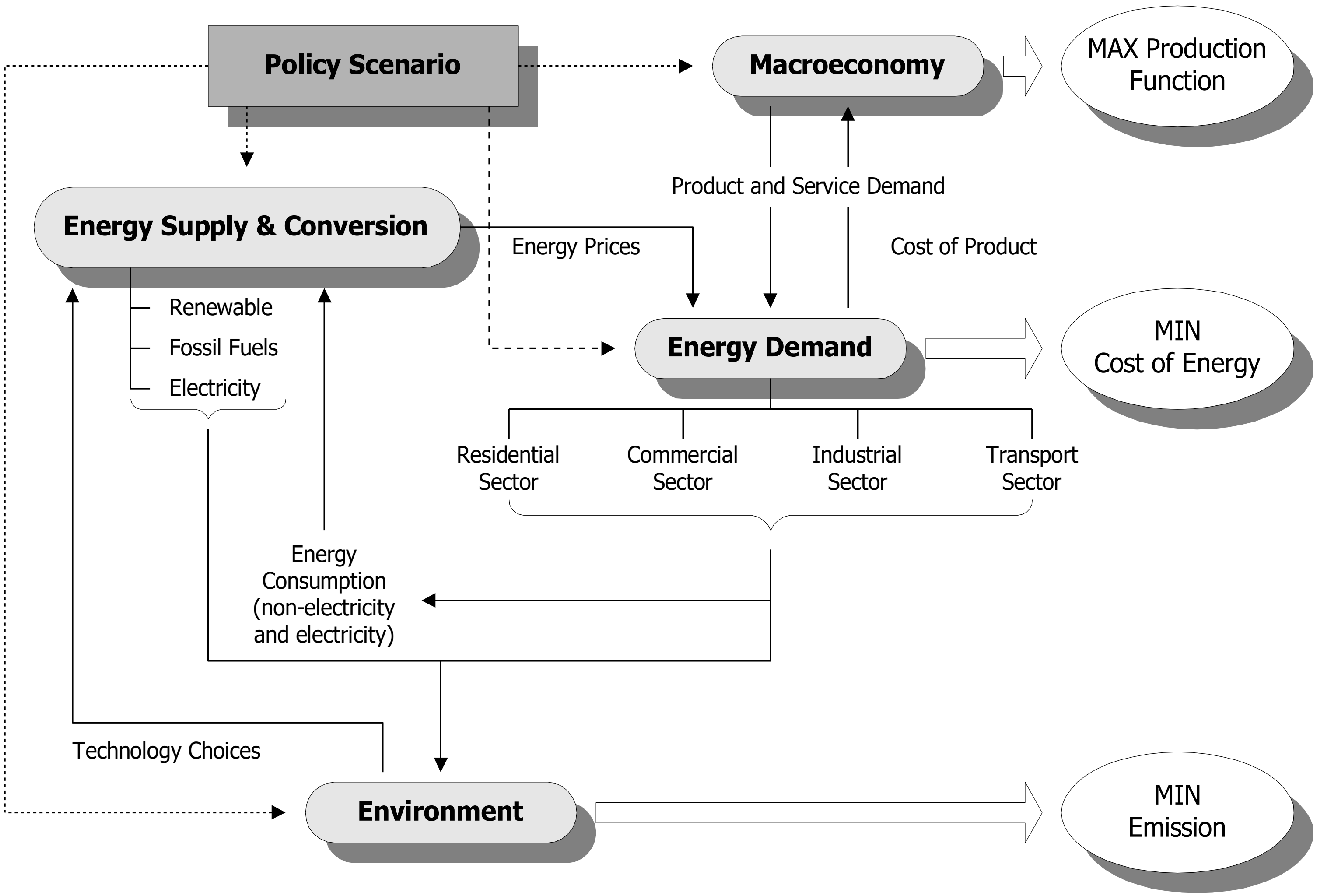
Source: Crespo, 2018

Energy-Economy Linkages

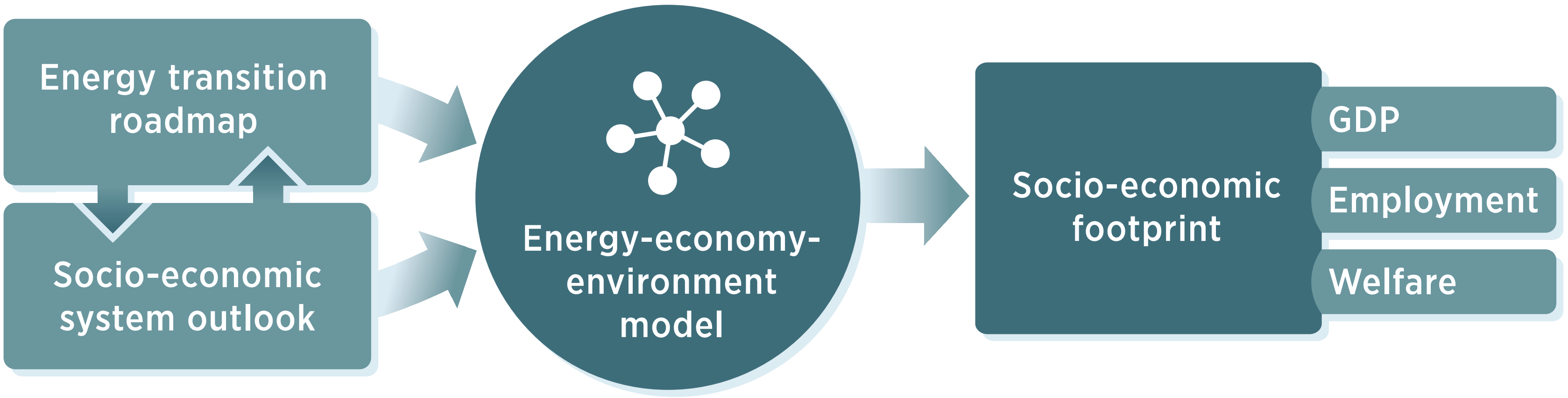


Source: Munasinghe

Energy-Economy-Environment Linkages

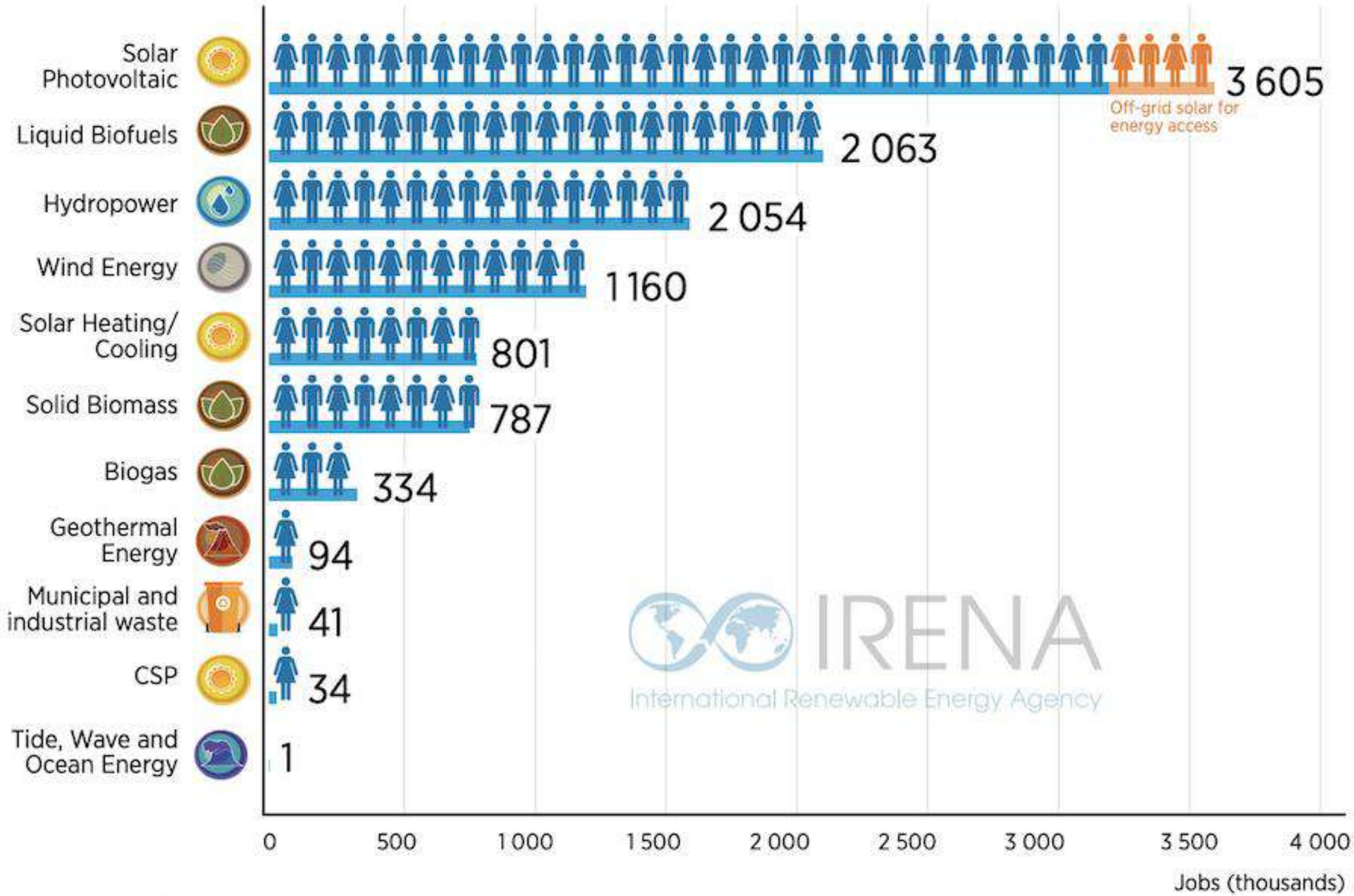


Energy-socio-economic



Source: IRENA

FIGURE 5: **RENEWABLE ENERGY EMPLOYMENT BY TECHNOLOGY**

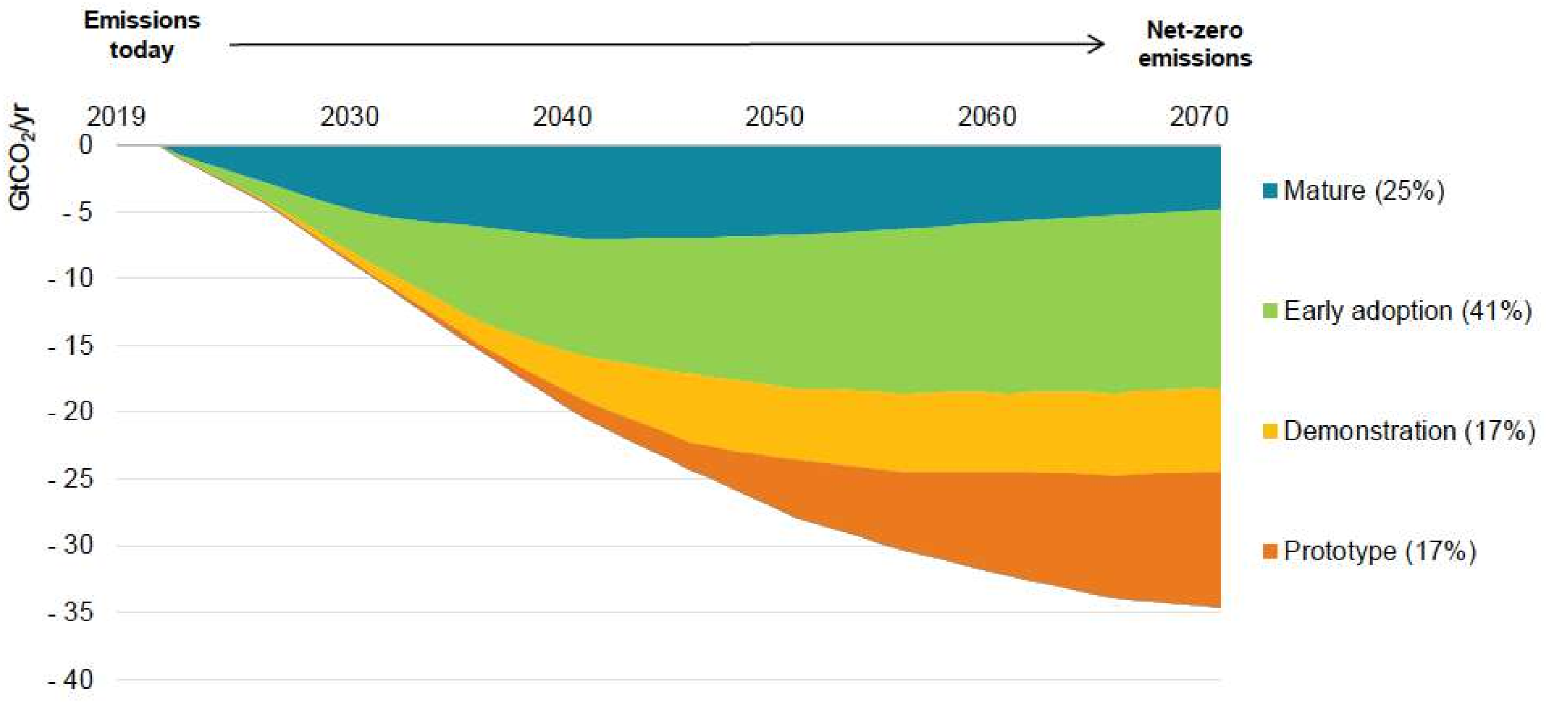


Source: IRENA jobs database.

Note: Another 7600 jobs, not shown separately here, cannot readily be broken down by individual renewable energy technology.

Key enablers technologies for sustainable energy systems transition

CO_2 emissions reductions by current technology readiness category

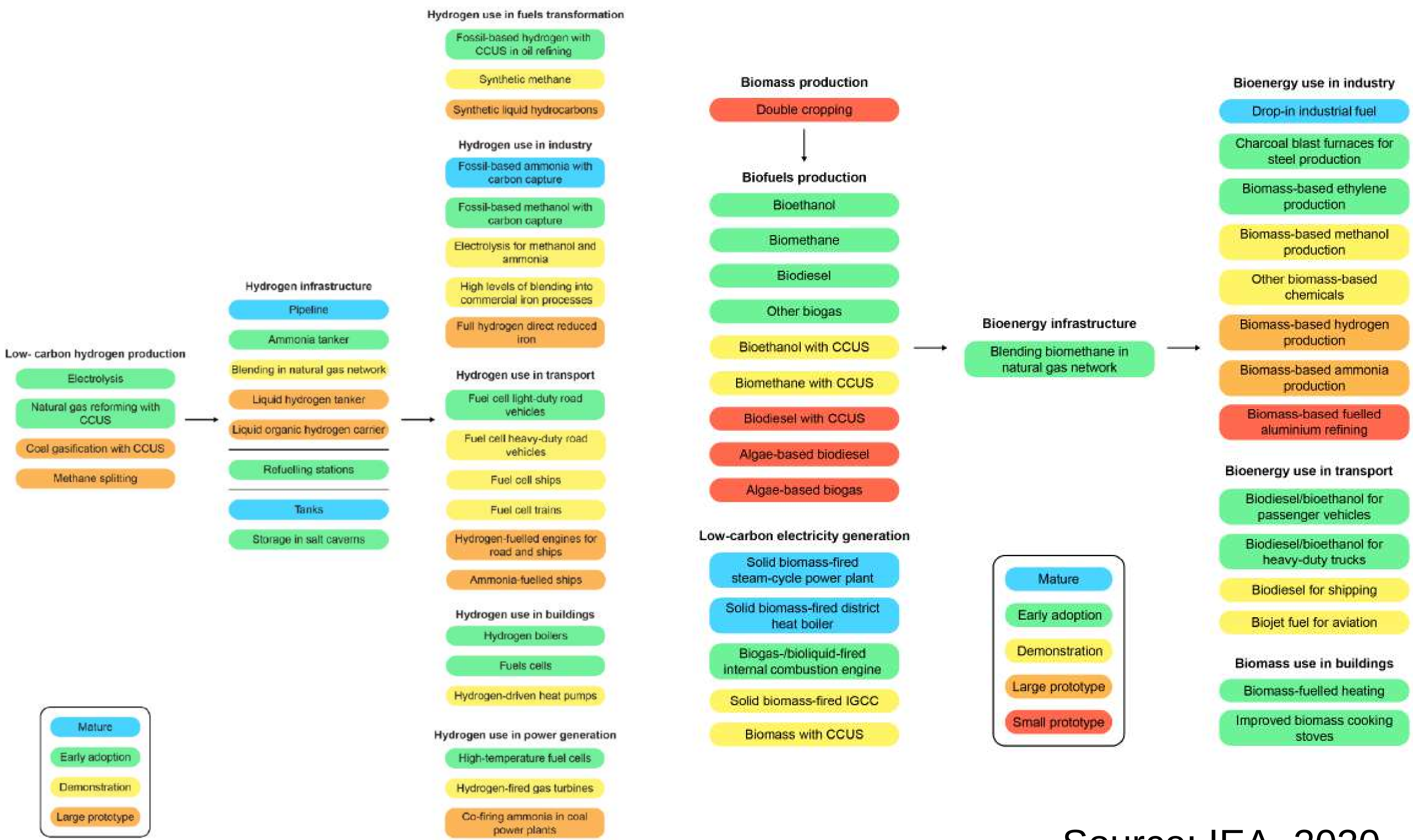


Source: IEA, 2020

TRL of Low-carbon electricity and CO_2 value chains

Source: IEA, 2020

TRL of Low-carbon hydrogen and bioenergy value chains



Source: IEA, 2020

Power generation performances

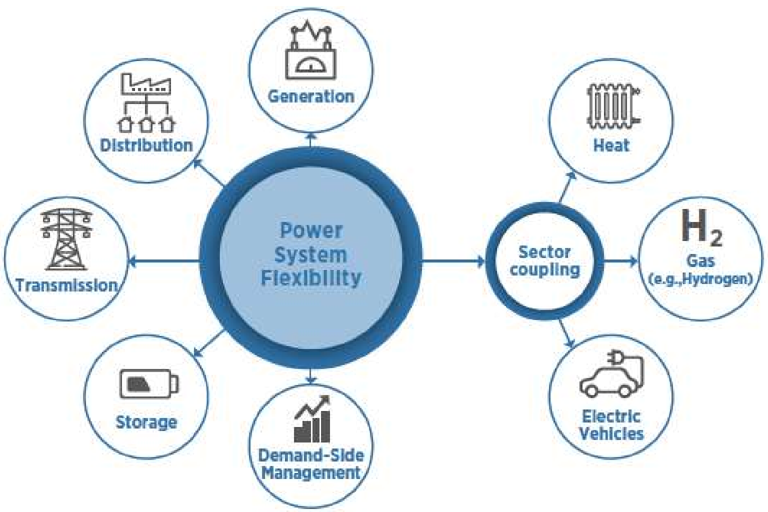
- **Energy efficiency** (%), **Heat rate** (mmbtu/kWh)
- **LCOE** (cent UD/kWh)
- **Carbon footprint** (CO_2e/kWh)
- **Power flexibility**

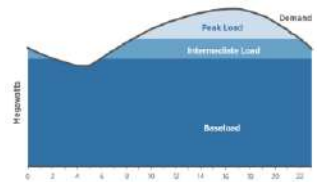
Power system flexibility – *the ability to respond in a timely manner to variations in electricity supply and demand*

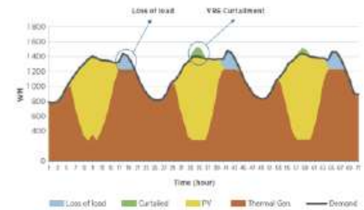
- **System values**

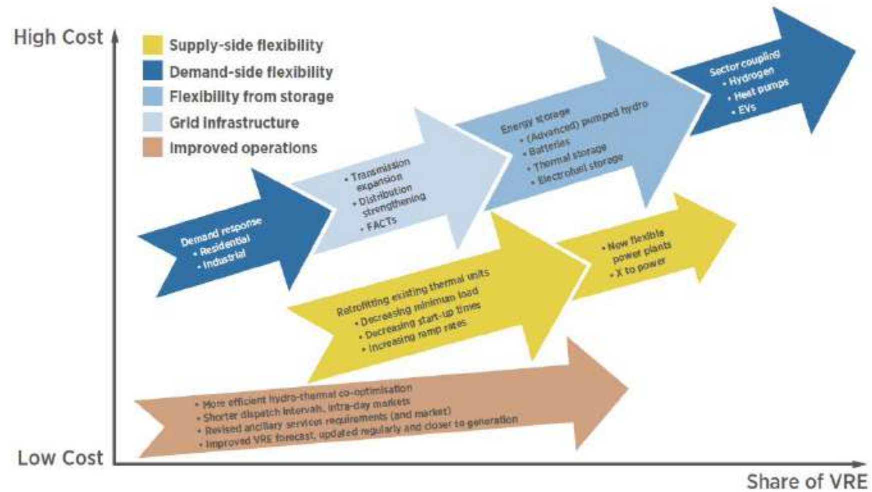
The System Value – *more holistically evaluates economic, environmental, social and technical outcomes of potential energy solutions across markets.*

Power system flexibility enablers



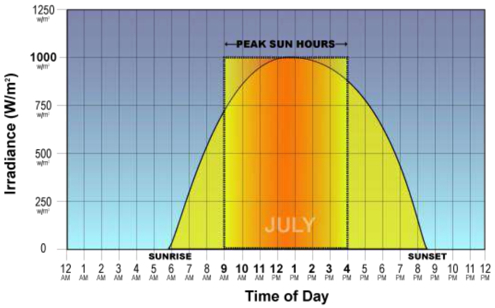


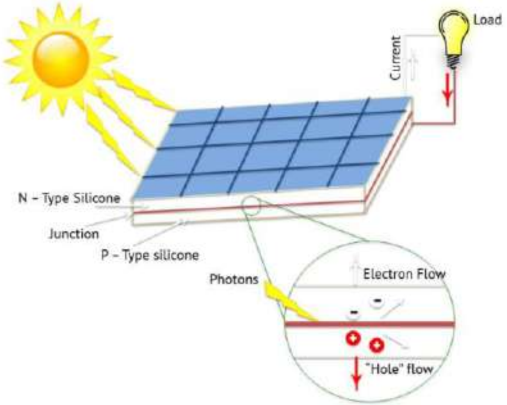




Source: IRENA, 2018

Solar to electricity





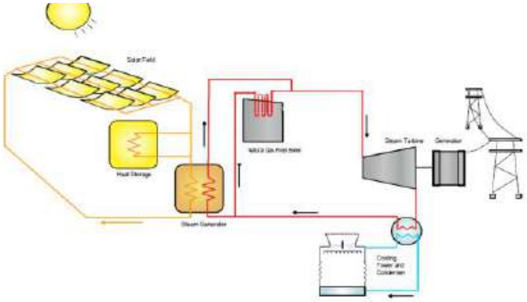
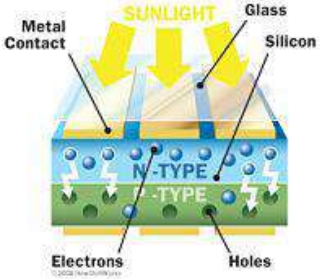
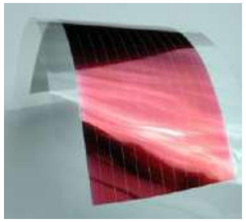
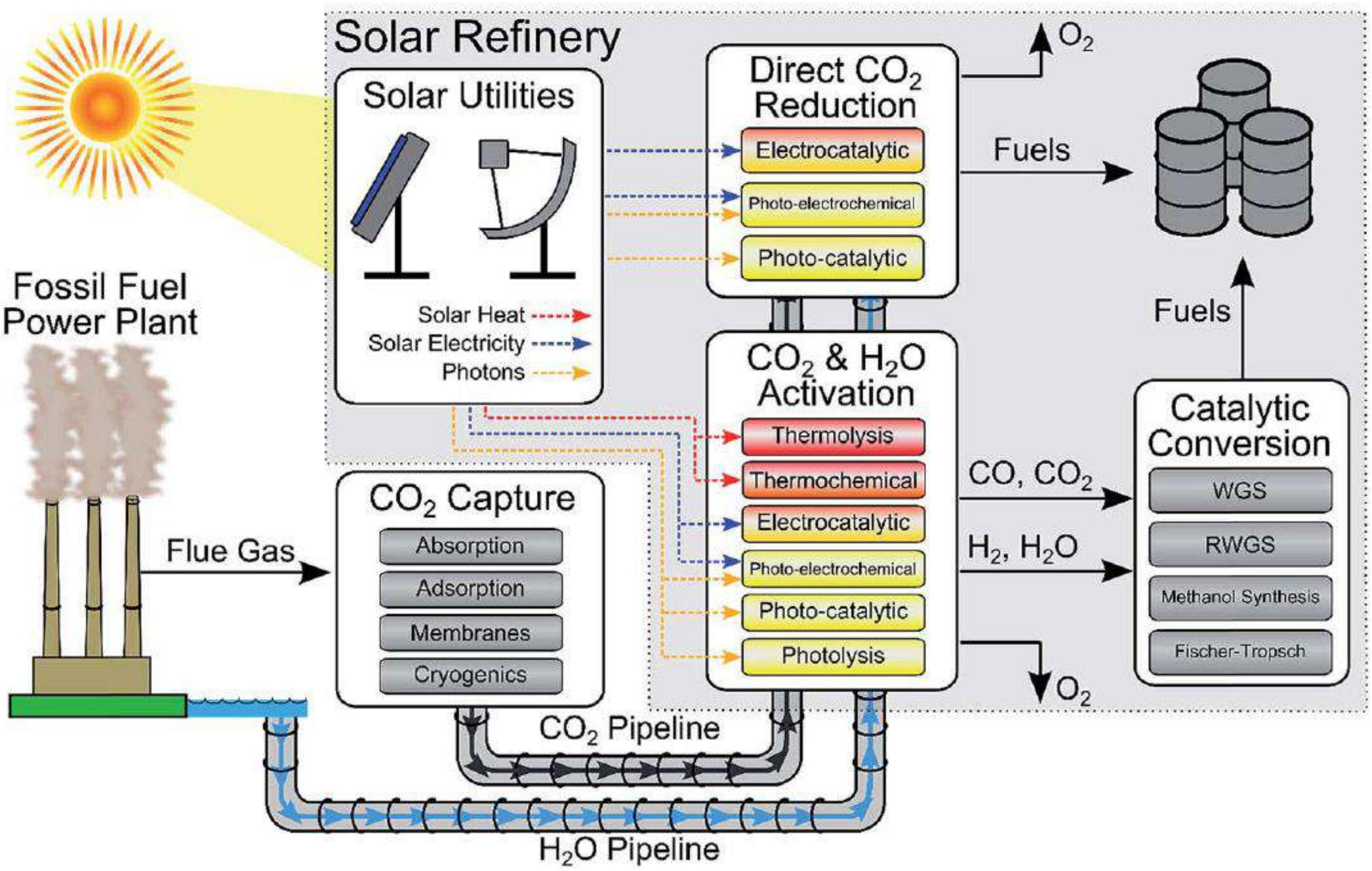


Figure 5-2: Process diagram of a trough plant





Solar Refinery



Source:Herron et al., 2015

Solar Fuels

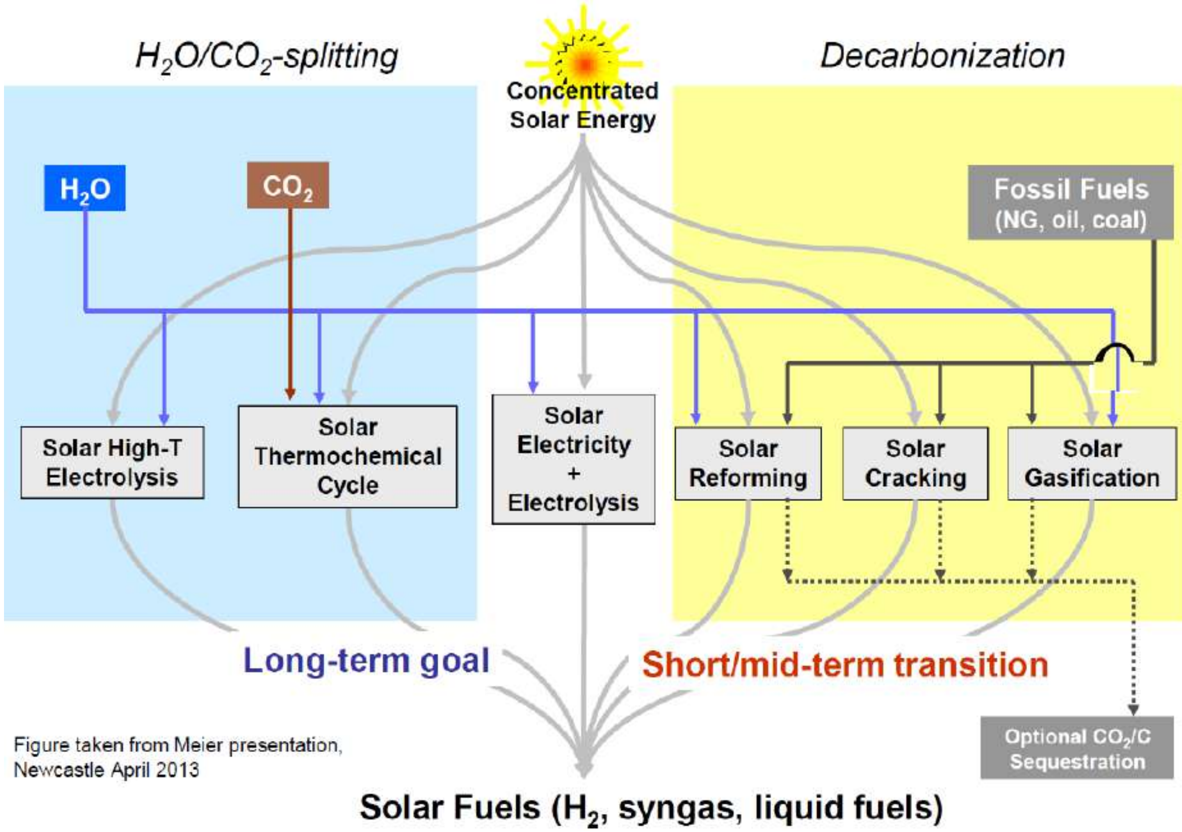
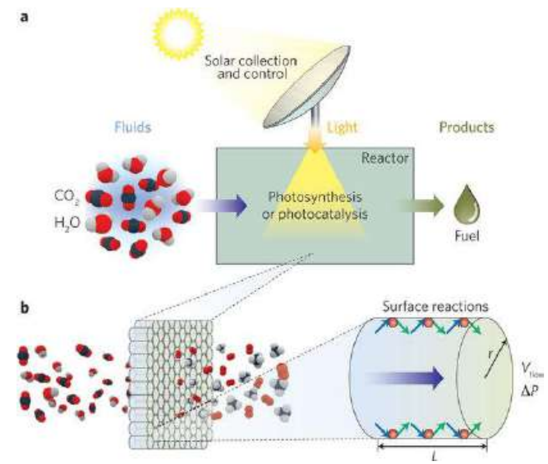
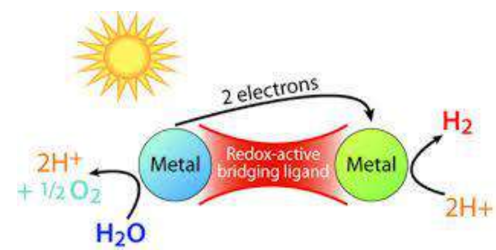


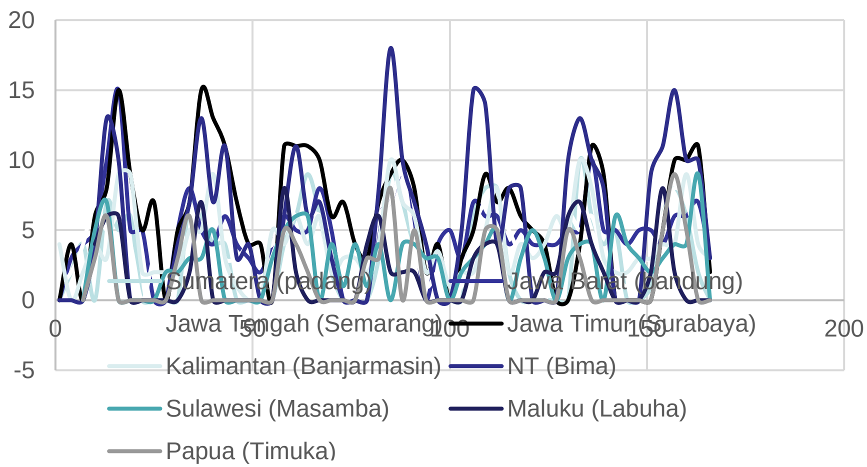
Figure taken from Meier presentation, Newcastle April 2013



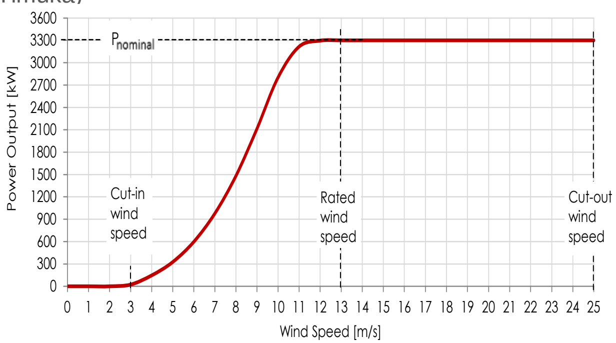


Source: ITP, Erickson et al, 2011

Wind power



20
15
10
5
0
-5
0
50
100
150
200
Sumatera (padang)
Jawa Barat (Bandung)
Jawa Tengah (Semarang)
Jawa Timur (Surabaya)
Kalimantan (Banjarmasin)
NT (Bima)
Sulawesi (Masamba)
Maluku (Labuha)
Papua (Timuka)



Power Output [kW]
3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
$P_{nominal}$
Cut-in wind speed
Rated wind speed
Cut-out wind speed
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Wind Speed [m/s]

Hydro power & Geothermal power

The available power can be expressed as:

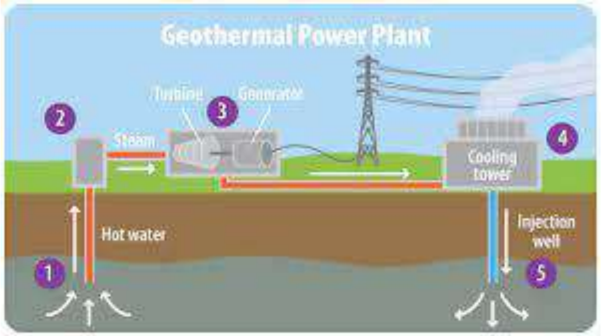
$$P = \eta \rho Q g h$$

where
$\mathbf{P}$ = available power (W)
η = efficiency of the turbine (0,8)
ρ = density of water (1000 kg/m^3)
$\mathbf{Q}$ = water flow (m^3/s)
$\mathbf{g}$ = acceleration due to gravity (9,81 m/s^2)
$\mathbf{h}$ = height (m)

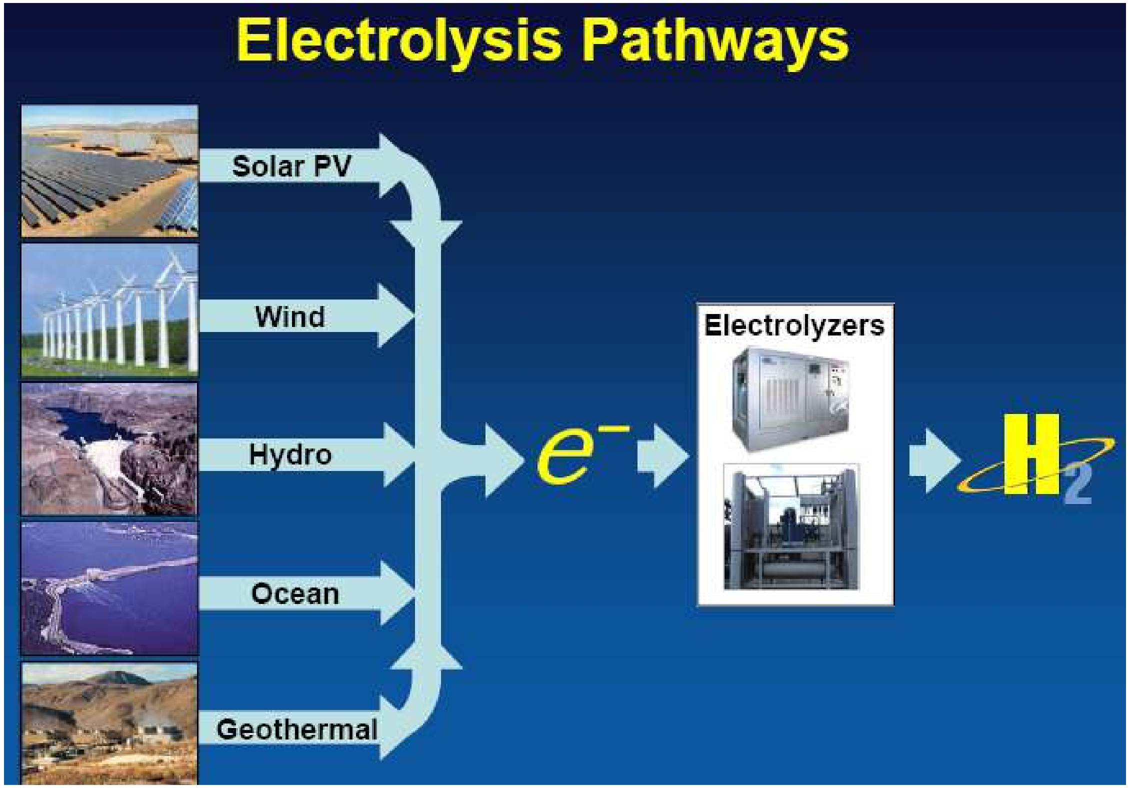

Run of the River plants


Storage hydropower

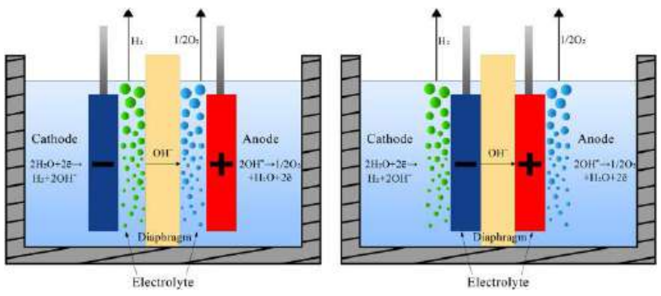

Pumped hydro storage

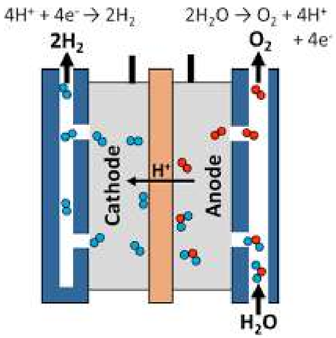


Green hydrogen via PtG



Electrolyzers: Alkaline & PEM





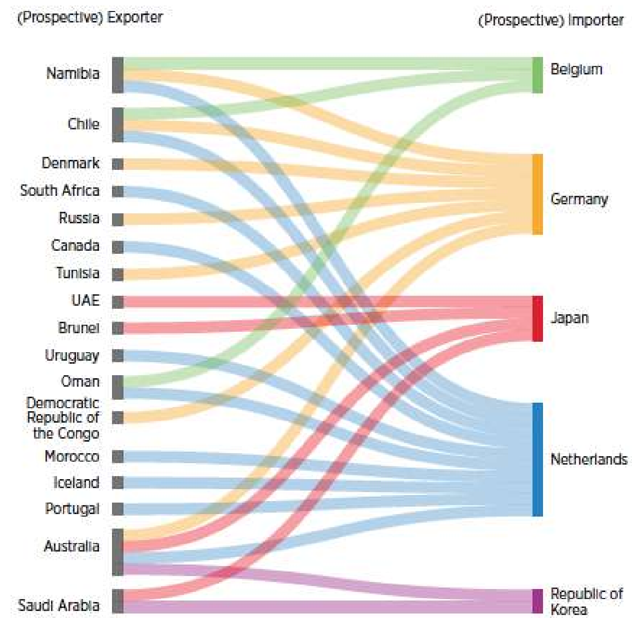
20 largest giga-scale green hydrogen projects and selected country bilateral trade agreements

1. **HyDeal Ambition (67GW)** .... Western Europe
2. **Unnamed (30GW)** .... Kazakhstan
3. **Western Green Energy Hub (28GW)** .... Australia
4. **AMAN (16GW)**[a] .... Mauritania
5. **Asian Renewable Energy Hub (14GW)** .... Australia
6. **Oman Green Energy Hub (14GW)**[a] .... Oman
7. **AquaVentus (10GW)** .... Germany
8. **NortH2 (10GW)** .... Netherlands
9. **H2 Magallanes (8GW)** .... Chile
10. **Beijing Jingneng (5GW)** .... China
11. **Project Nour (5GW)**[a] .... Mauritania
12. **HyEnergy Zero Carbon Hydrogen (4GW)**[a] .... Australia
13. **Pacific solar Hydrogen (3.6GW)** .... Australia
14. **Green Marlin (3.2GW)** .... Ireland
15. **H2-Hub Gladstone (3GW)** .... Australia
16. **Moolawatana Renewable Hydrogen Project (3GW)**[a] – Australia
17. **Murchison Renewable Hydrogen Project (3GW)** – Australia
18. **Unnamed (3GW)** .... Namibia
19. **Base One (2GW)**[a] .... Brazil
20. **Helios green Fuels Project (2GW)** .... Saudi Arabia

Note: Size refers to electrolyser capacity. Information based on announced plans.

a. Estimated electrolyser capacity based on a comparison with similar-sized schemes.

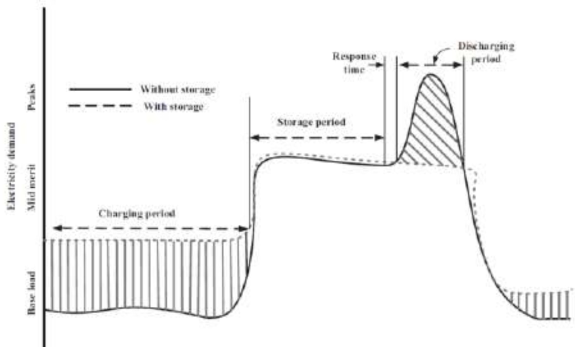
Disclaimer: This map is provided for illustration purposes only. Boundaries shown on this map do not imply any endorsement or acceptance by IRENA. Map source: Natural Earth, 2021



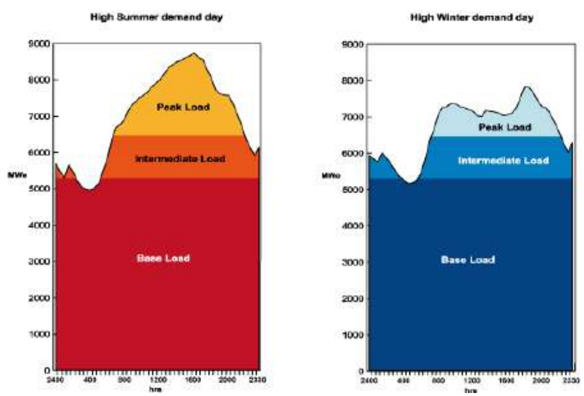
Note: Figure covers hydrogen trade related agreements only, based on public announcements and is not exhaustive. Private agreements and those that focus exclusively on technology co-operation are not included. MOU = Memorandum of Understanding.

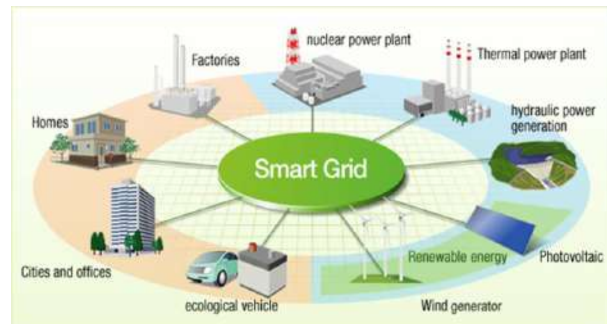
Source: IRENA, 2022

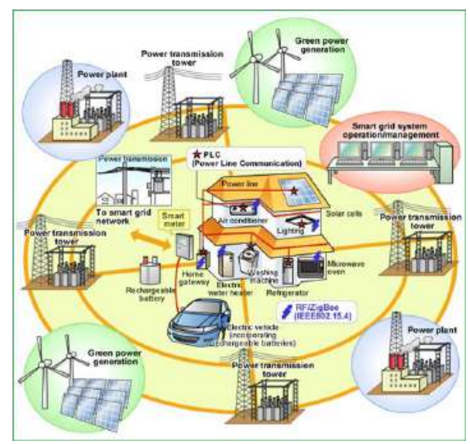
Energy management using storage



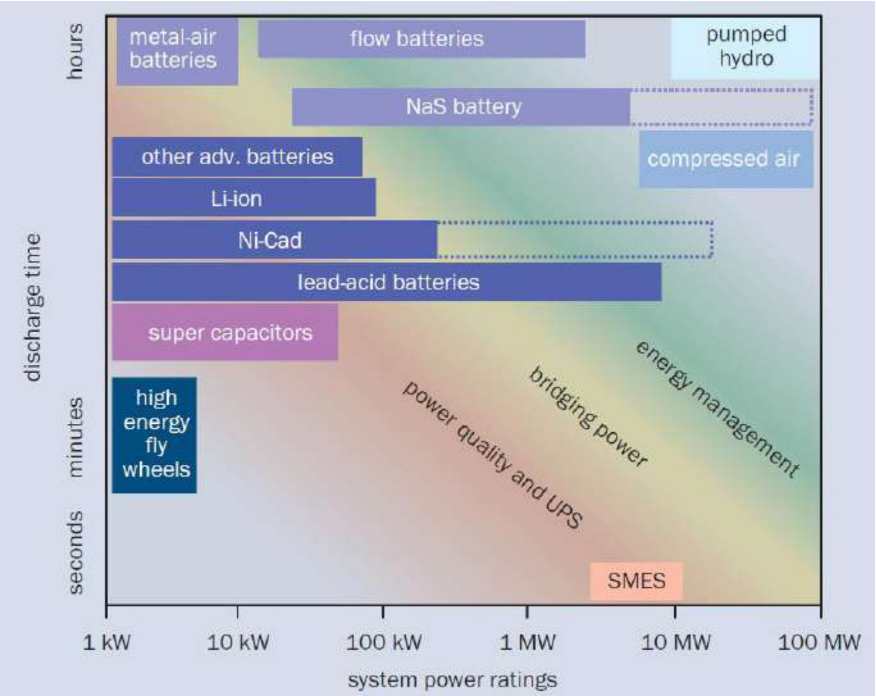
Load curves for Typical electricity grid





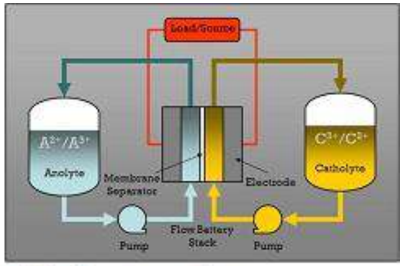


Types of electricity energy storage



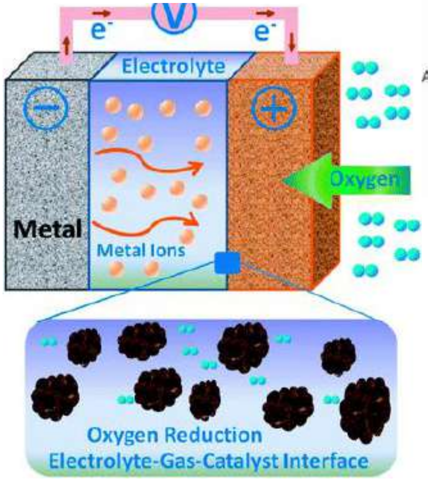
Source: Institute of Physics

Batteries

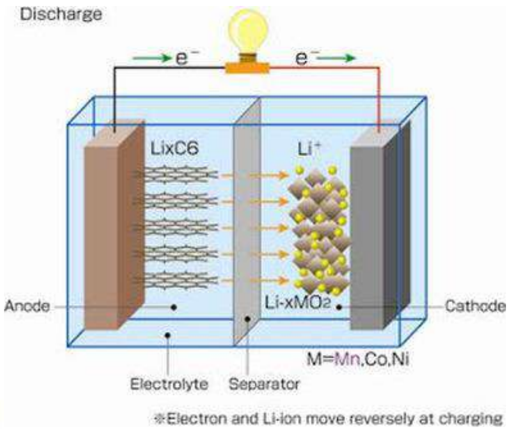


- Discharge reaction
  - $C^{3+} + e^- \rightarrow C^{2+}$ (reduction)
  - $A^{2+} \rightarrow A^{3+} + e^-$ (oxidation)
- Charge reaction
  - $C^{2+} \rightarrow C^{3+} + e^-$ (oxidation)
  - $A^{3+} + e^- \rightarrow A^{2+}$ (reduction)

Redox flow battery

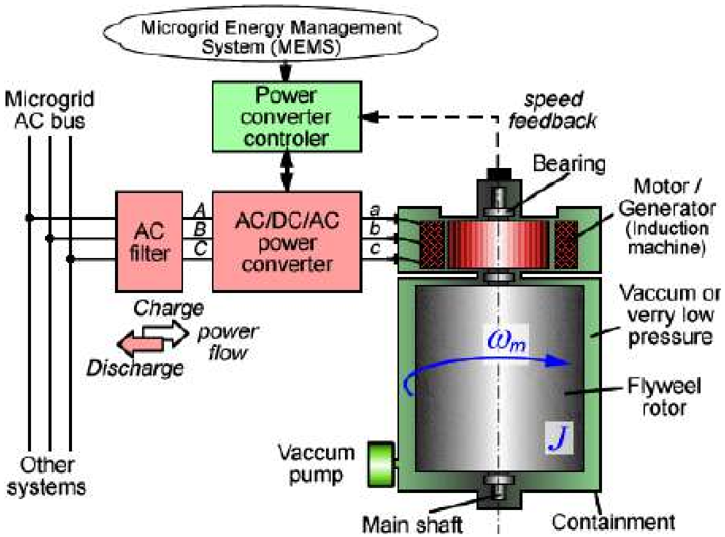


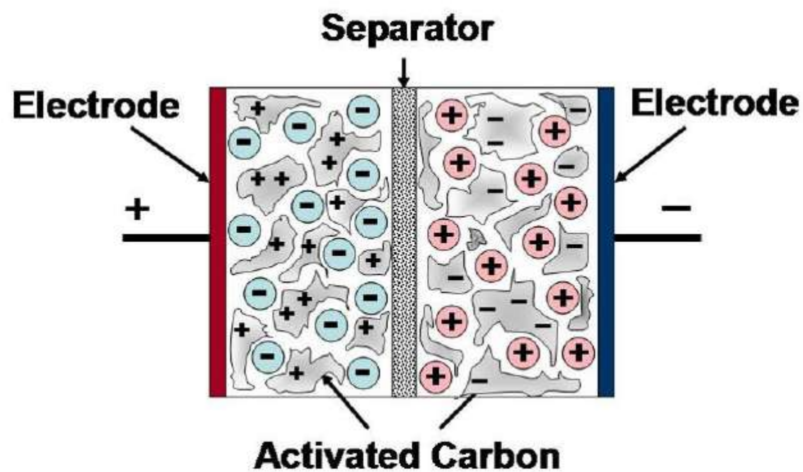
Metal-air battery



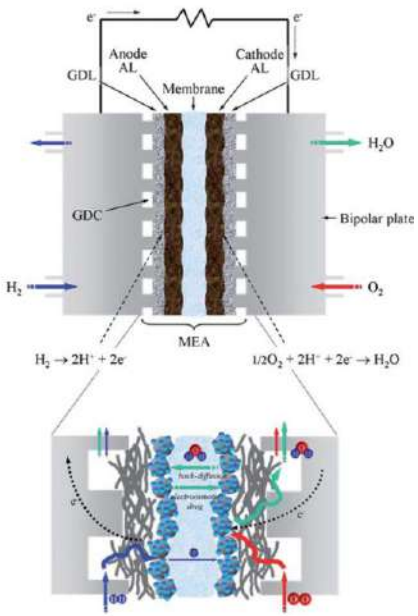
Li-Ion Battery

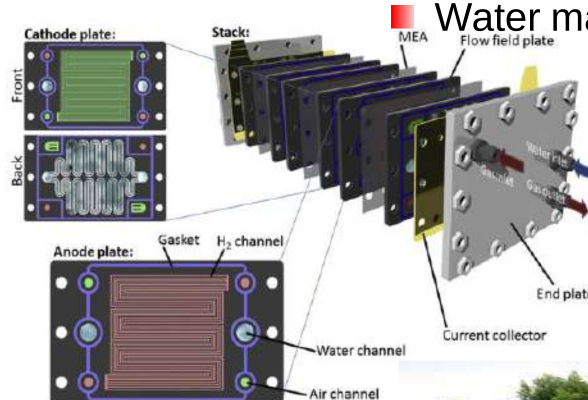
Super capasitor & fly whell





Proton exchange membrane FC -H2





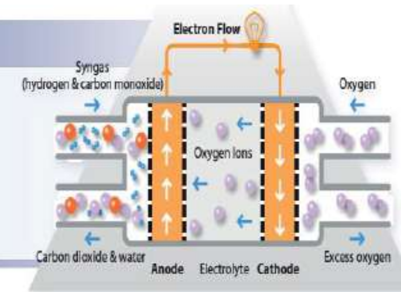
Issue:
- Durability & degradation
- Water management

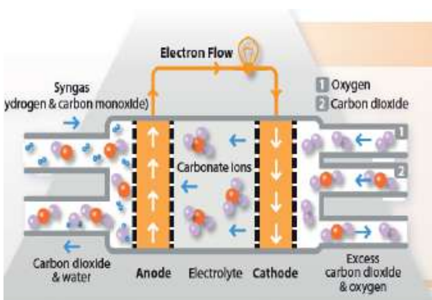
Source: Millichamp, 2015

Solid Oxide & Molten Carbonate FCs

SOFC – Solid Oxide Fuel Cells

- Electrolyte: solid ceramic, such as stabilised zirconium oxide
- A precious metal catalyst is not necessary
- Can run on hydrocarbon fuels such as methane
- Operate at very high temperatures, around 800°C to 1,000°C
- Best run continuously due to the high operating temperature
- Popular in stationary power generation



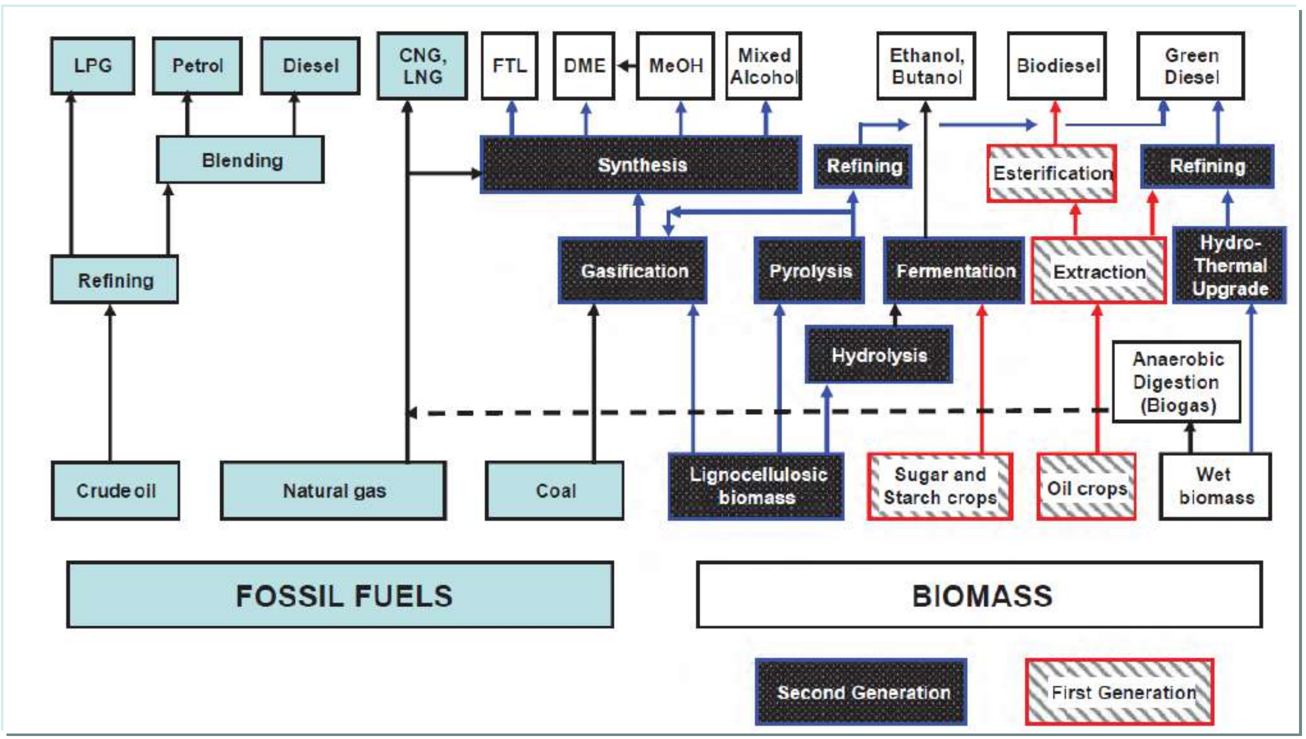


Molten Carbonate Fuel Cells – MCFC

- Electrolyte: a molten carbonate salt suspended in a porous ceramic matrix
- A precious metal catalyst is not necessary
- Can run on hydrocarbon fuels such as methane
- Operate at around 650°C
- Best run continuously due to the high operating temperature
- Most fuel cell power plants of megawatt capacity use MCFCs, as do large combined heat and power plants

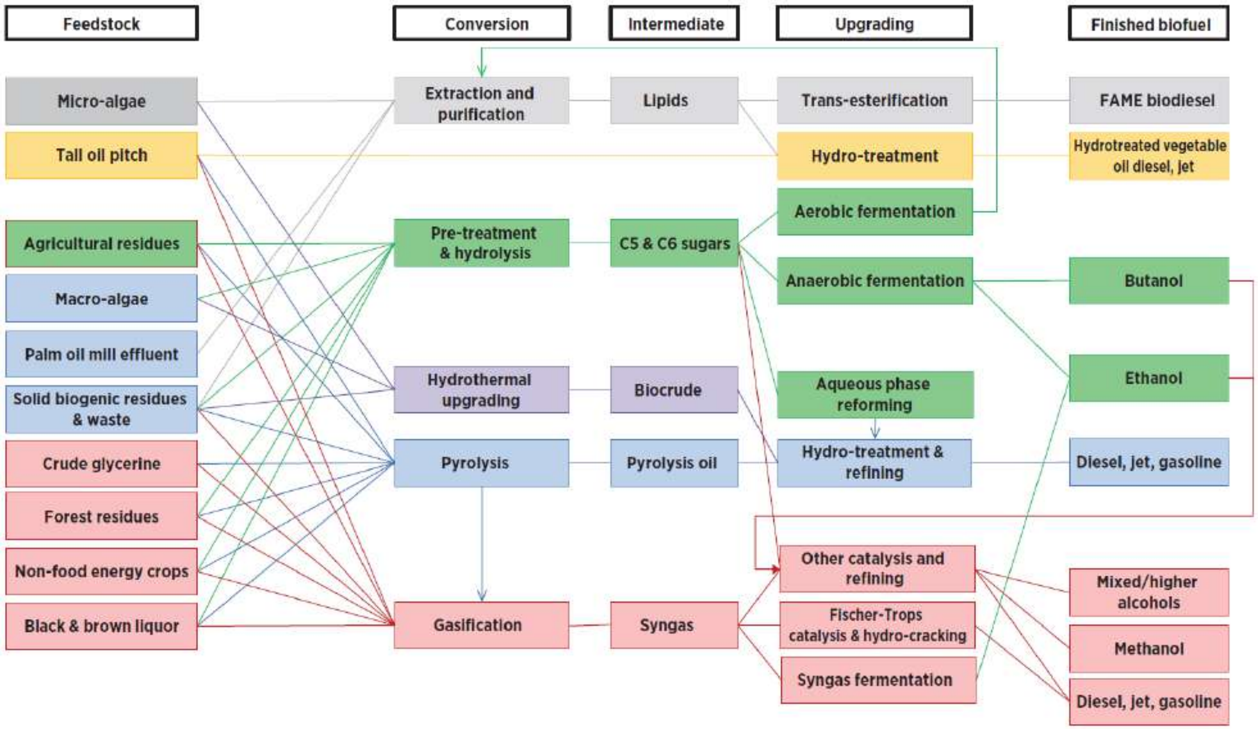
Source: Fuelcelltoday

Production path to liquid fuels



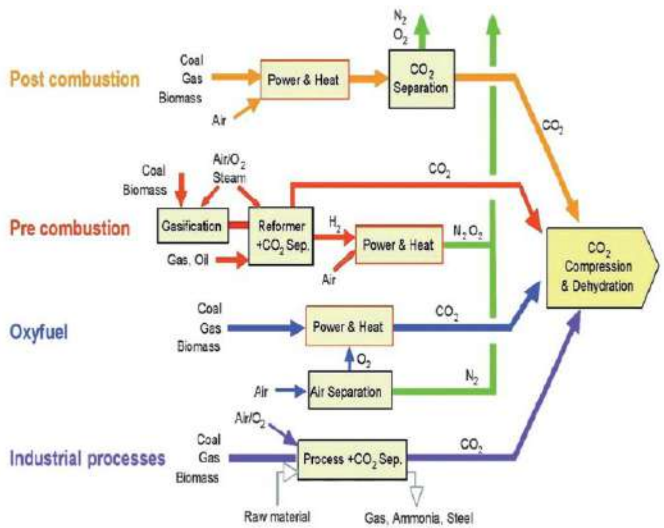
Source:IIASA

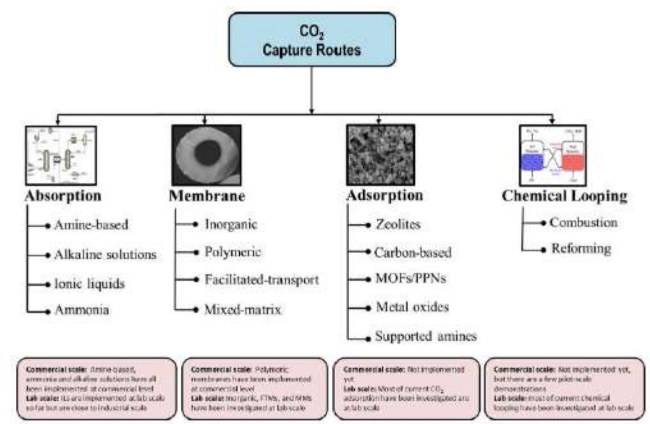
Advanced biofuels pathways



Source: IRENA. 2016

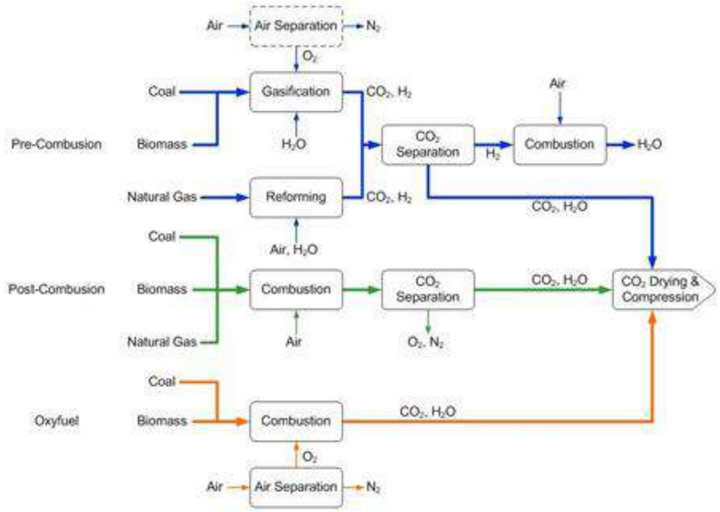
Carbon Capture Technologies

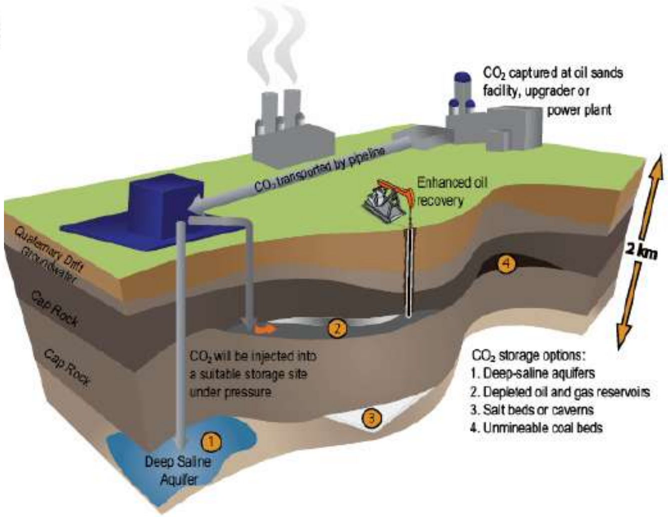




Source: Al-Mamoori et al, 2017

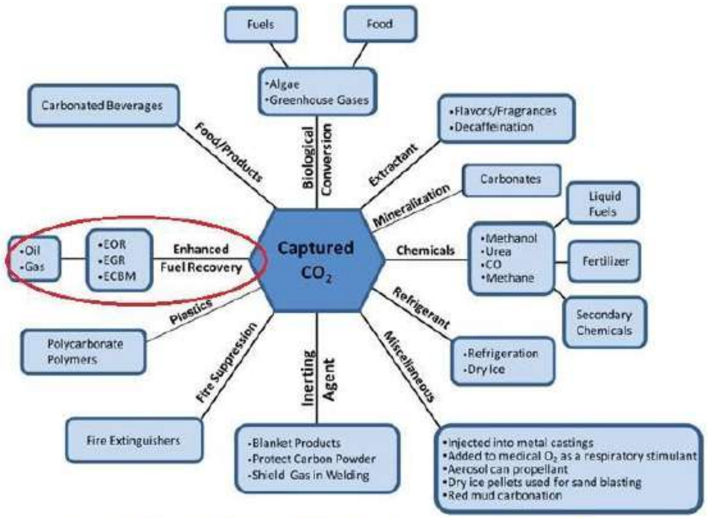
What is CCS



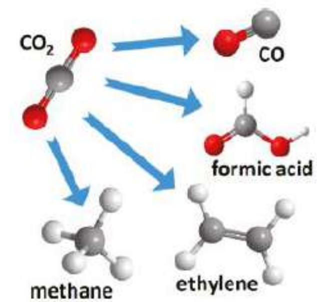


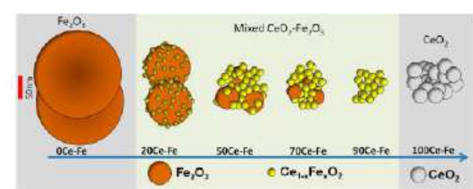
Source: CO2 solution

CO_2 Utilization



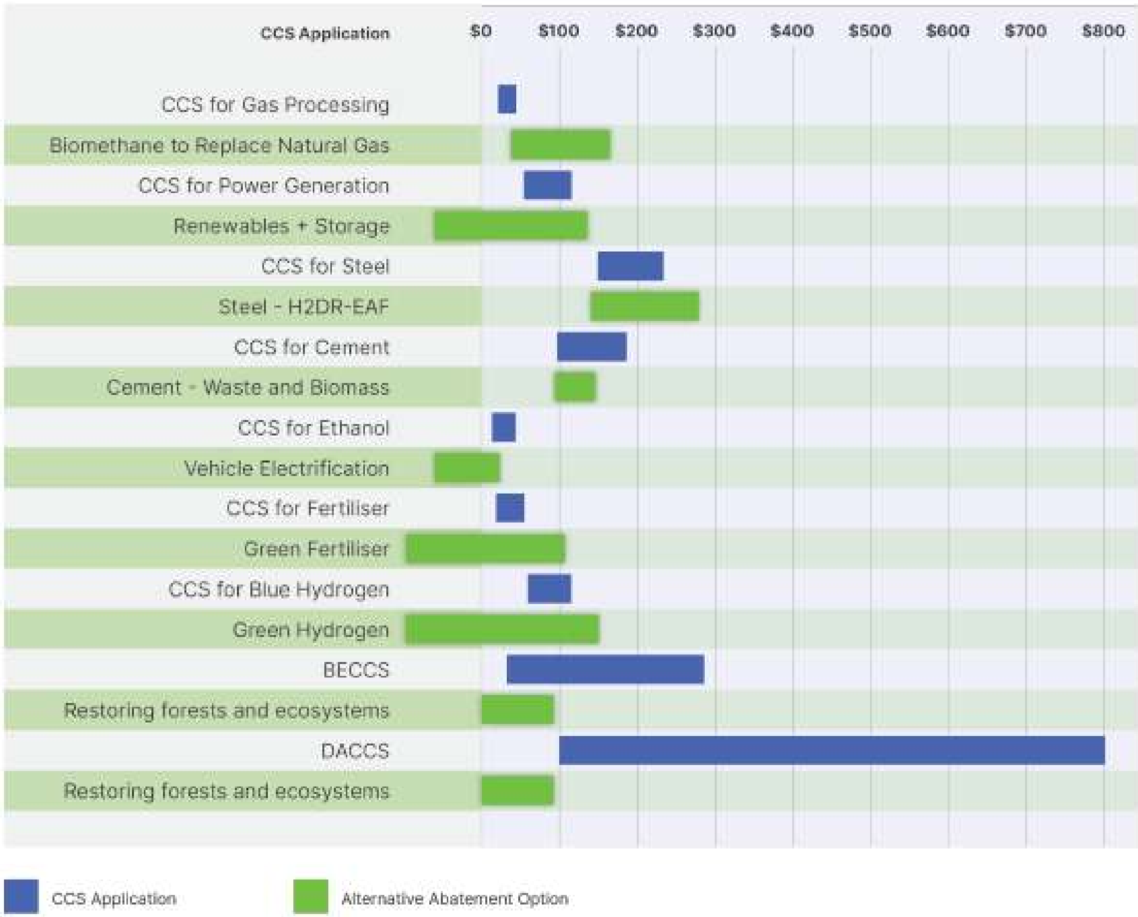
Source: www.netl.doe.gov/research/coal/carbon-storage/research-





Source: Whipple et al, 2010

CCS applications



Source: Michael Salt, IEEFA, 2022

Supergrids

WHAT ARE SUPERGRIDS?

Supergrids are high-capacity power transmission lines using either high-voltage direct current (**HVDC, above 500 kV**) or ultra-high-voltage direct current (**UHVDC, above 800 kV**) power lines.

By enabling **high volumes of electricity** to flow across **long distances**, supergrids enhance **cross-border integration** and help to connect **resource-rich areas** with renewable energy potential to **major electricity demand centres**.

1 BENEFITS

Direct current (DC) power lines show substantially lower power losses than alternating current (AC) lines. Power flow is also more controllable in DC systems, allowing more flexible operation. Supergrids can:

- Transmit renewable energy from resource-rich areas to relatively distant demand centres
- Boost the flexibility and reliability of local grids
- Connect two onshore points using offshore HVDC links (bootstraps)

2 KEY ENABLING FACTORS

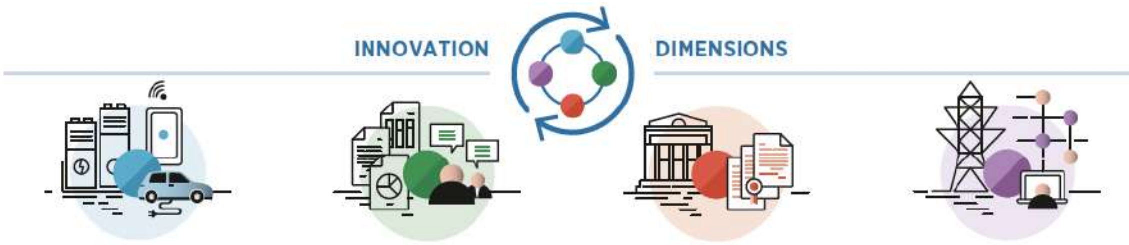
- Addressing political and regulatory challenges
- Addressing technical challenges related to network protection

3 SNAPSHOT

- → Xilingol League–Taizhou in China is the world's highest-voltage (± 800 kV) and highest-capacity (10 GW) DC line in operation
- → One of the world's longest HVDC lines is being constructed in India, with a length of 1 830 km
- → In Germany, HelWin1 is a 130 km HVDC line that can transmit up to 576 MW of offshore wind energy from the North Sea to more than 700 000 consumers

Source: IRENA, 2019

Innovation landscape for a renewable-powered future



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

Source: IRENA, 2019

Emerging approaches for energy transition

- Integrates new technologies, green hydrogen, e-fuels & e-chemicals, CCUS, BECCS, energy storages, and energy efficiency technologies for end users
- Integrates multi-energy carriers, sector coupling, power to x, process-and grid centric systems,
- Resolving temporal and spatial resolution, intermittently of VRE and demand flexibility by electrification, spatial granulation for inter-regional linkages for energy trade,
- Increasing role of digitalisation, smart grids, and machine learning
- Tackle uncertainty, integration short term uncertain behaviour in a long-term energy system planning, and technology progress,
- Inclusion of socio-economic equity, behaviour change and sustainability, giving insights in energy systems for a just transition.

Thank you