In the Pursuit of the Net Zero Goal and Sustainability: Adoption of Green Hydrogen Technologies, CO_2 Refineries & Biomass Valorization

Ganapati D. Yadav

National Science Chair (SERB/DST/GOI)

Emeritus Professor of Eminence

Former Vice Chancellor

INSTITUTE OF CHEMICAL TECHNOLOGY Mumbai

June 8, 2022

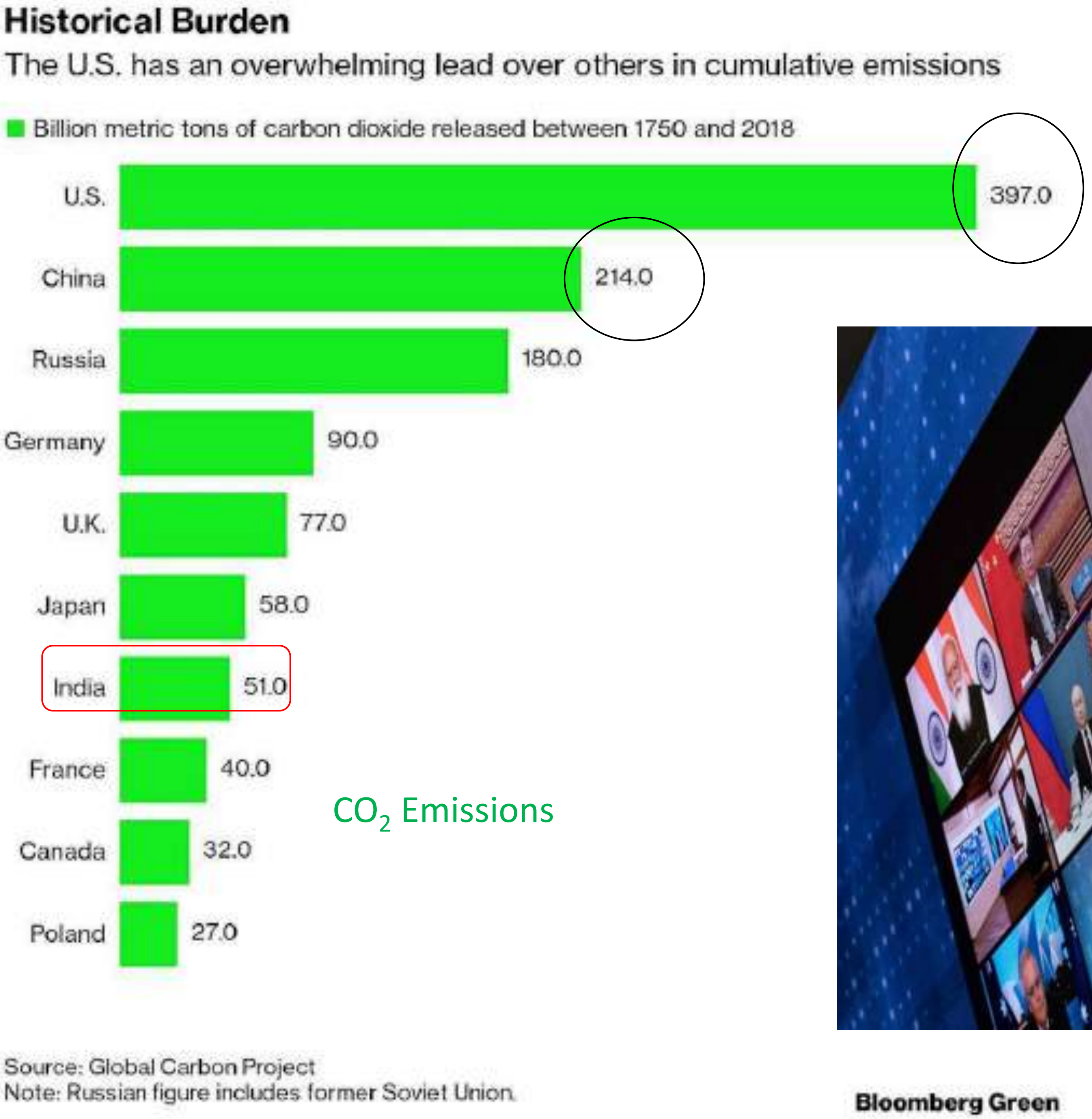
Workshop on Awareness and Capacity Building in Hydrogen Production and Energy uses: Towards a Net-Zero strategy (ACBHPE-2022)

PARIS AGREEMENT 2015

- United Nations Framework Convention on Climate Change’s (UNFCCC) 21st Conference of the Parties (COP 21) and adopted on December 12, 2015.
- A consensus on an accord comprised of commitments by 195 nations to combat climate change and adapt to its impacts.

Leaders Summit on Climate
April 22-23, 2021

- To accelerate actions to address the climate crisis, including emissions reductions, finance, innovation and job creation, and resilience and adaptation.



CO_2 Emissions

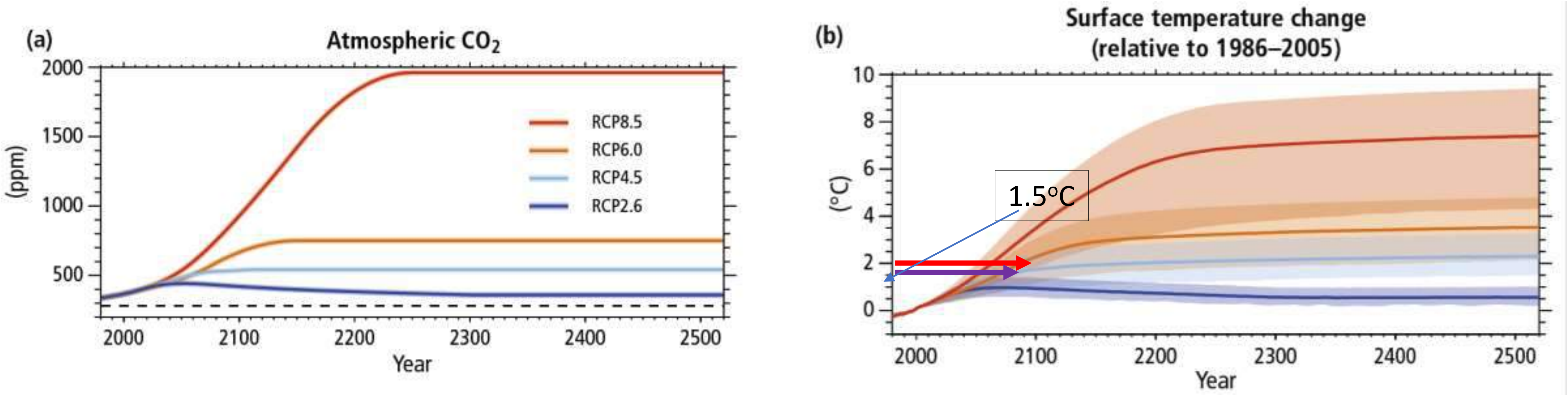
Climate Summit April 2021

COP26 day one: India commits to net zero by 2070

<u>Why not 2050?</u>

Atmospheric CO_2 concentrations

Source: IPCC *Intergovernmental Panel on Climate Change show projected concentrations of CO_2*

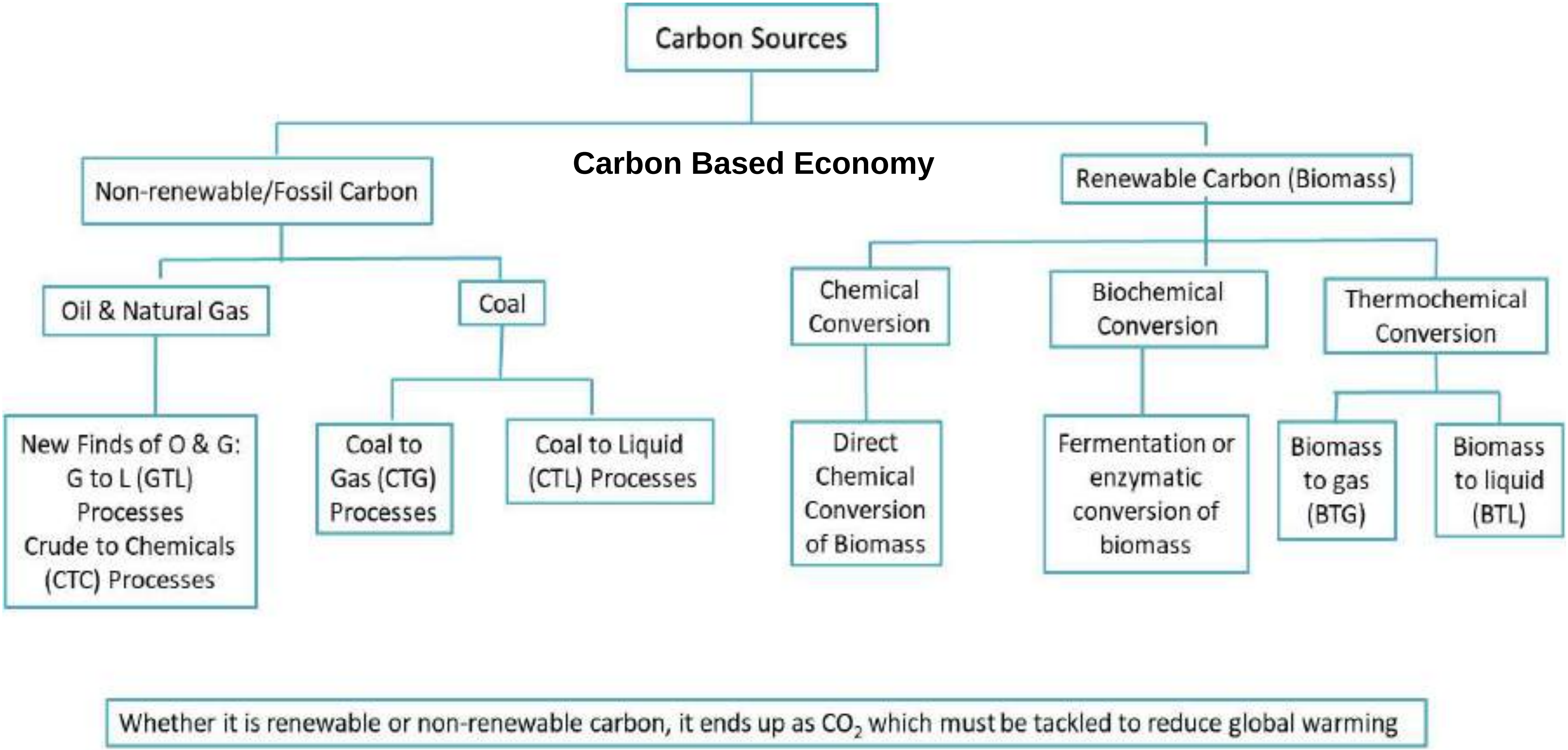


410 ppm in Jan 2020

412 ppm Jan 2021

420.69 ppm 1 June 2022

Carbon Based Economy



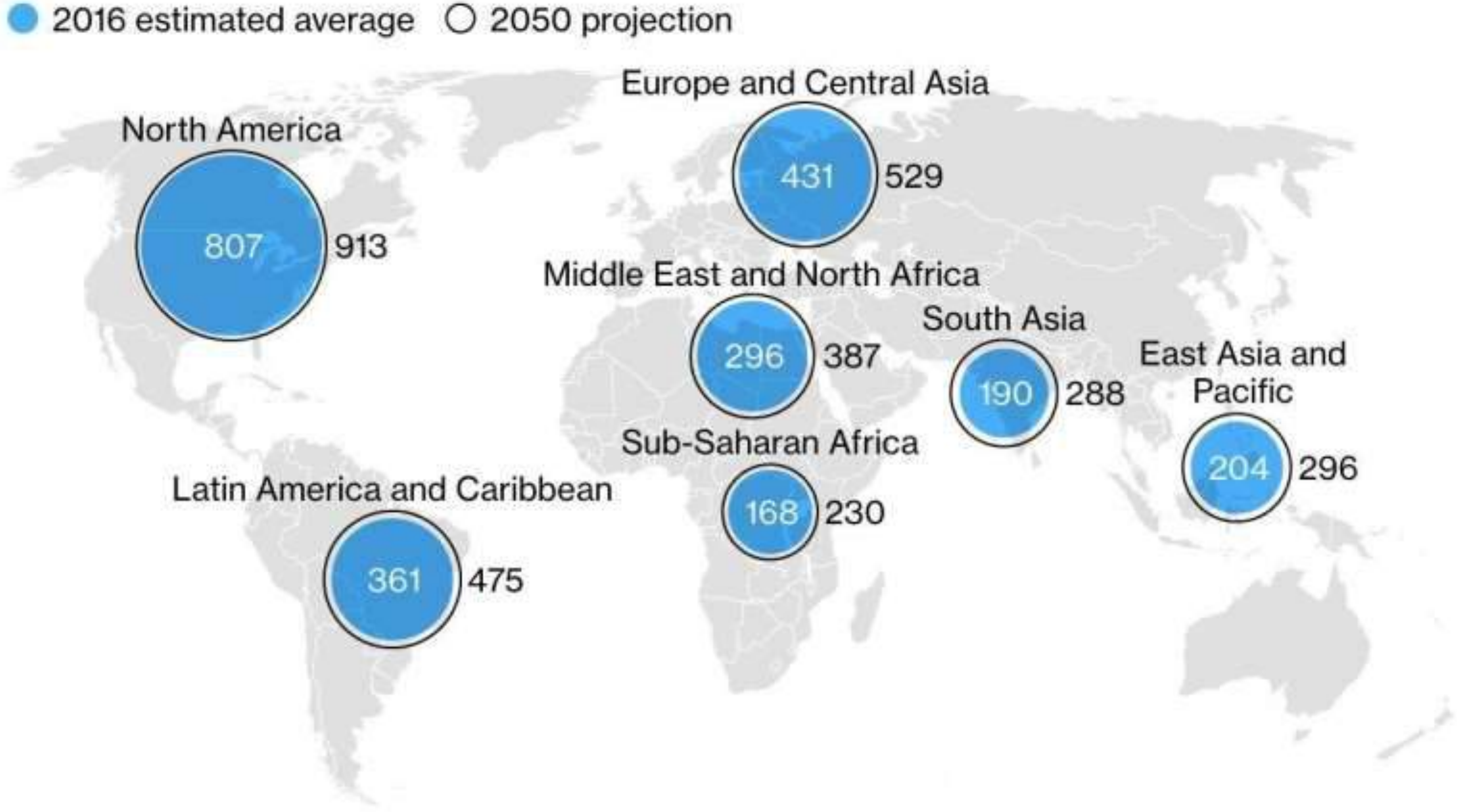
Yadav et al. (2020):Production of Fuels and Chemicals in The New World: Critical Analysis of Choice between Crude Oil and Biomass vis-à-vis Sustainability and The Environment, Clean Tech Env Pol. 22, 1757–1774(2020). https://doi.org/10.1007/s10098-020-01945-5

Can you show any 3 man-made materials or products without the use of chemicals ?

Prize of 100 million pounds waiting for anybody since 2008

Waste Generation Is Rising Globally

Kilograms of solid waste each person creates a year

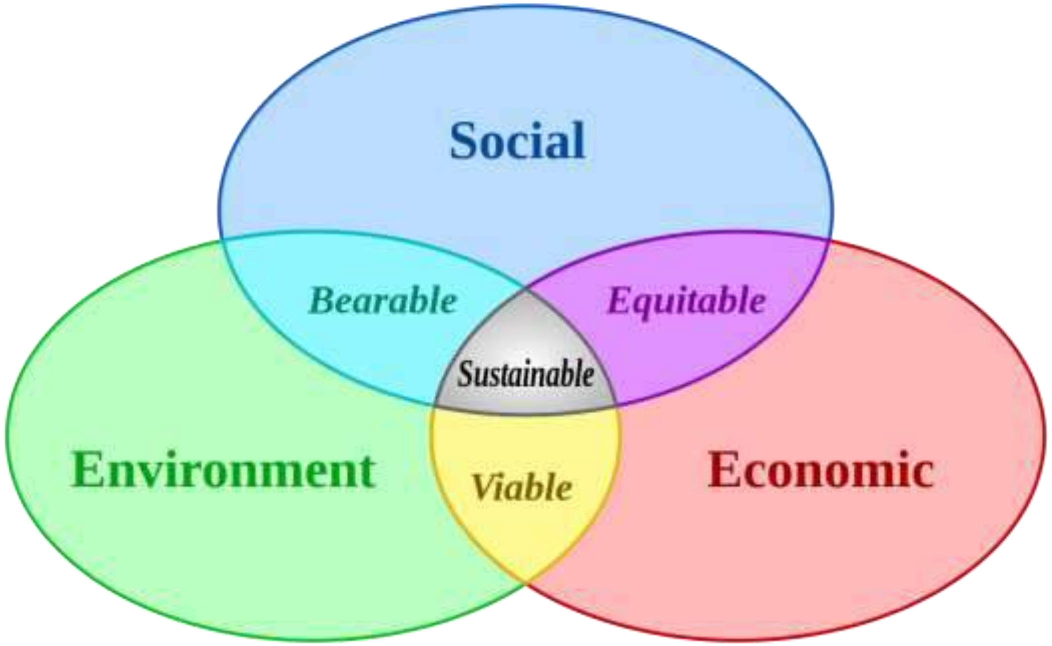


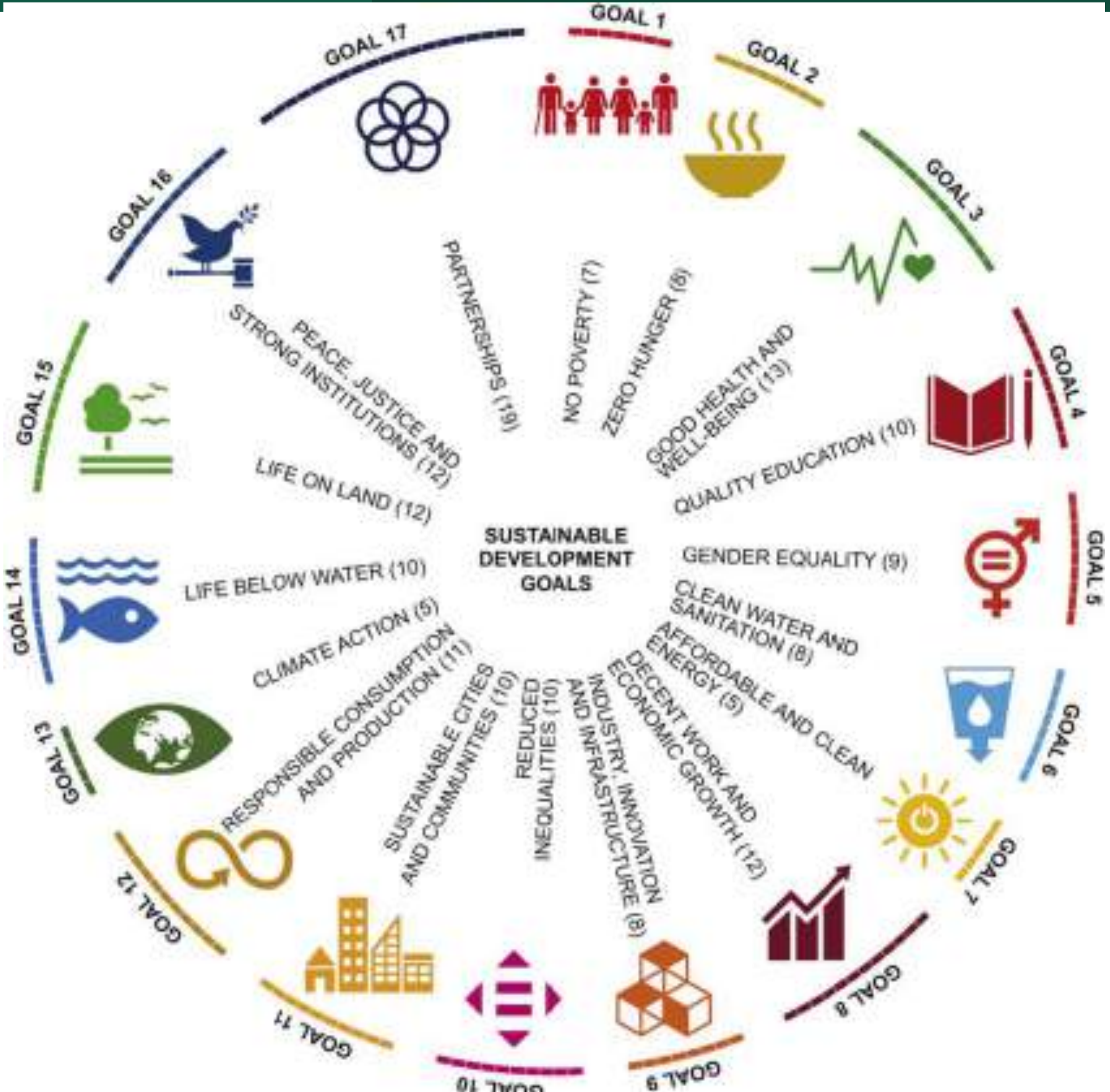
Source: World Bank

Notes: Data availability and methodology vary by country or region. Latest available data were adjusted to 2016 for comparison. Figures include only residential, commercial and institutional waste.

Sustainable Development

UN 17 SDG





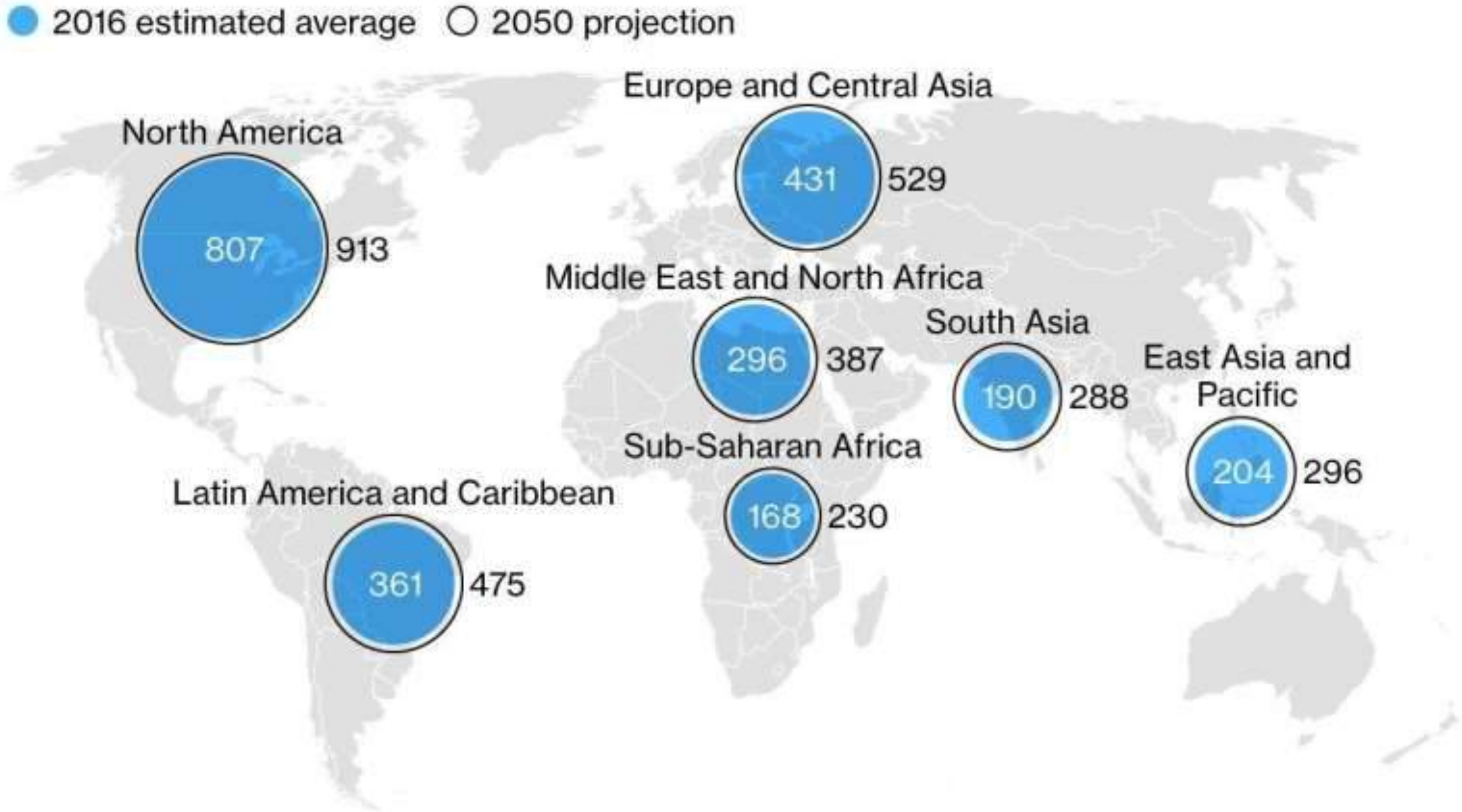
RECYLE ENGINEERING: Physical, Chemical and Biological

MATERIAL RECYCLING, SUSTAINABILITY & ZERO WASTE SOCIETY

We will need 3 Earths, if we don’t recycle, reuse and reduce waste

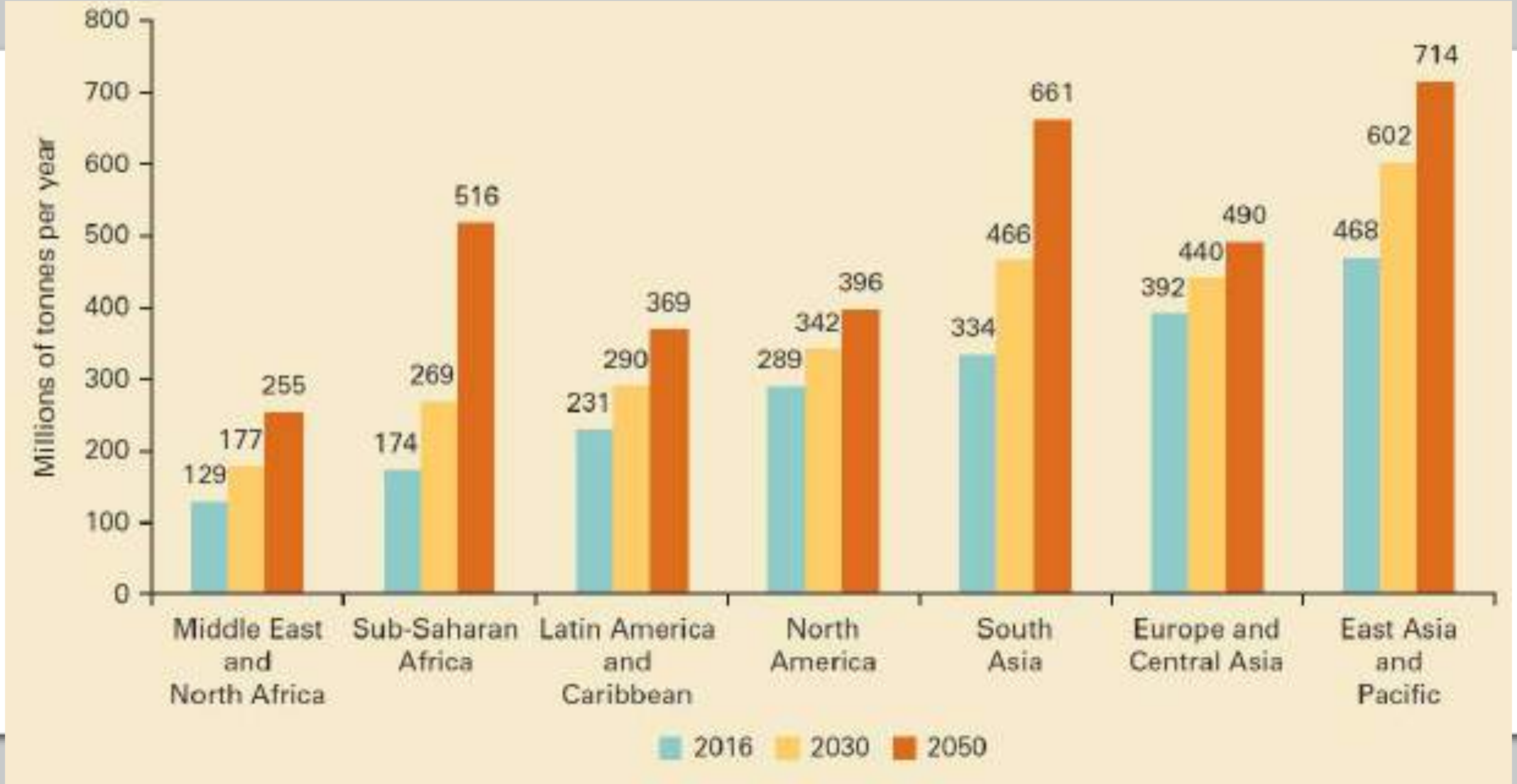
Waste Generation Is Rising Globally

Kilograms of solid waste each person creates a year



Source: World Bank

Notes: Data availability and methodology vary by country or region. Latest available data were adjusted to 2016 for comparison. Figures include only residential, commercial and institutional waste.

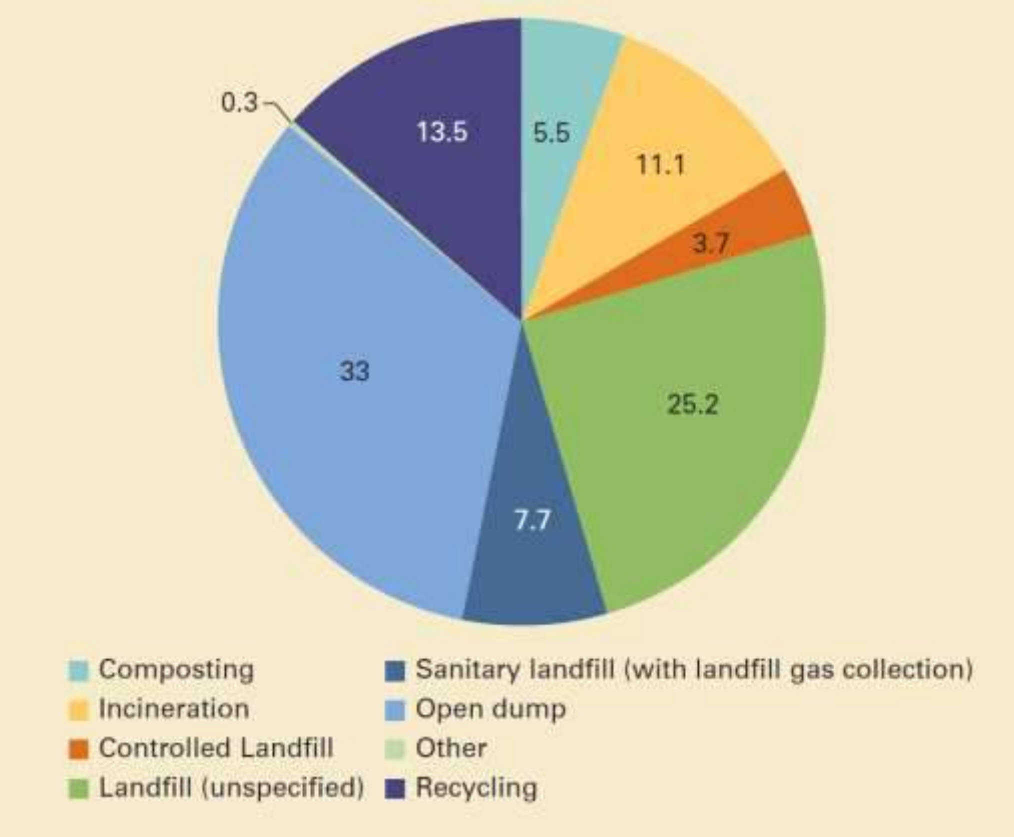


Waste 2.0

- The world generates 2.01 billion tonnes MSW waste annually, with at least 33 percent of that—extremely conservatively—not managed in an environmentally safe manner.
- Waste generated per person per day averages 0.74 kilogram but ranges widely, from 0.11 to 4.54 kilograms.
- Though they only account for 16 percent of the world's population, high-income countries generate about 34 percent, or 683 million tonnes, of the world's waste.
- (Source: The World Bank)

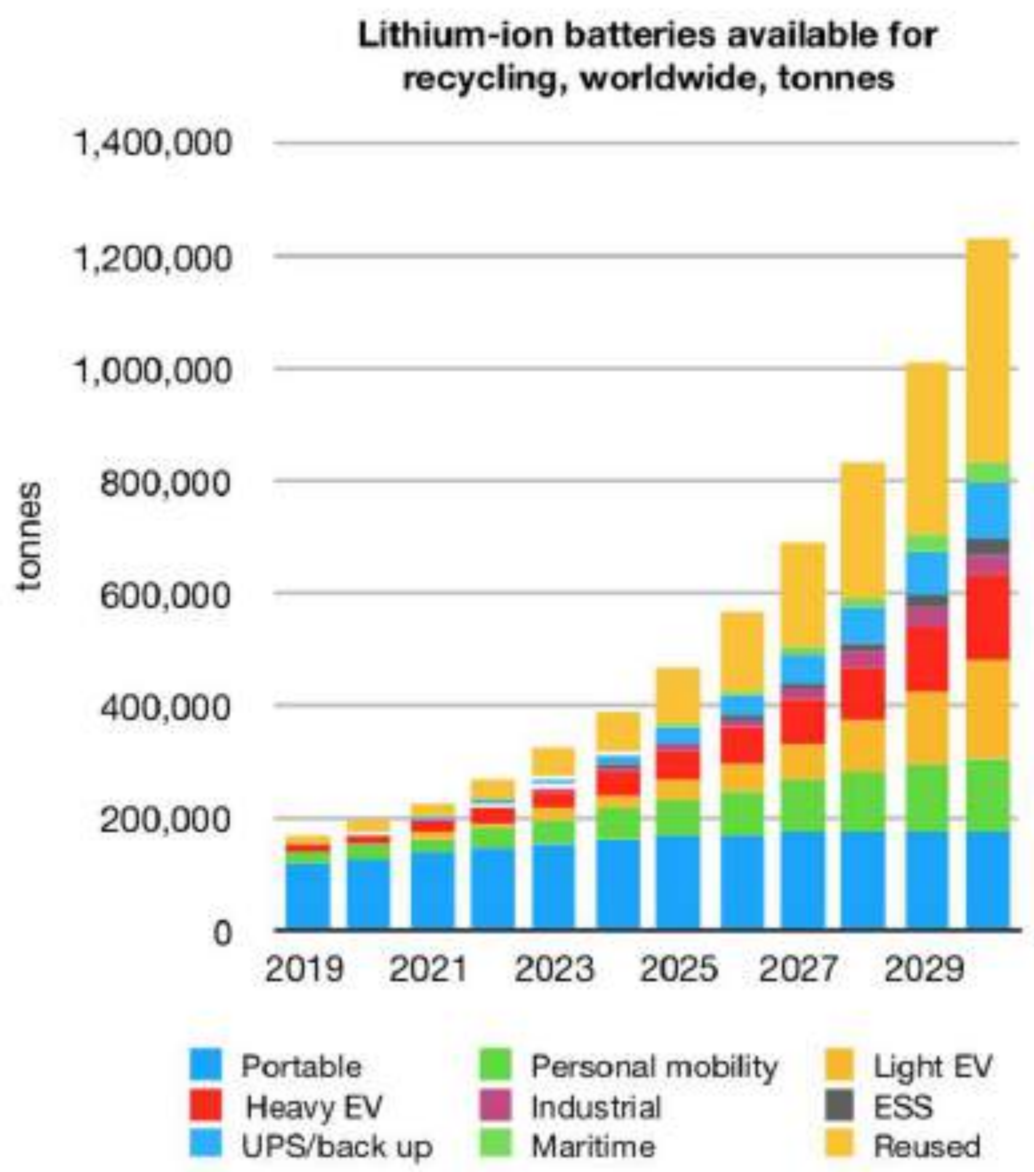
Global treatment and disposal of waste (%)

- **1.6 billion** tons of CO_2 equivalent GHG emissions were generated from solid waste treatment and disposal in 2016, or 5% of global emissions.
- Disposing of waste in open dumps and landfills without landfill gas collection systems.
- Food waste accounts for nearly 50% of emissions.
- Solid waste–related emissions are anticipated to increase to **2.38 billion** tons of CO_2-equivalent per year by **2050** if no improvements are made in the sector.



Circular Energy Storage

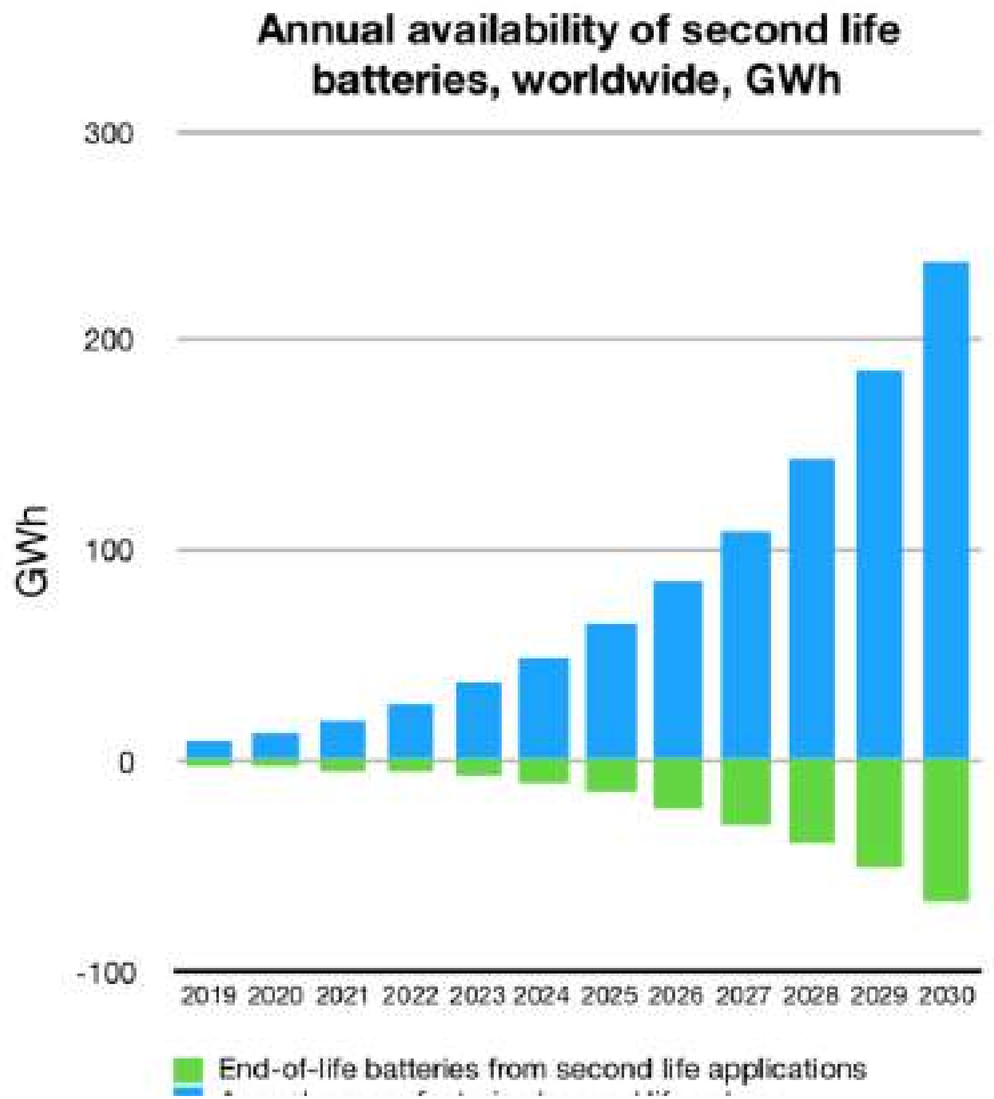
- China to dominate recycling and second life battery market worth US$45bn by 2030
- 2019-2030: 1,000GWh of remanufactured and second life batteries
- While portable electronics batteries will be the overall biggest sector lithium battery waste will come from,
- 75% of electric vehicle batteries – everything from e-scooters to buses, forklifts and trucks by 10 years' time could be remanufactured into other vehicles or stationary energy storage systems



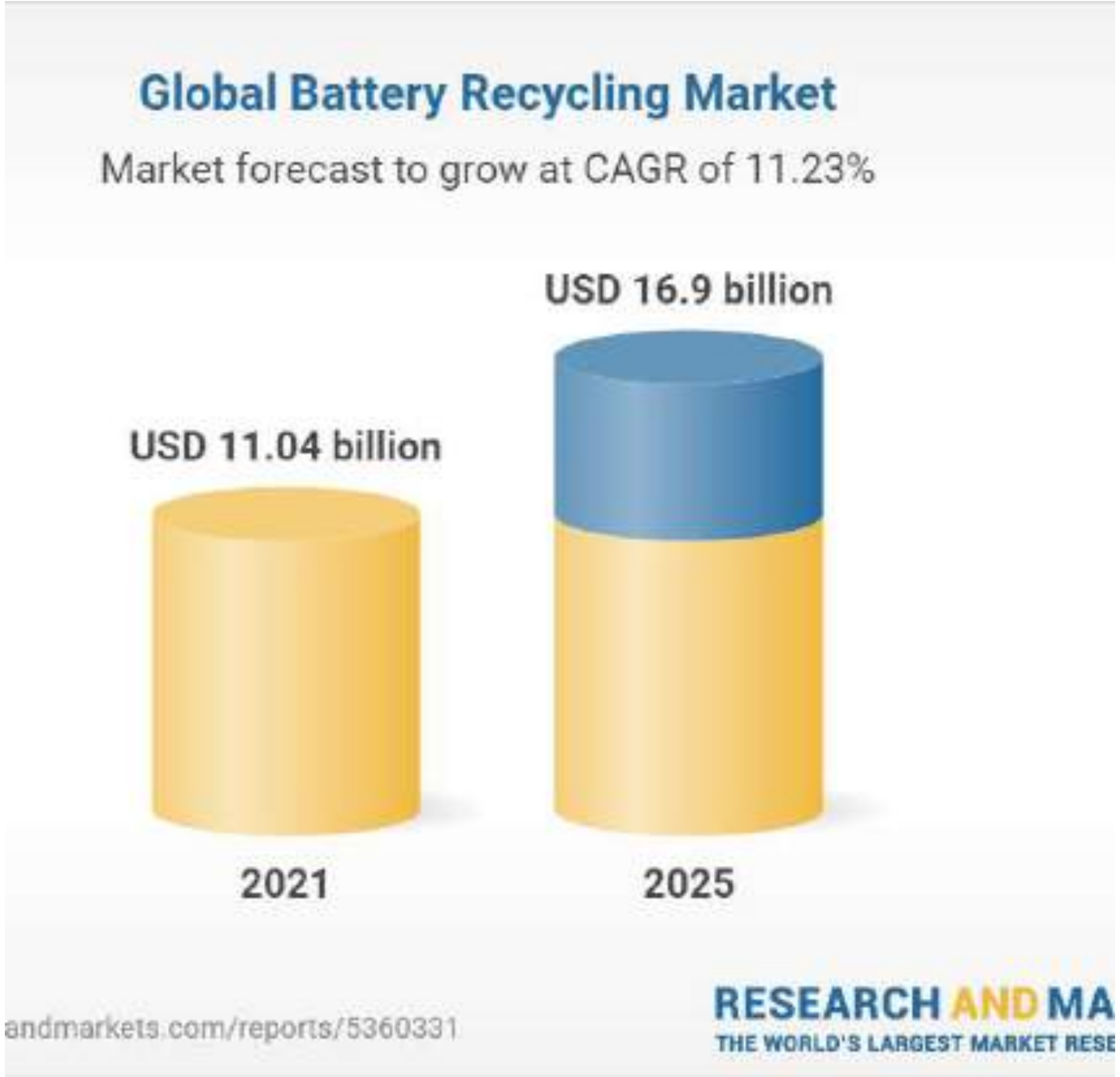
- Source: Circular Energy Storage

Battery Recyclability

Highly recyclable nature of the battery product is still often overlooked, as well as its suitability for second life repurposing, make it an important technology for sustainability and climate change mitigation.



Global Battery Recycling



GLOBAL PRIMARY BATTERY RECYCLING MARKET 2021-2025

Market growth will **ACCELERATE** at a **CAGR** of over

8%

Incremental growth ($M)

2020 2025

62.77

The market is **FRAGMENTED** with several players occupying the market

Growth Contributed by **EUROPE**

83%

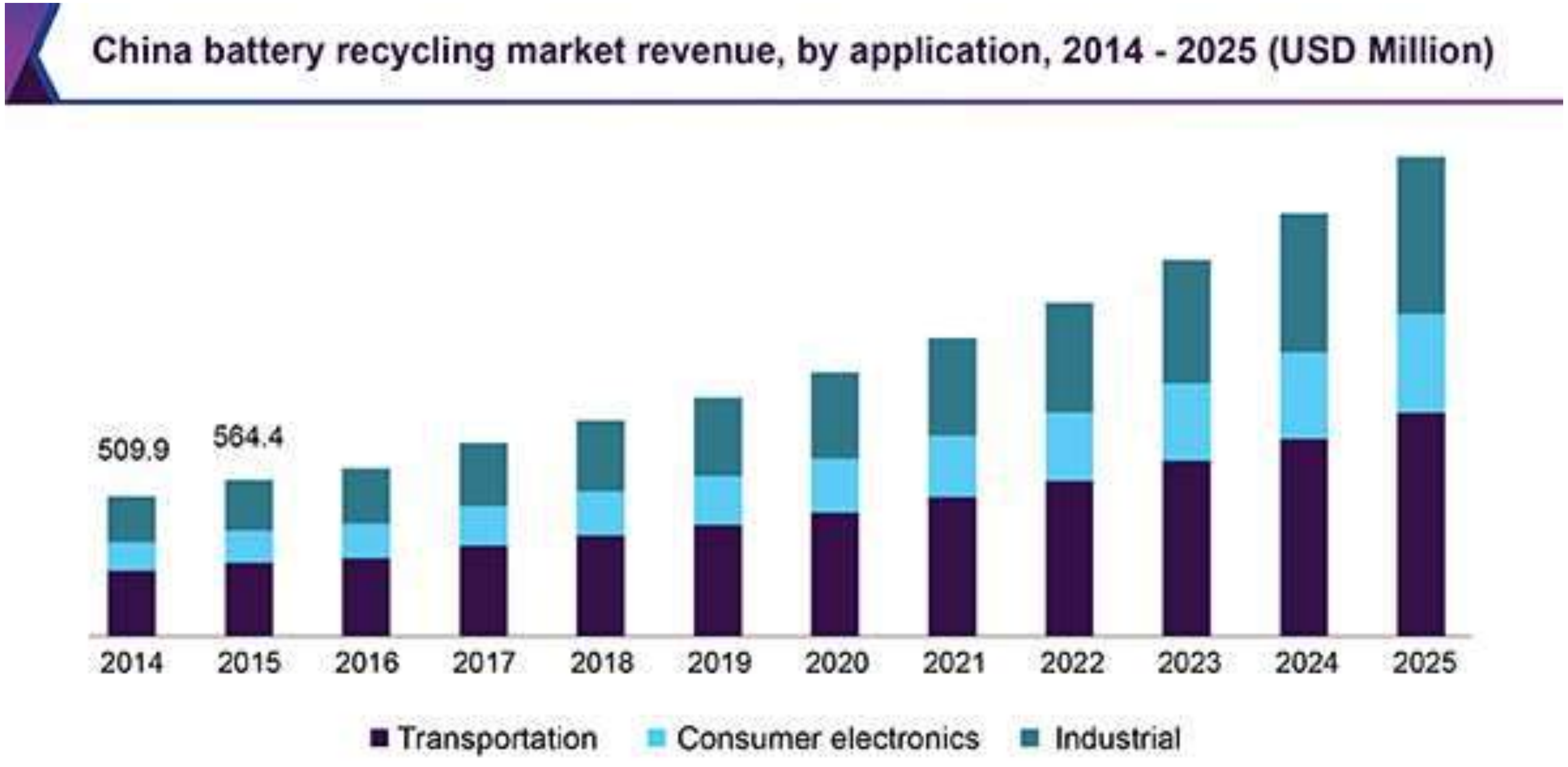
Growth for **2021**

7.56%

Market impact:

NEGATIVE

Battery Recycling



Source: Grand view research

- The global battery recycling market size was valued at USD 8.74 billion in 2016. Stringent government regulations and the growing end-use industries including transportation, consumer electronic, and industrial applications are expected to elevate the demand.
- The resources for new battery production are limited in comparison to the projected demand from various end-use industries. Battery recycling is important not only for the recovery of valuable materials and metals but also for efficient waste management in a bid to eliminate hazardous environmental impacts. The use of recovered metal for recycled battery production can also help in the reduction of CO_2 emissions to a large extent and energy requirements related to mining.

Energy, Environment and Climate Change

Energy and environment are intimately connected.

More energy, more environmental damage

The climate change is due to the overuse of fossil fuels leading to emissions of CO_2 which is currently at 419.2 ppm.

The energy needs of the world are increasing day by day and use of carbon-based fuels will continue to rise.

Jan. 2020: 410 ppm; Jan. 2021: 412 ppm (Slow down in economy)

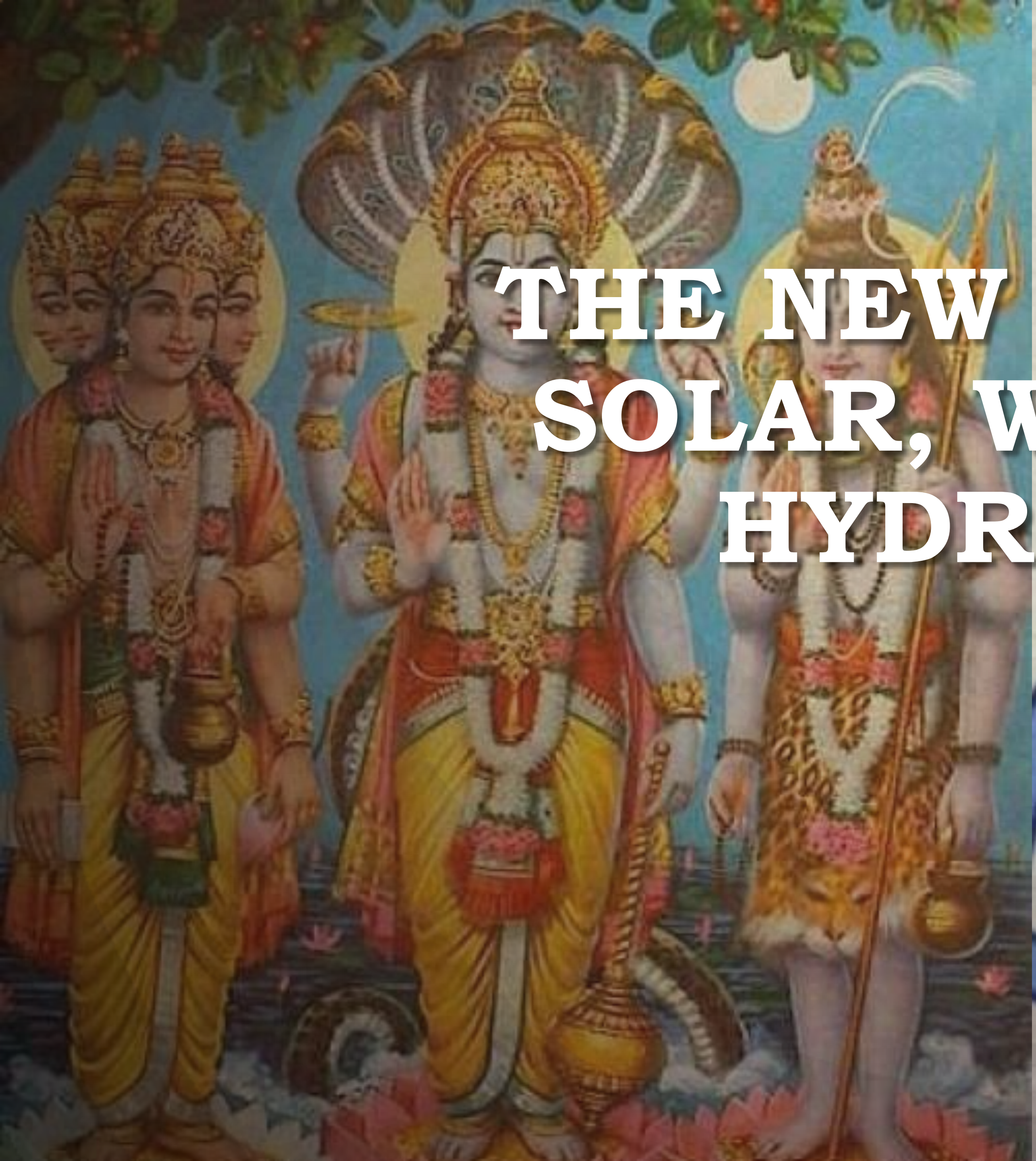
May 24, 2022: 420.2 ppm

In order to meet the requirements of international treaties, the use of renewable resources is advanced.

Is biomass as energy source new?

Should it be used for energy?

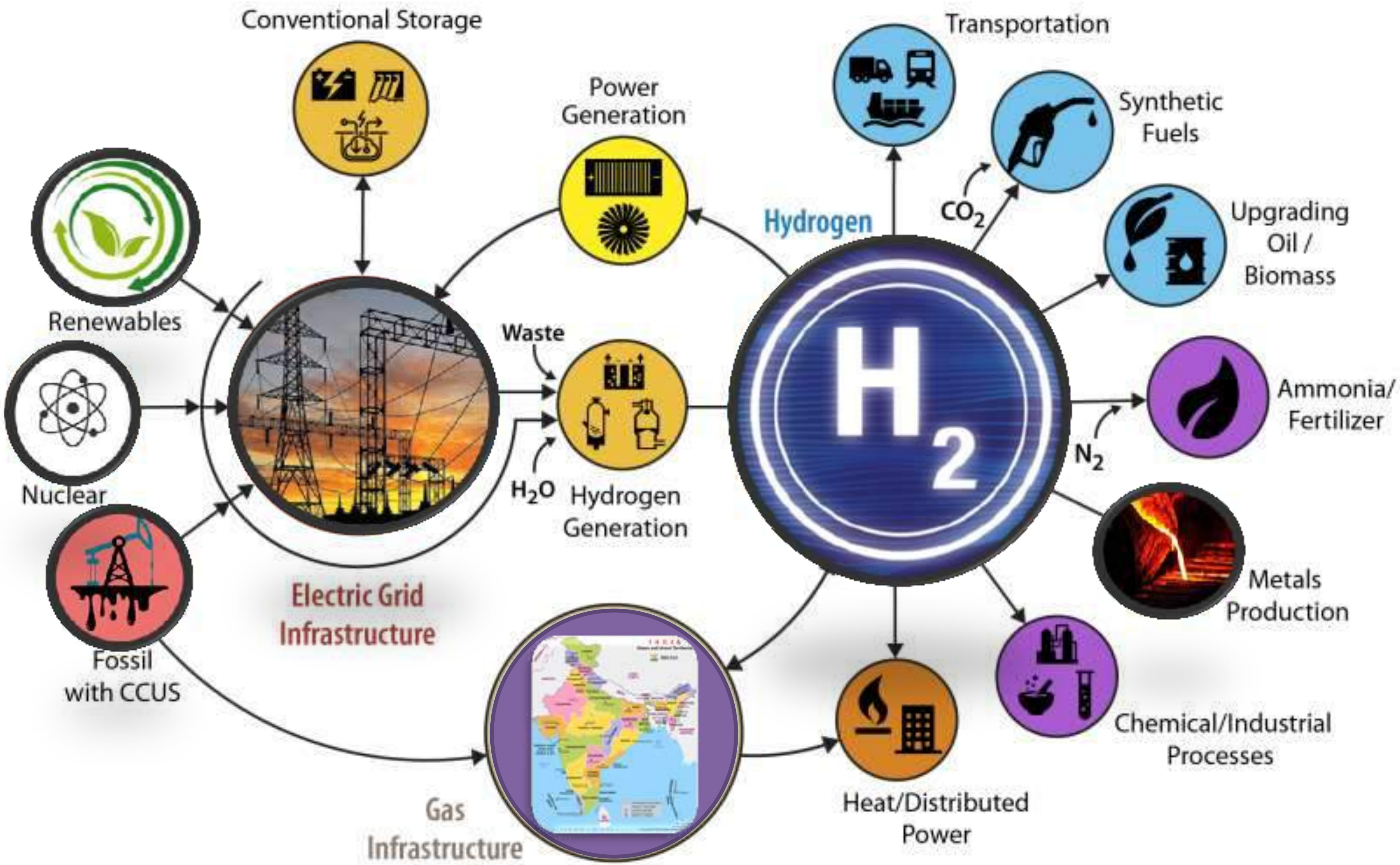
THE NEW TRINITY : SOLAR, WIND AND HYDROGEN



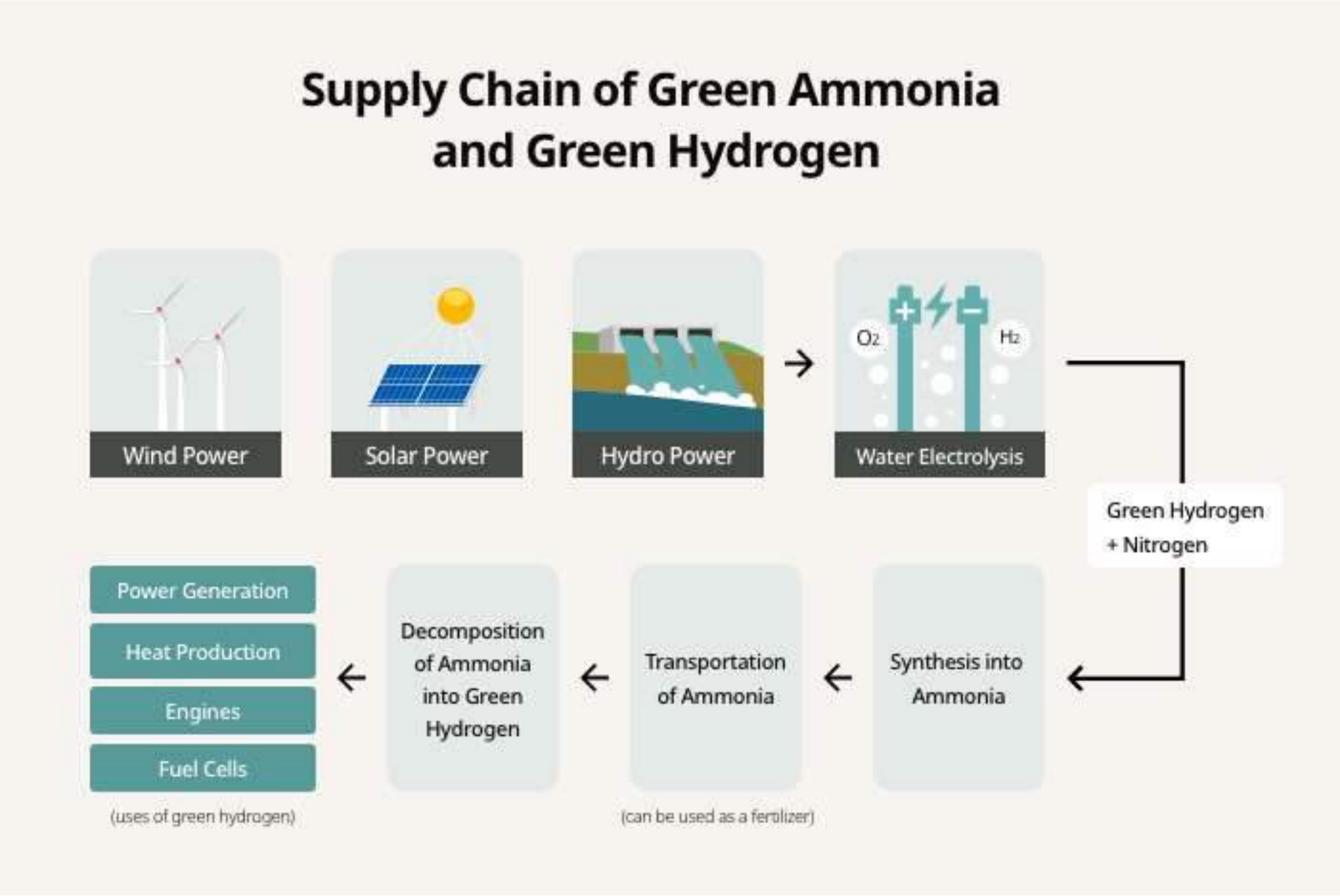
Ministry of Power, GoI, notifies Green Hydrogen Policy, Feb. 17, 2022

Water & Air as feedstock 2030

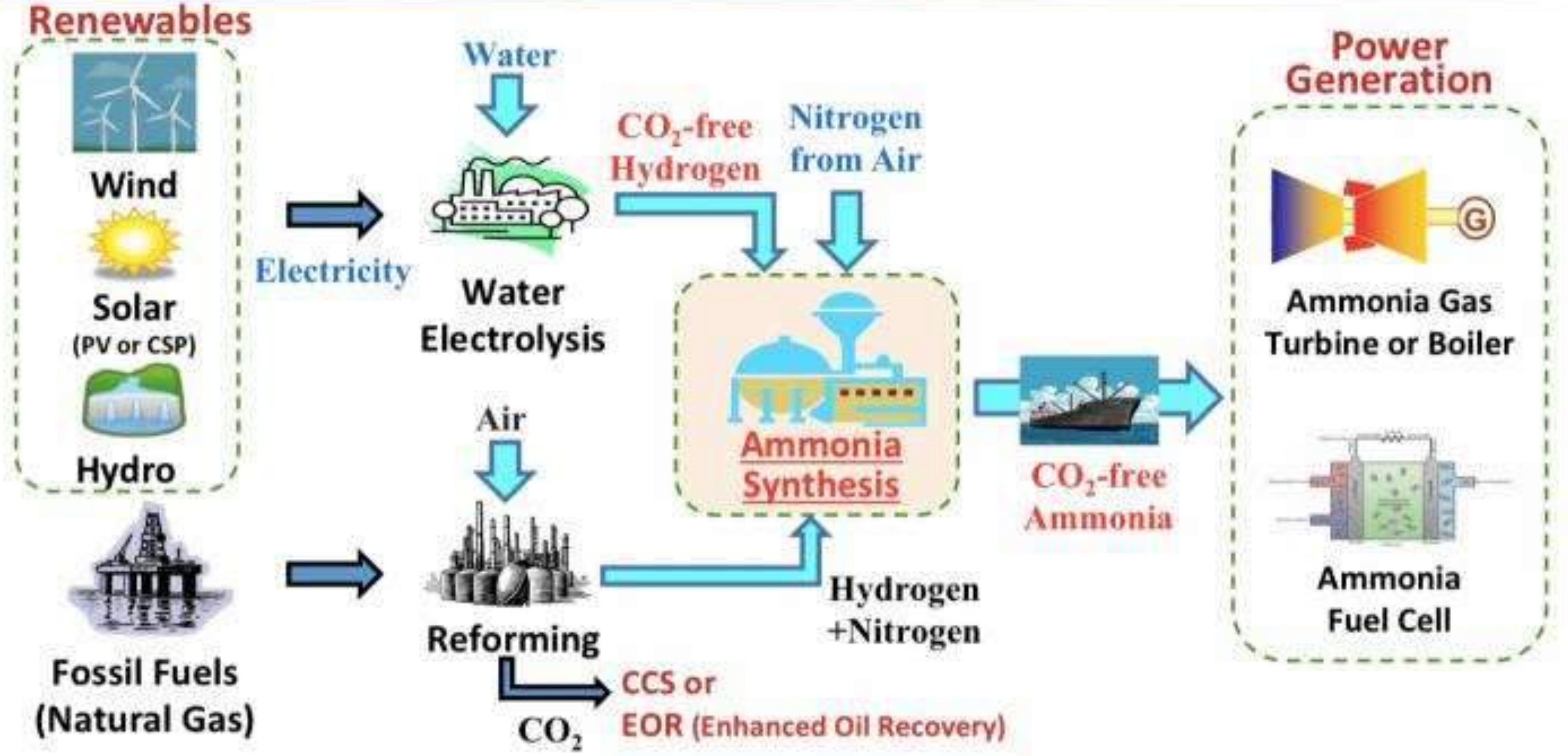
- The implementation of this policy will reduce dependence on fossil fuel and also reduce crude oil imports.
- To meet 50 per cent of the country's energy requirements using renewable energy sources by 2030.



Benefits of Hydrogen Economy


Supply Chain of Green Ammonia
and Green Hydrogen
Wind Power
Solar Power
Hydro Power
O2
H2
Water Electrolysis
Green Hydrogen
+ Nitrogen
Synthesis into Ammonia
Transportation of Ammonia
(can be used as a fertilizer)
Decomposition of Ammonia into Green Hydrogen
Power Generation
Heat Production
Engines
Fuel Cells
(uses of green hydrogen)

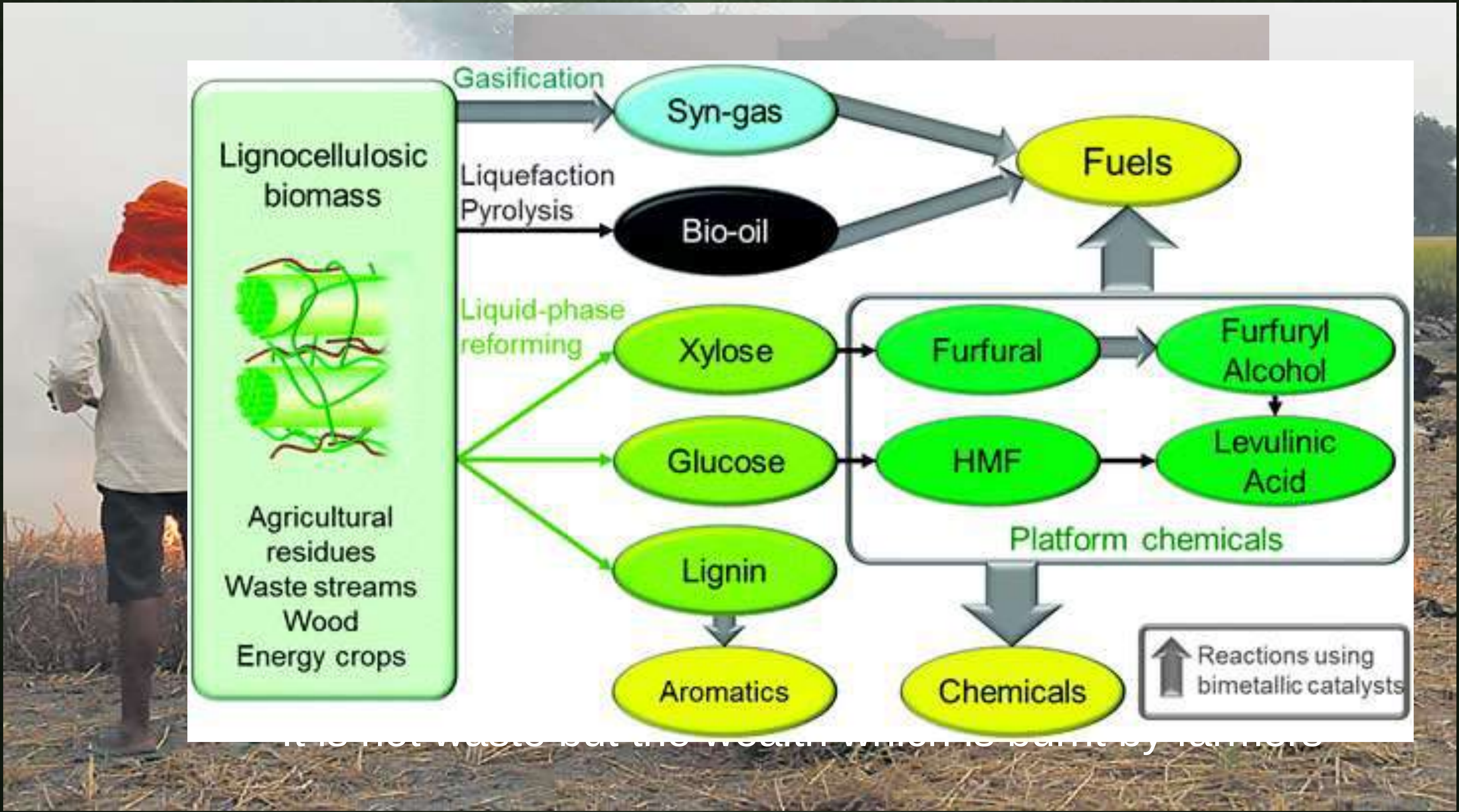
Supply Chain of CO_2-free Ammonia

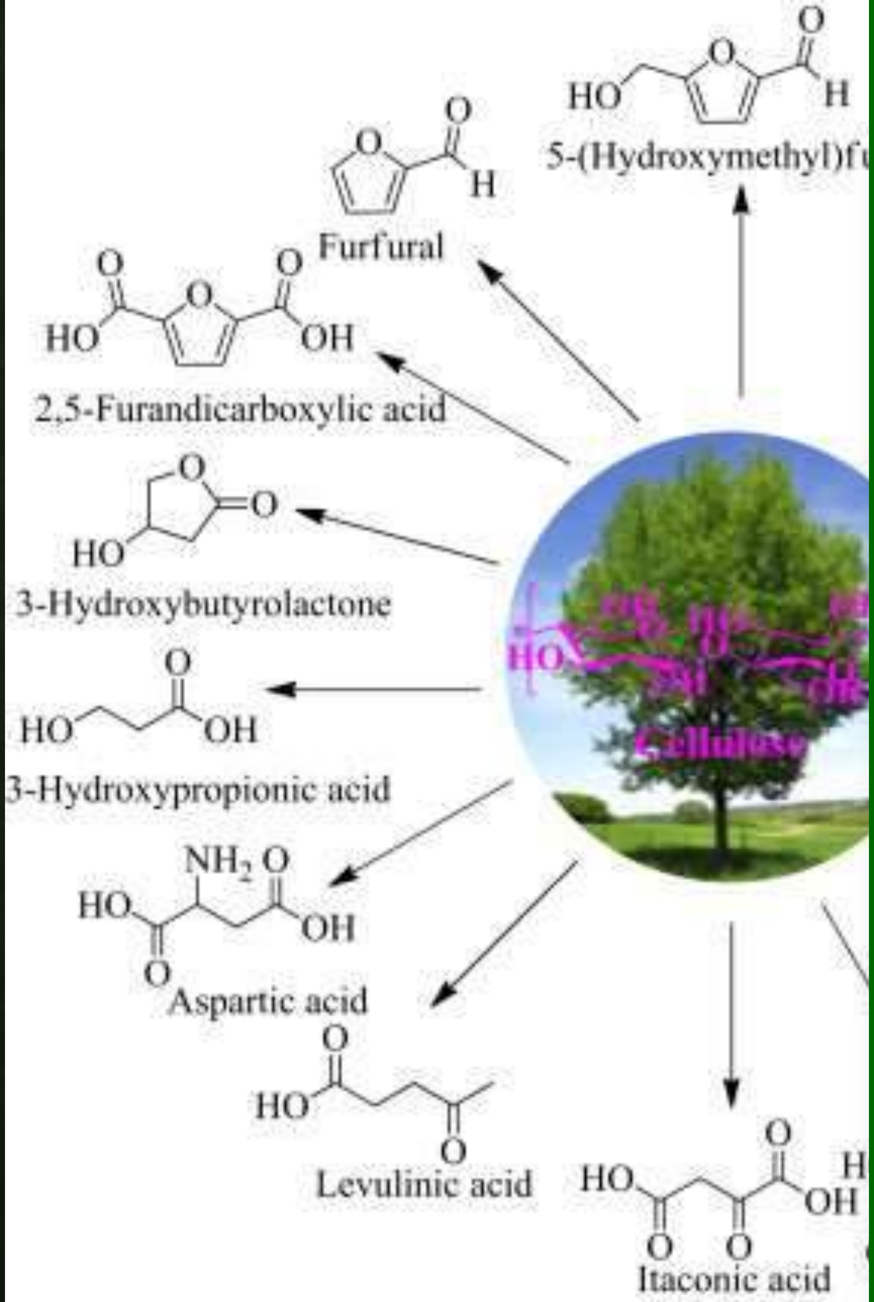


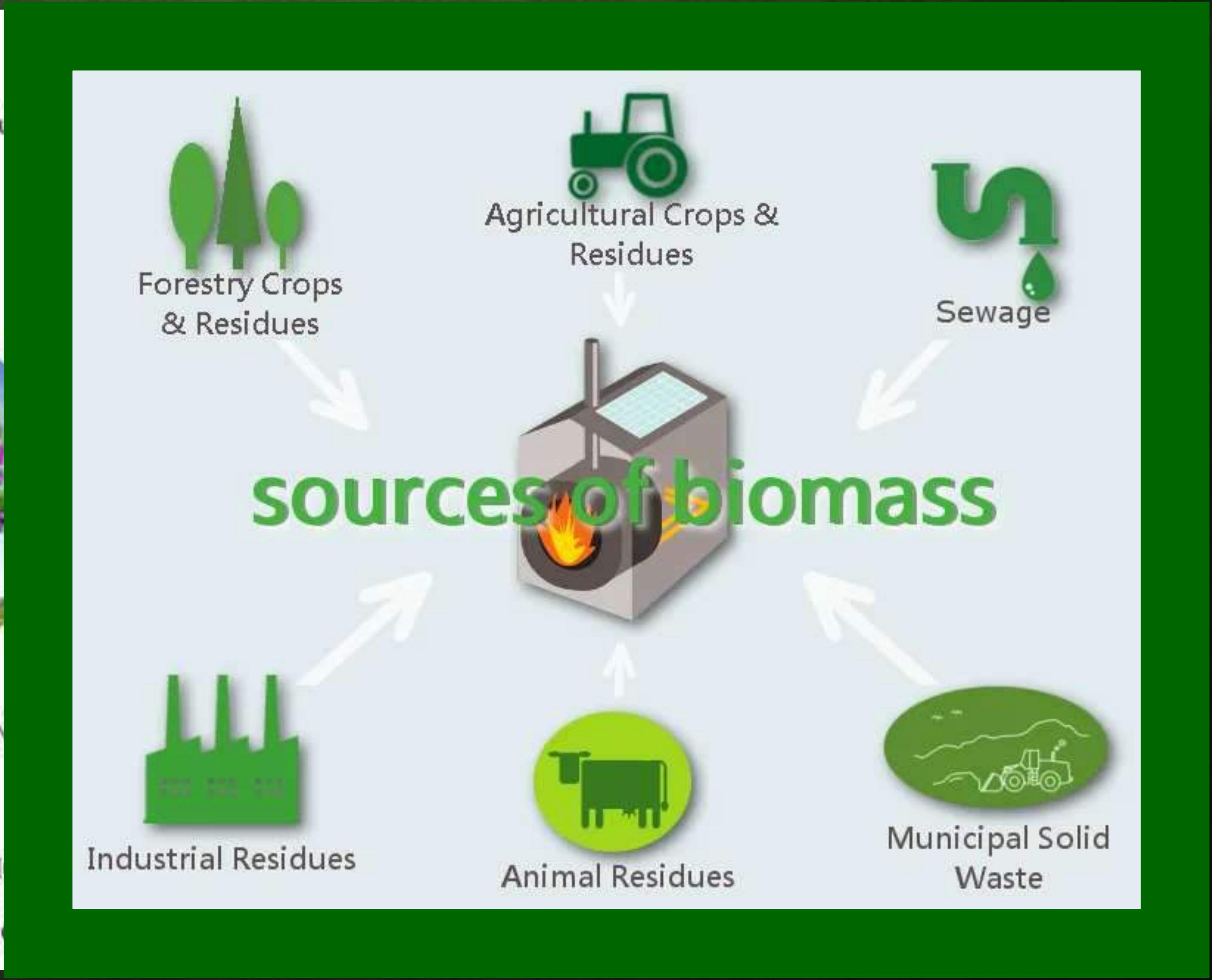
Carbon based fuels and H_2 as Saviour

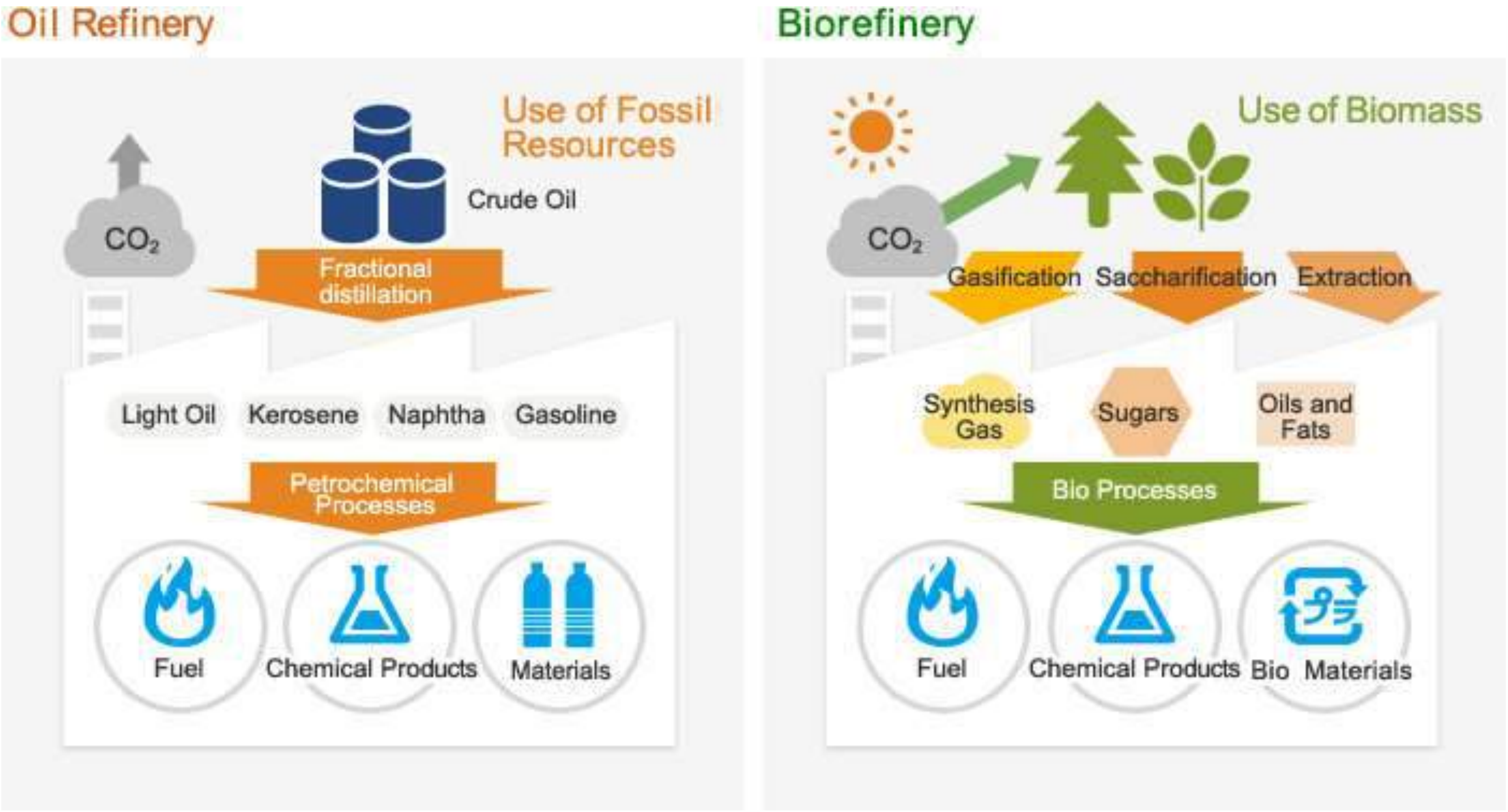
- Whether the carbon is coming from fossil fuels or biofuels, there is a need to convert CO_2 into fuels, chemicals and materials.
- Hydrogen is the cleanest fuel which can be produced from hydrocarbons or from water and can be used to convert CO_2 into useful products, and treatment of (waste) biomass into hydrocarbons with the help of novel catalysts.
- Hydrocarbons can also be reformed into hydrogen, but CO_2 needs to be utilized.
- Hydrogen will be the SAVIOUR for the planet EARTH.

Ref: G.D. Yadav, The Case for Hydrogen Economy, *Millennium Post*, 14th Feb. 2021; Guest Editorial, Current Science, March 2021


Gasification
Syn-gas
Fuels
Lignocellulosic biomass
Liquefaction
Pyrolysis
Bio-oil
Liquid-phase reforming
Xylose
Furfural
Furfuryl Alcohol
Glucose
HMF
Levulinic Acid
Platform chemicals
Lignin
Agricultural residues
Waste streams
Wood
Energy crops
Aromatics
Chemicals
Reactions using bimetallic catalysts

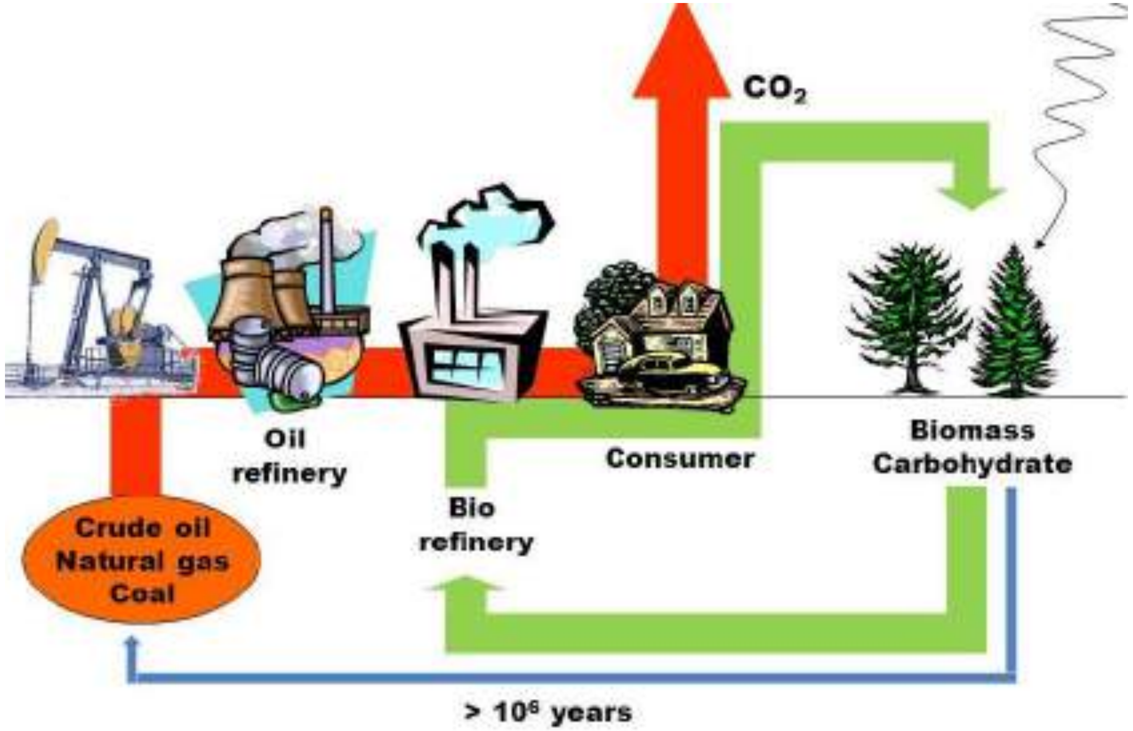

5-(Hydroxymethyl)fu
Furfural
2,5-Furandicarboxylic acid
3-Hydroxybutyrolactone
3-Hydroxypropionic acid
Cellulose
Aspartic acid
Levulinic acid
Itaconic acid


Forestry Crops & Residues
Agricultural Crops & Residues
Sewage
sources of biomass
Industrial Residues
Animal Residues
Municipal Solid Waste

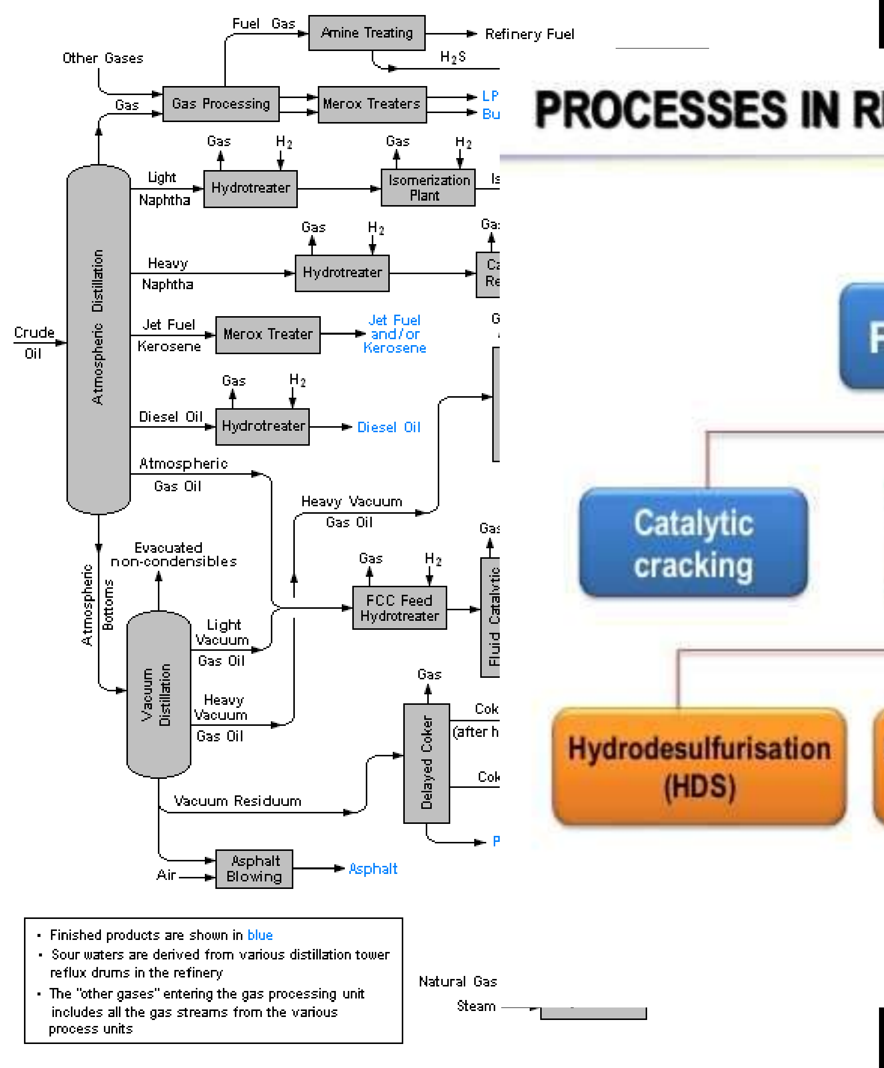

Oil Refinery
Use of Fossil Resources
CO_2
Crude Oil
Fractional distillation
Light Oil
Kerosene
Naphtha
Gasoline
Petrochemical Processes
Fuel
Chemical Products
Materials
Biorefinery
Use of Biomass
CO_2
Gasification
Saccharification
Extraction
Synthesis Gas
Sugars
Oils and Fats
Bio Processes
Fuel
Chemical Products
Bio Materials

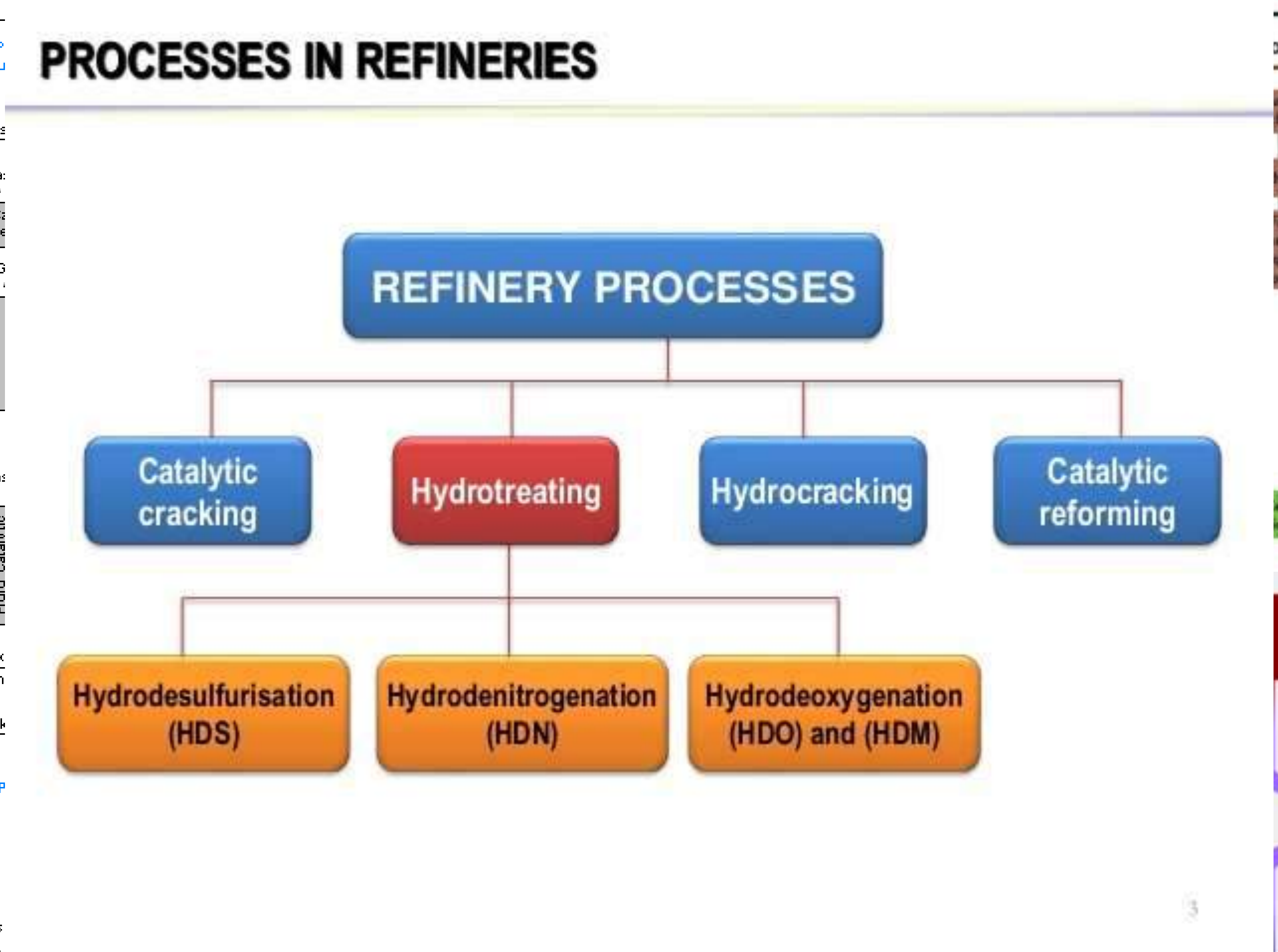
Basic Questions for Planners and Energy Experts

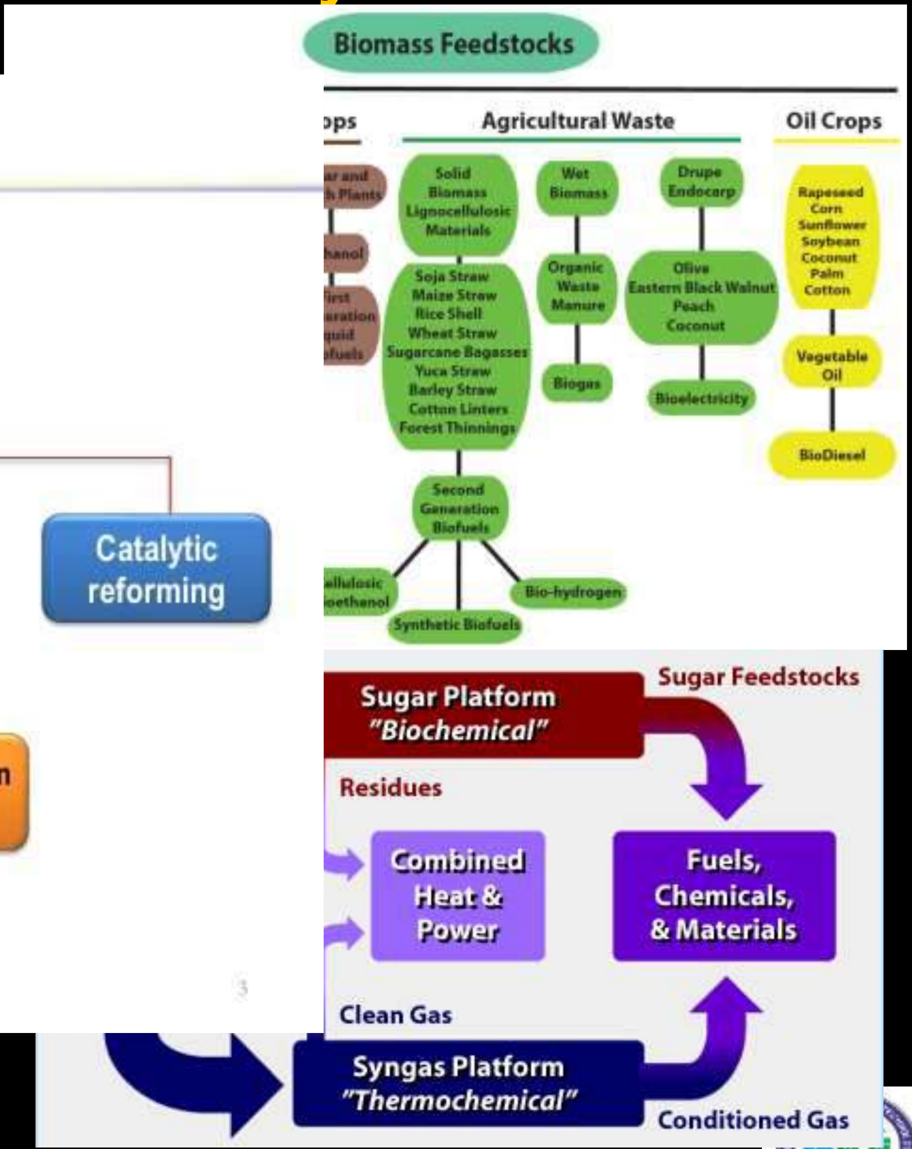
- Should biomass be wasted on making low value high volume biofuels?
- Biomass to chemicals & materials.
- What will happen in 2054 ?
- How to have a net-zero economy by 2050



Hydrogen Usage in Oil Refinery & Biorefinery

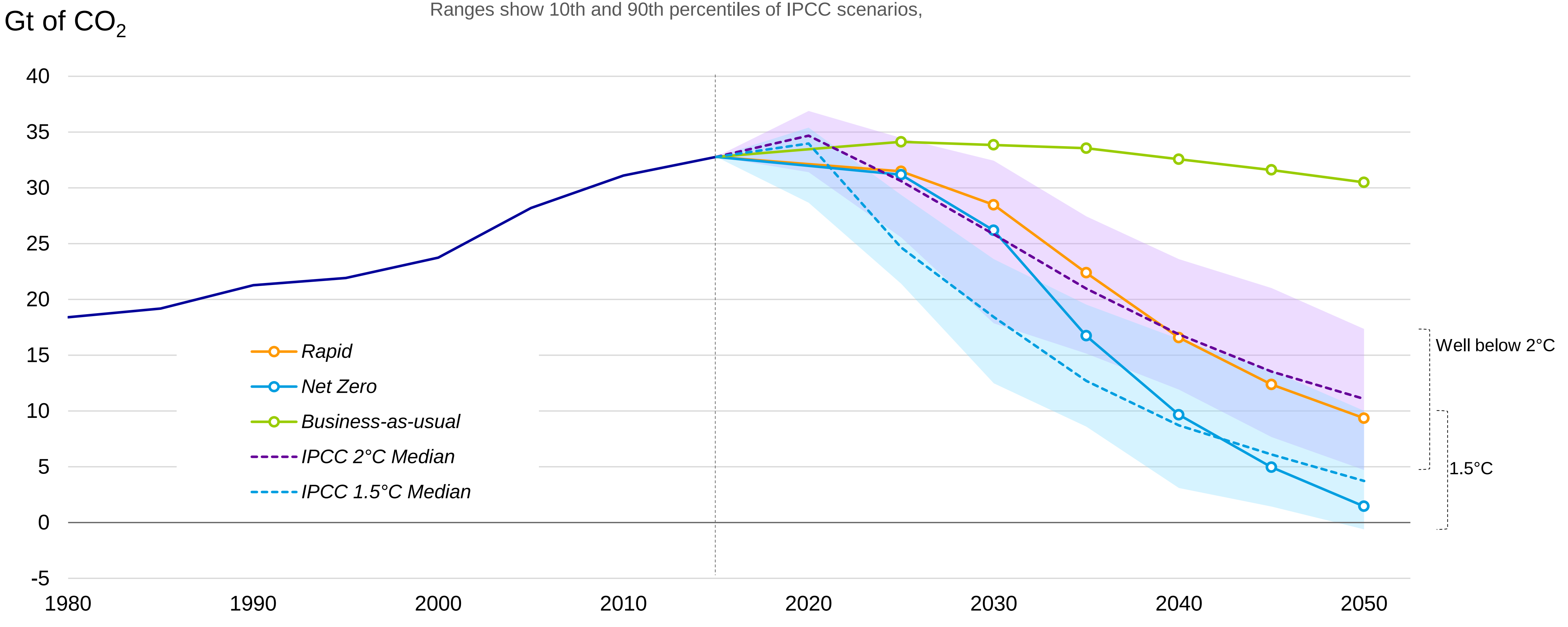






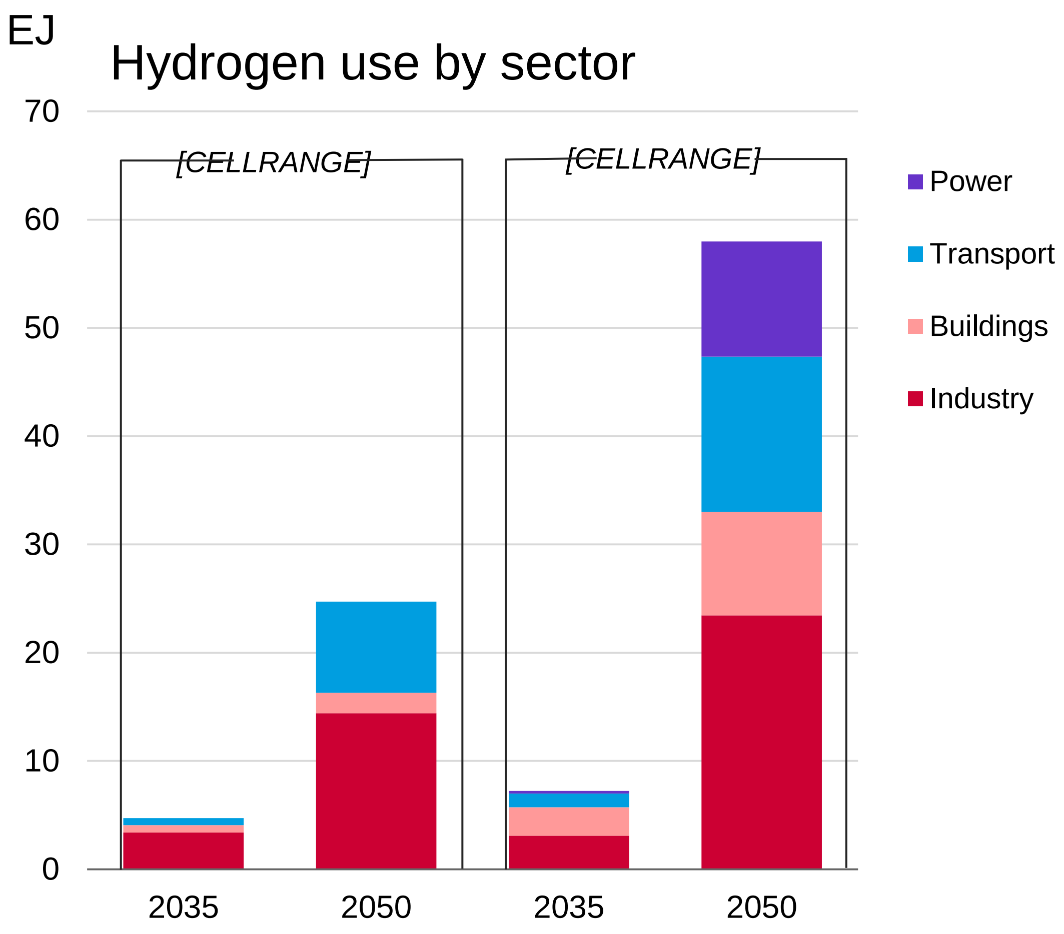
Three scenarios to explore the energy transition: BP Energy Outlook 2020/2021

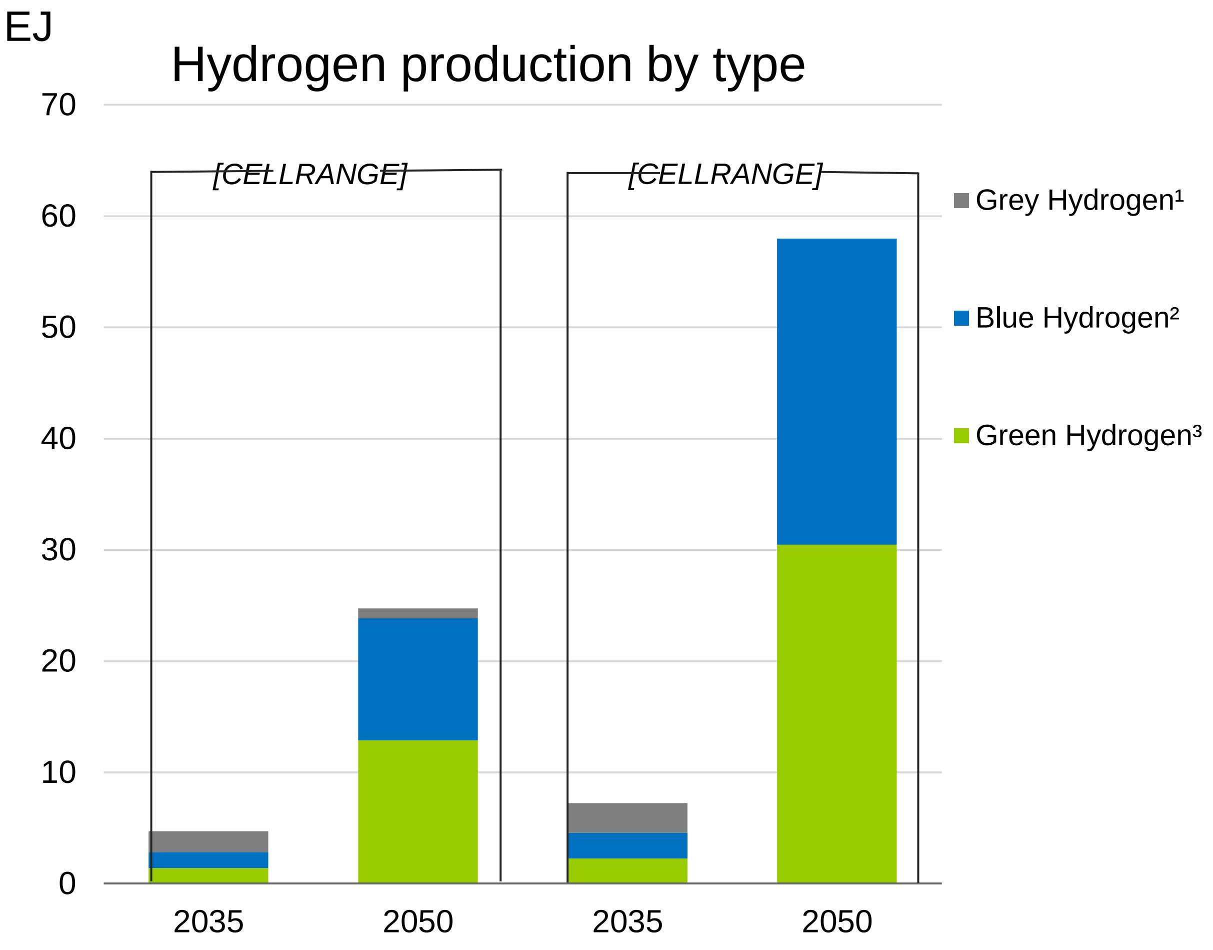
CO_2 emissions from energy use



Consumption and production of hydrogen

EU, IHC, BNEF: Hydrogen growth from 2% of the global energy mix in 2018 to 13–24% by 2050, at ~ 8% CAGR at the mid-point. Investment of USD 150B by 2030





1) produced from natural gas (or coal), without CCUS.
2) produced from natural gas (or coal) with CCUS
3) made by electrolysis, using renewable power

H_2 The Cleanest Fuel

COLOURLESS AND ODOURLESS

DOES NOT EASILY SPONTANEOUSLY COMBUST, IGNITION POINT 570 ^{o}C (<PETROL 500 ^{o}C)

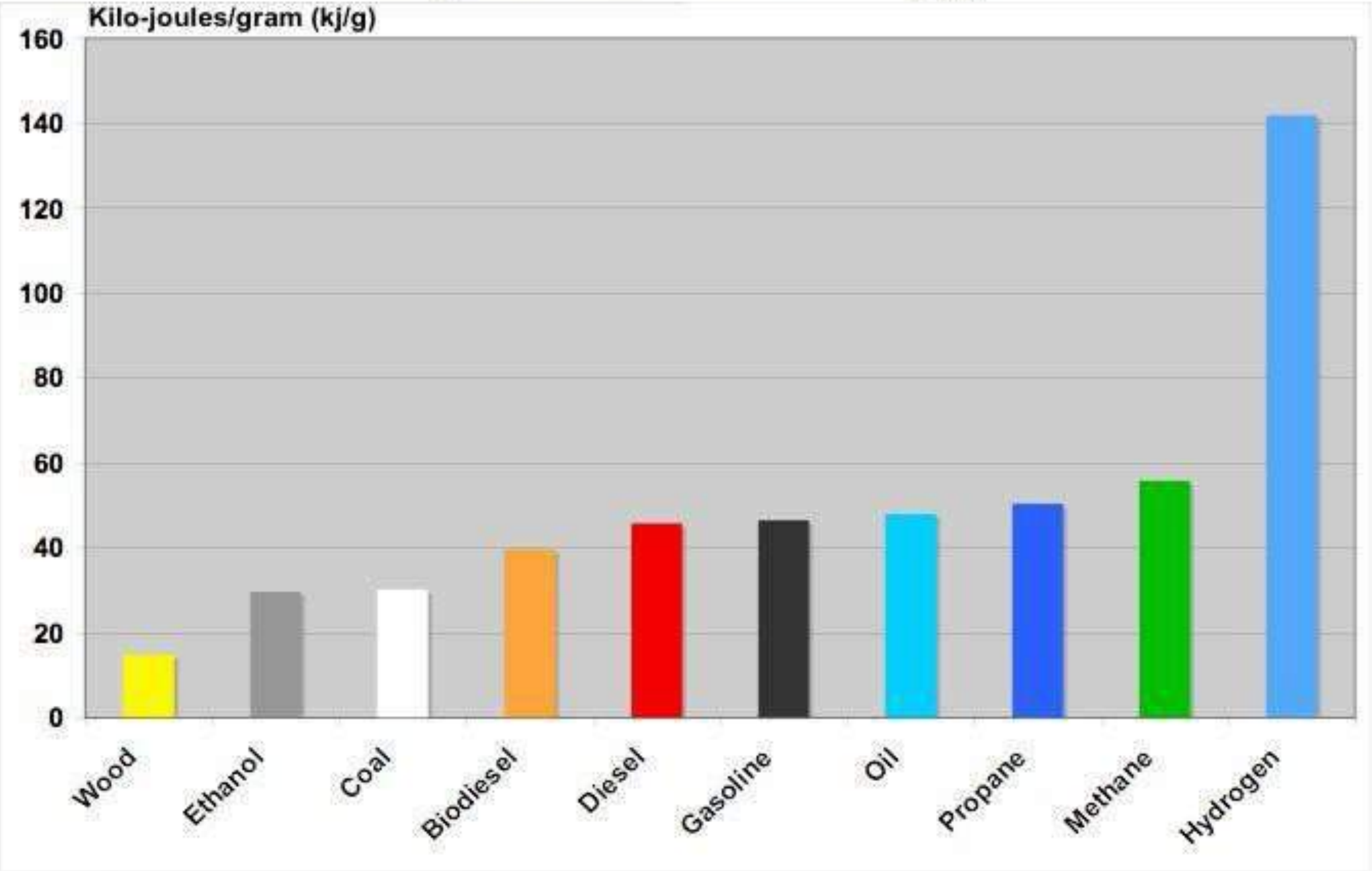
LIGHTEST WEIGHT

EXTREMELY LOW BOILING TEMPERATURE (-253 ^{o}C)

HIGH COMBUSTION TEMPERATURE (3000 ^{o}C)

PRODUCES NO FLAMES WHEN BURNT; REDUCES GREEN HOUSE EFFECTS

Specific Energy



Source: DOE, Green Econometrics research

Hydrogen Production

For the hydrogen economy to be a reality, hydrogen must be produced cheaply and in an ecofriendly manner, and it should serve as the commercial fuel that would provide a substantial portion of the country’s energy demand and services.

Net-(carbon)-zero economy, green hydrogen will have to play a dominant role

Green, Blue and Grey Hydrogen

1

Green H_2 : Electrolysis of water using clean electricity from wind, solar, hydro, or nuclear energy or Thermochemical Processes like Cu-Cl or I-S cycles. Gold standard. Zero GHG emissions.

2

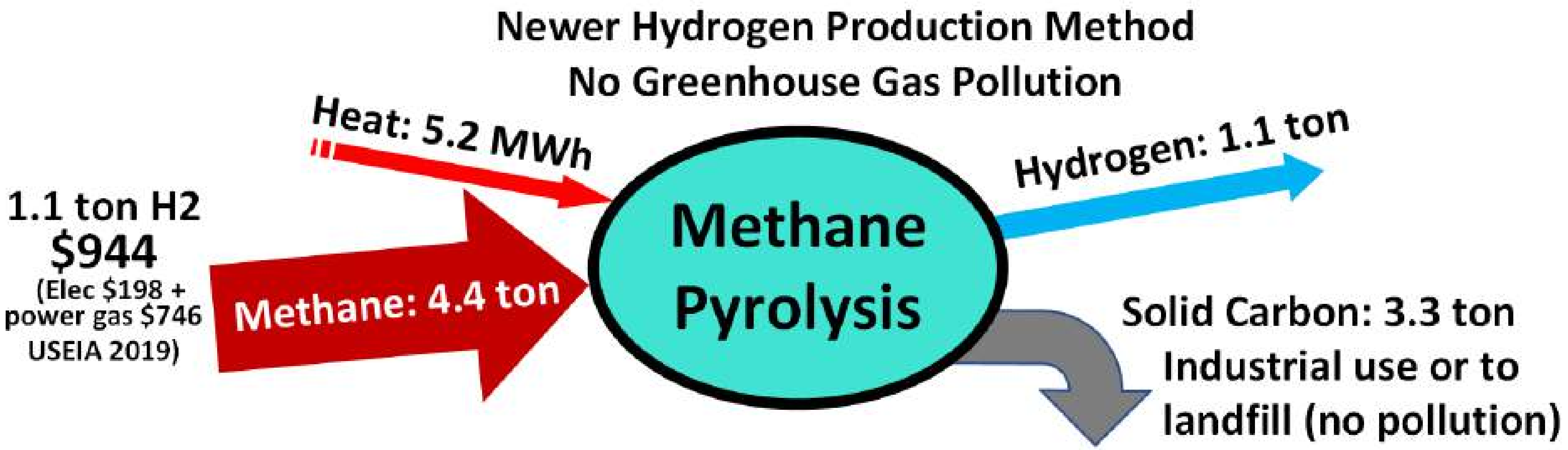
Blue H_2: Steam reforming of (waste) biomass, biogas, biooil, or natural gas giving the other C as CO_2.

Captures up to 90% of the C having low to moderate carbon intensity.

3

Grey H_2: Steam reforming of fossil coupled with co-generation of carbon dioxide; and this method is the most common technology which is increasingly unpalatable because of the emissions of carbon dioxide.

Hydrogen production without carbon dioxide



Five shades of hydrogen

Green

Electricity from renewable sources is used to electrolyse water H_2O and separate the hydrogen H_2 and oxygen O

Blue

Produced using natural gas via "steam reformation"; most of the greenhouse gas emissions are captured and stored

Turquoise

Produced using natural gas via "pyrolisis" by separating methane into hydrogen H_2 and solid carbon dioxide CO_2

Grey

Produced using natural gas via "steam reformation", but with no carbon capture and storage

Brown

Produced using coal instead of natural gas, but with no carbon capture and storage; this remains the cheapest form

Cost comparison of different hydrogen production technologies

Brown	Grey	Blue	Green
Coal	Natural gas	Natural gas	Renewable electricity
Gasification No CCS	Steam methane reforming No CCS	Advanced gas reforming CCS	Electrolysis
Highest GHG emissions (19 tCO_2/tH_2)	High GHG emissions (11 tCO_2/tH_2)	Low ((0.	
\$1.2 to \$2.1 per kg H_2	\$1 – \$2.1 per kg H_2	\$1.5 -	

ICT Mumbai-OEC Process
\$ 0.95 per kg Hydrogen plus 0.80 credit for Oxygen for 100 TPD capacity

Note: GHG – greenhouse gas; CCS – carbon capture and storage; tCO_2/tH_2 – tonne of carbon dioxide per tonne of hydrogen.
Source: IEA, The Future of Hydrogen, Karuizawa, Japan, June 2019.

ICT-OEC Cu-Cl Thermochemical Process for Green Hydrogen Production: Pilot to Commercial Scale Roadmap-Make in India !

G.D. Yadav,

D.Sc., D.Eng. *FNA, USNAE, FTWAS*

National Science Chair (SERB/DST)

Emeritus Professor of Eminence

Institute of Chemical Technology Mumbai

Brief Overview

ICT in collaboration with OEC have been developing hydrogen production technology using thermochemical Cu-Cl cycle with indigenous efforts since 2007.

2007-11

Phase I

Proof of concept

2012-15

Phase II

Laboratory Scale engineering process

2014-17

Molten Salt study

Investigation of properties of molten salt as heat storage medium

2015-17

Phase II

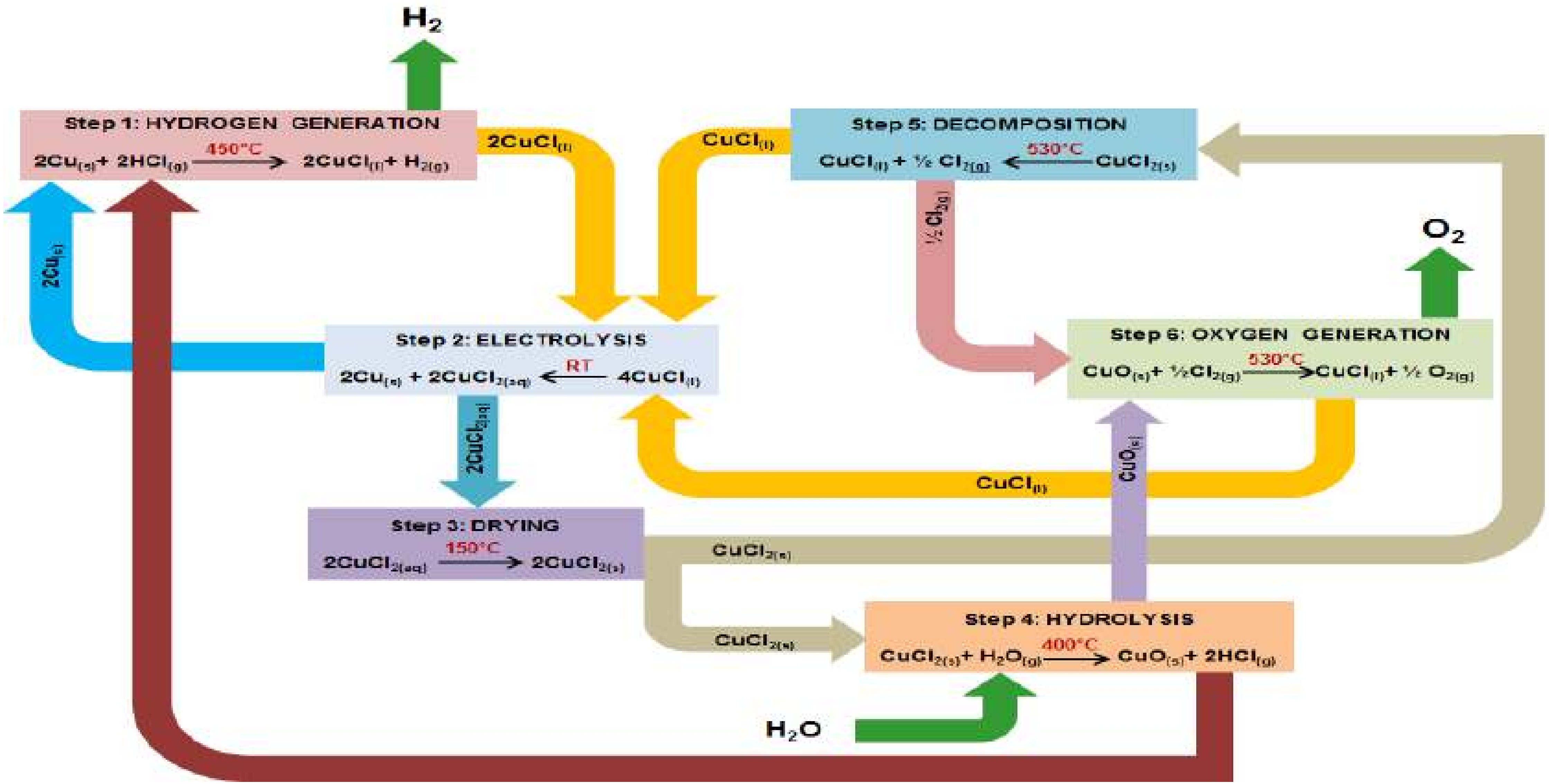
Continuation of closed loop experimental studies & development of electrodes alternative to platinum on CuCl Cycle

2017- ongoing

Phase III (Pilot scale)

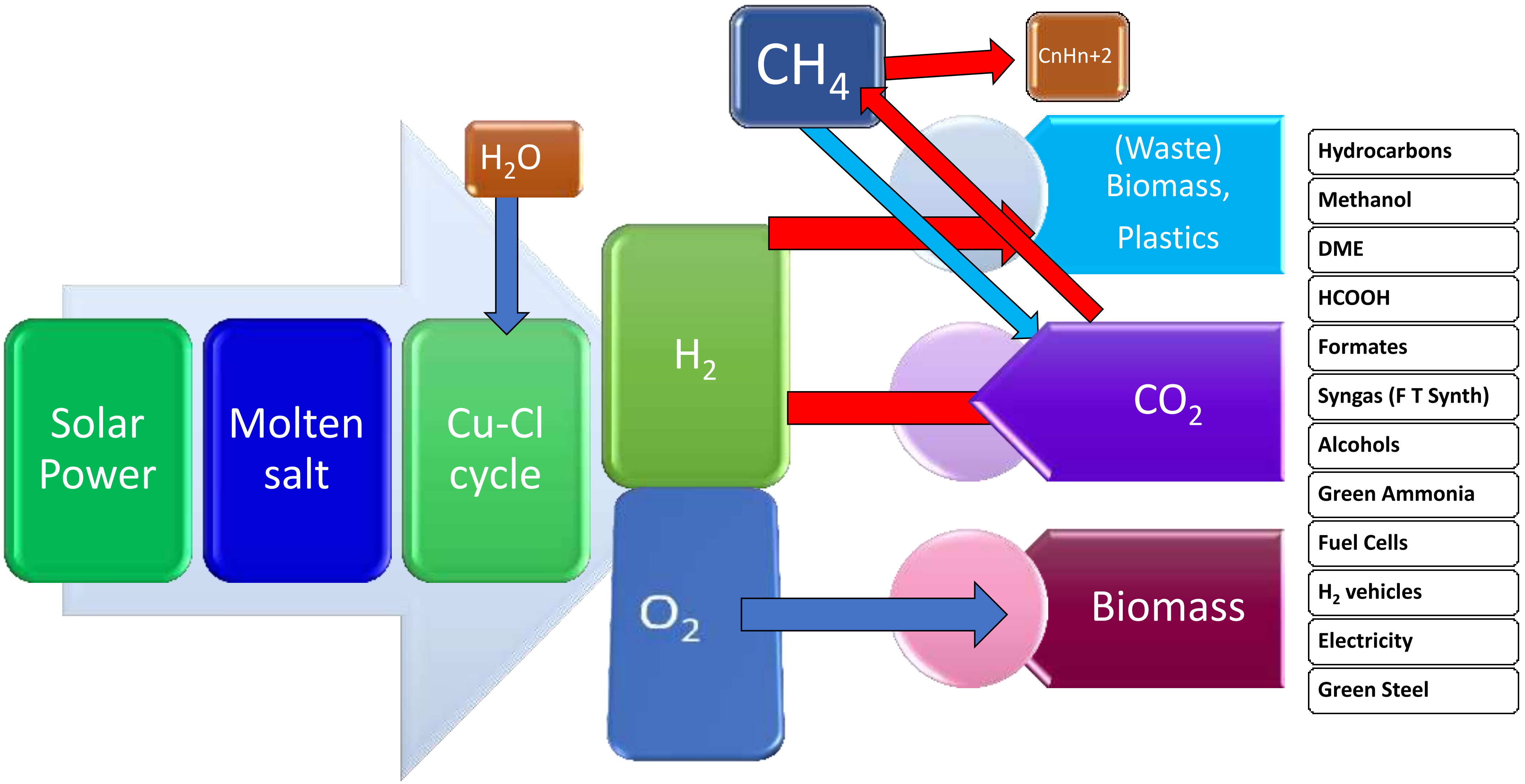
Further investigations on ICT-OEC CuCl Cycle: Studies on Separations, Material screening and integration of molten salt media

ICT-OEC CuCl Cycle



PARIS AGREEMENT 2015: NET ZERO GOAL

Green Hydrogen, CO_2 Refineries & ICT Mumbai's Contribution `



Projected cost of hydrogen by ICT-OEC Process: ~ 1 USD/kg

@ G.D. Yadav

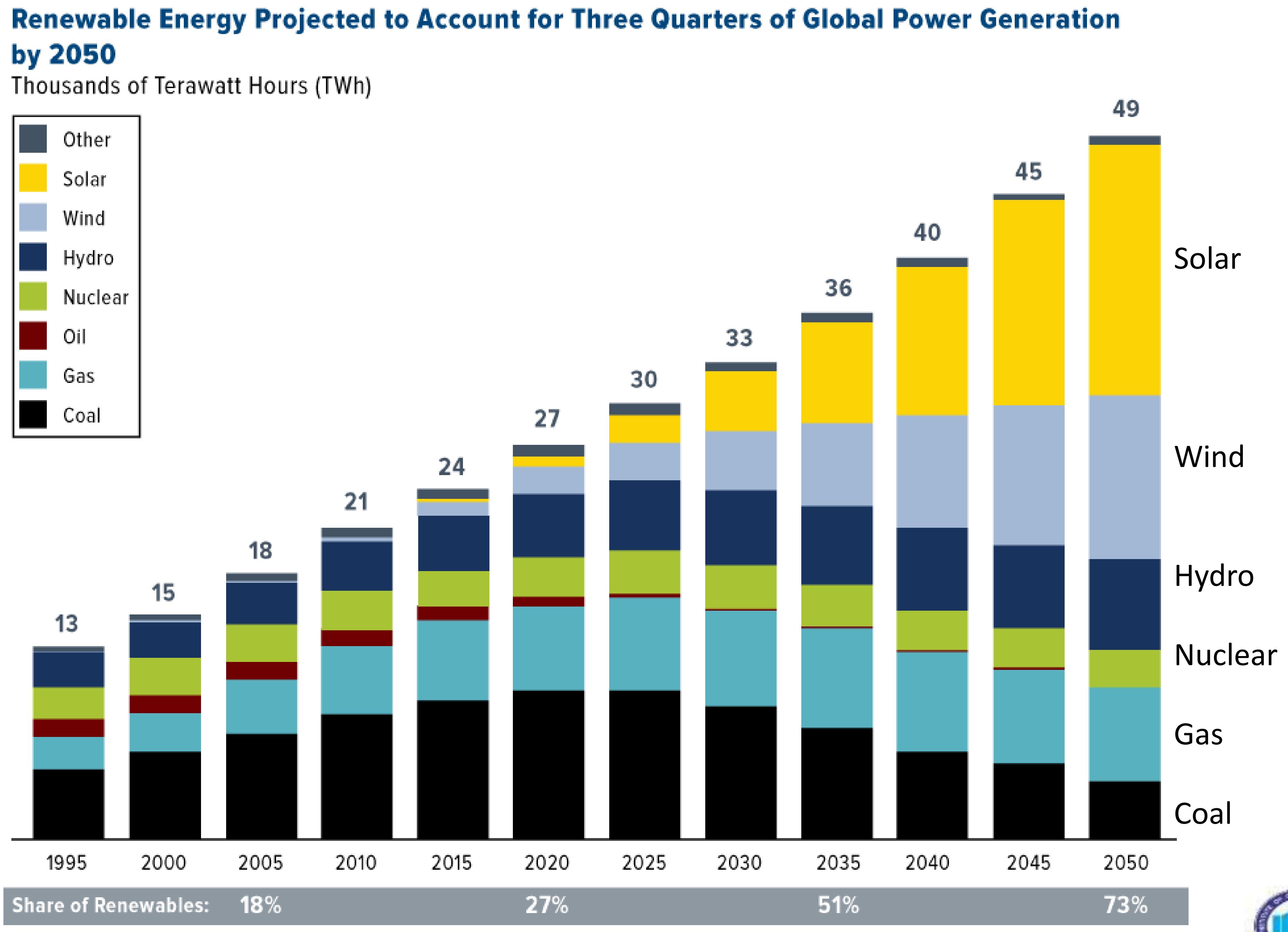
Cost Comparison of Hydrogen for CuCl plant

		Hydrogen Production Capacity				
		12MTPY	50MTPY	100MTPY	1TPD	5TPD
		Cost (INR)	Cost (INR)	Cost (INR)	Cost (INR)	Cost (INR)
Fixed Capital Investment (FCI)	**INR**	111,099,913	261,569,423	396,465,107	862,145,746	2,264,449,775
Working Capital Investment (WCI)	**INR**	19,605,867	46,159,310	69,964,431	152,143,367	399,608,784
Total Capital Investment (TCI)	**INR**	130,705,780	307,728,733	466,429,538	1,014,289,114	2,664,058,558
TOTAL PRODUCT COST	**INR**	18,632,835	43,868,440	66,492,122	144,592,548	379,776,348
PLANT CAPACITY	**tons H_2/day**	0.03288	0.13699	0.274	1	5
LIFE OF CU-CL PLANT	**YEARS**	30	30	30	30	30
MOLAR COST OF HYDROGEN	**INR/kmol H_2**	726.503	410.508	311.107	185.350	97.365
	INR/kg H_2	360.369	203.625	154.319	91.940	48.296
	USD/kmol H_2	9.952	5.623	4.262	2.539	1.334
	USD/kg H_2	4.976	2.812	2.131	1.270	0.667

- Note: **1 kg of H_2 produces 8 kg O_2 which is valued at USD 0.1/kg, giving USD 0.8 credit** .

World Energy Scene

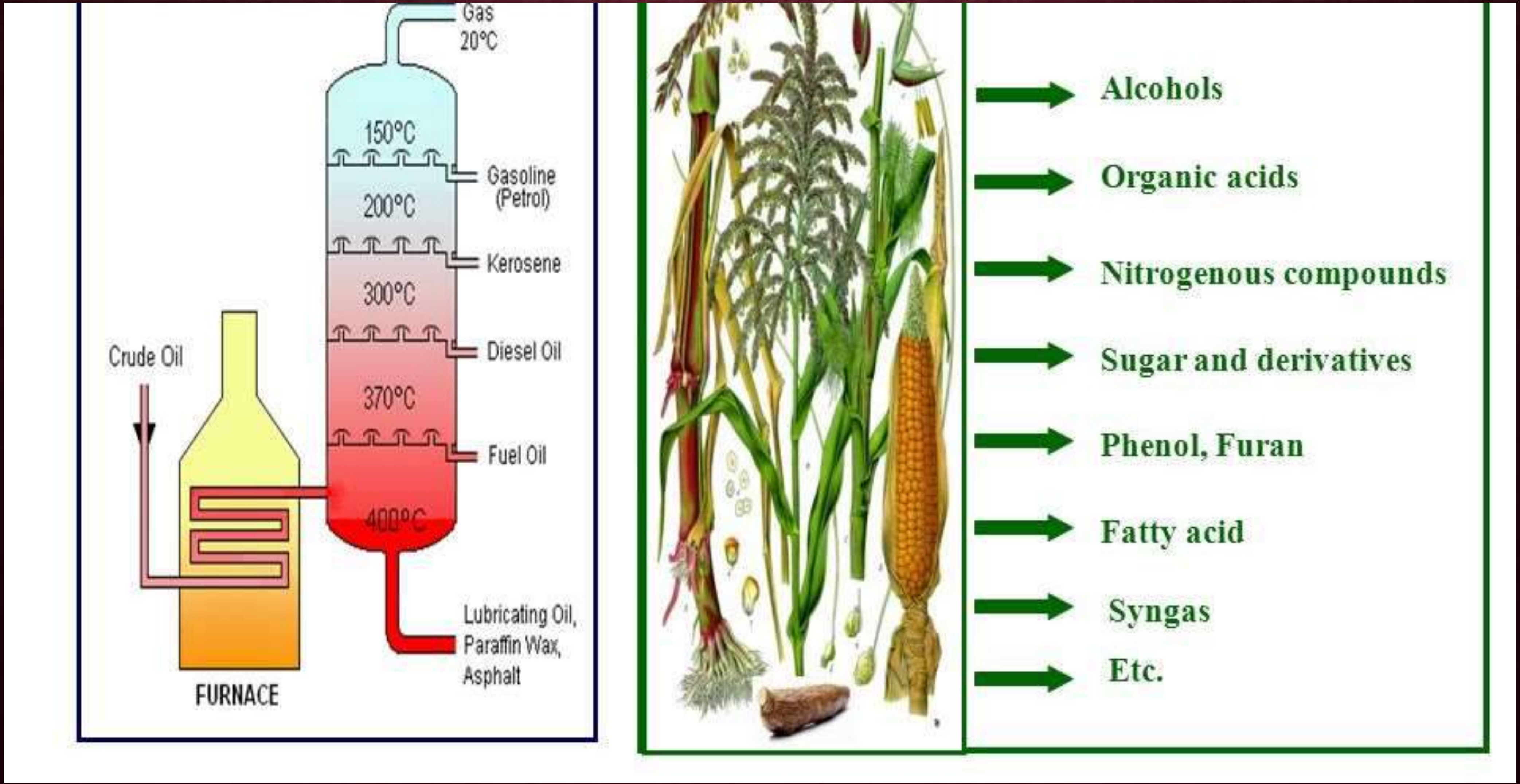
The share of the renewable energy will increase from current ~27% to ~51% by 2035 to ~73% by 2050 totaling 49000 TWh.

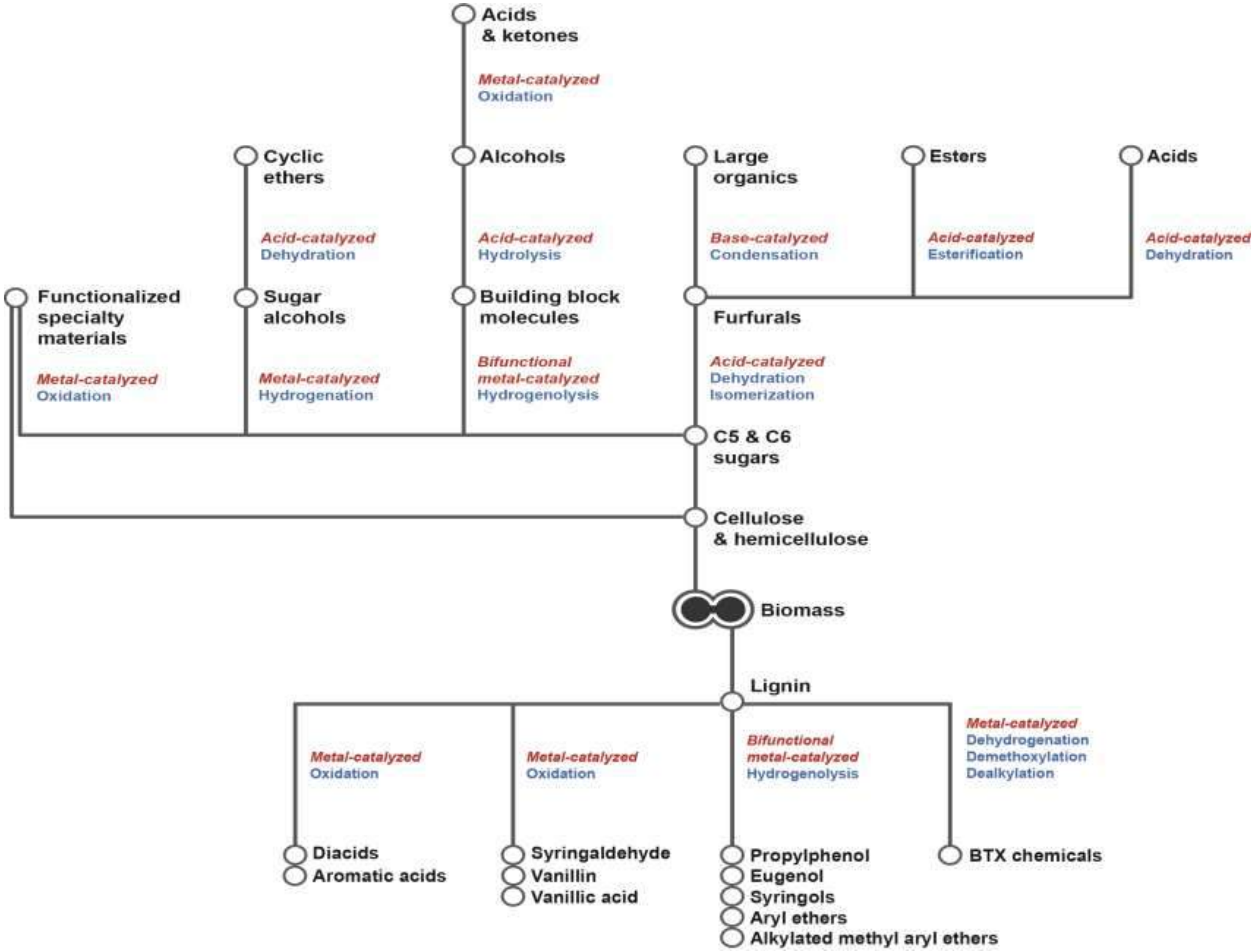


"Other" includes biomass, geothermal and marine.

Source: McKinsey Energy Insights' Global Energy Perspective (January 2019), U.S. Global Investors

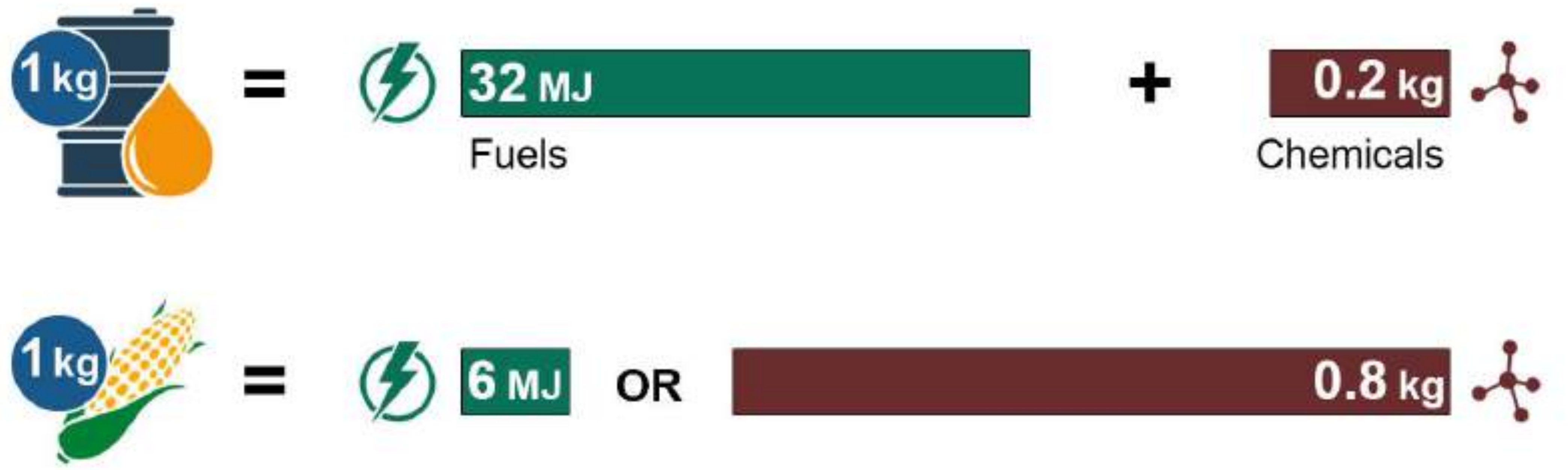
PETROLEUM REFINERY VS. BIOREFINERY





A rich catalog of catalytic processes is available for producing value-added chemicals from biomass.

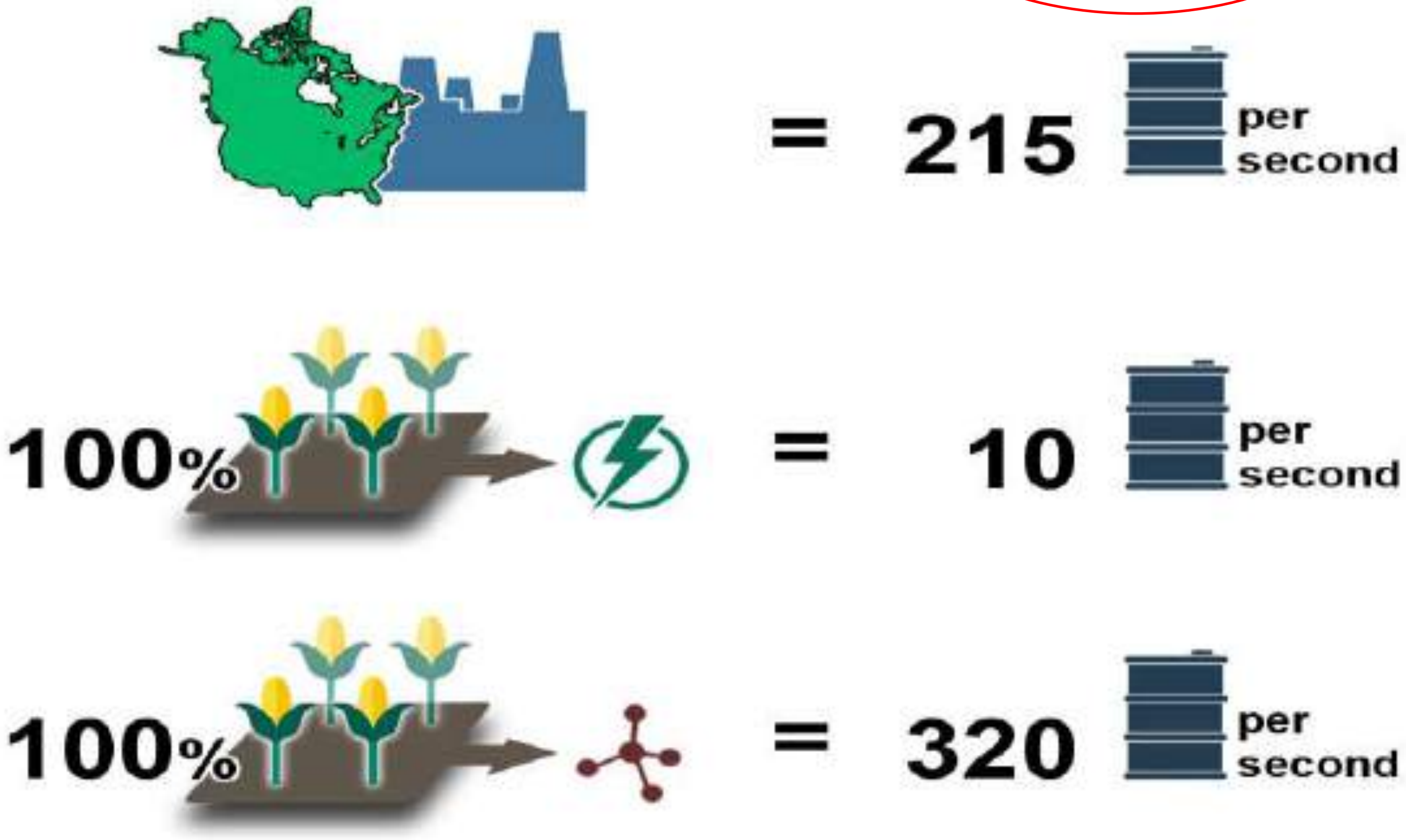
A path forward: Convert, not refine



Energy and mass balances on crude oil and biomass reveal that the latter is better suited for use as a feedstock for chemical manufacturing.

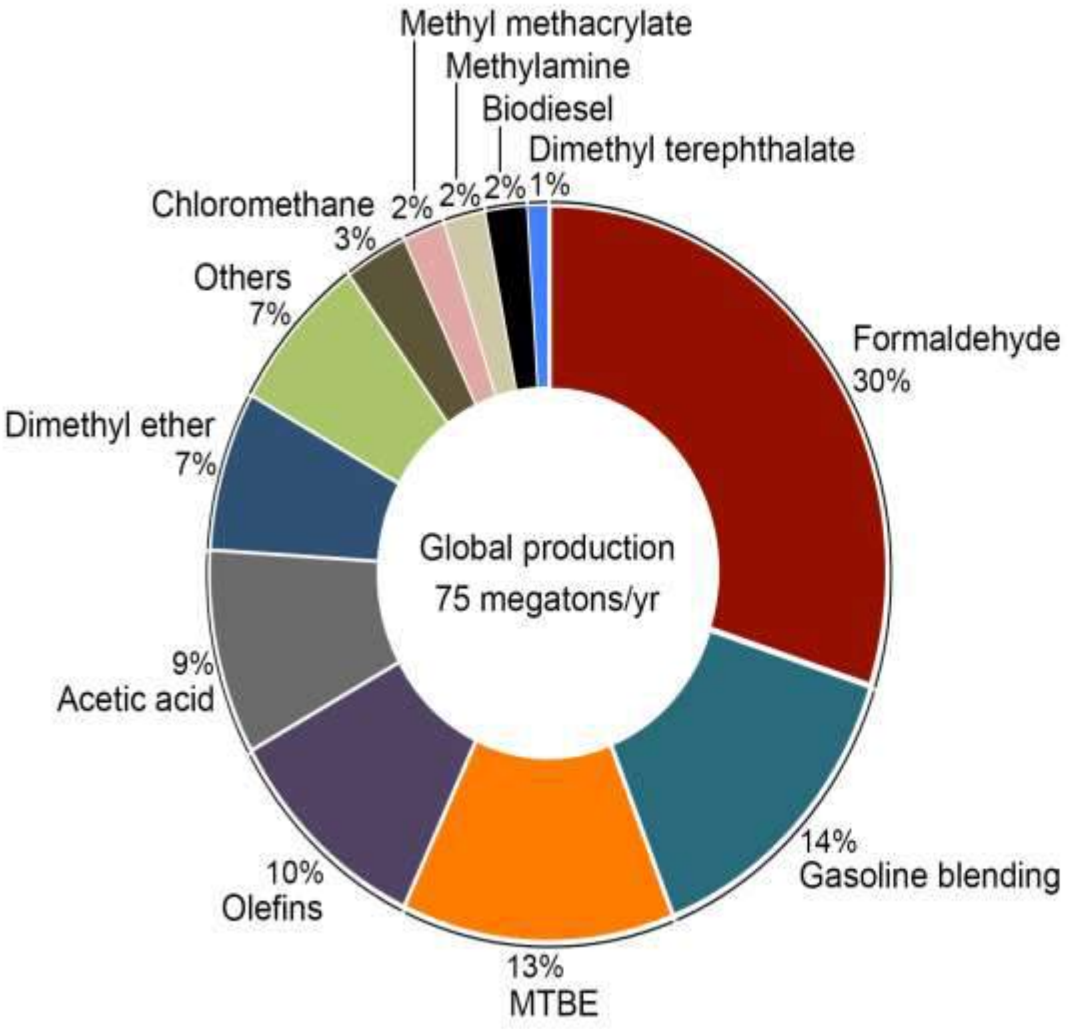
Yadav et al. Clean Tech. Environ. Policy, Sept 2020. https://doi.org/10.1007/s10098-020-01945-5

Which is Better?:Conversion to Chemicals or Fuels



The difference between the fuel and chemical production capacities for biomass, when scaled to refinery output, is even wider, thereby showing that biomass should be used to manufacture chemicals and not fuels. (Yadav et al 2020)

Methanol is a versatile feedstock for the production of fuels and chemicals, although it should be used for for chemical manu



Methanol Economy

Yadav et al. Clean Tech. Environ. Policy, Sept 2020. https://doi.org/10.1007/s10098-020-01945-5

Mondal & Yadav, Green Chem. 2021 : Methanol Economy

Consumer Plastics as Waste

Type 1: polyethylene terephthalate (PET), e.g., plastic beverage bottles

Type 2: high-density polyethylene (HDPE), e.g., milk jugs

Type 3: polyvinyl chloride (PVC), e.g., pipes used in plumbing, vinyl tubing, and wire insulation

Type 4: low-density polyethylene (LDPE), found in plastic sheets or packaging (e.g., bread bags)

Type 5: polypropylene (PP), in bottle caps, packaging, and plastic furniture

Type 6: polystyrene (PS), e.g., drinking straws, beverage lids, and Styrofoam

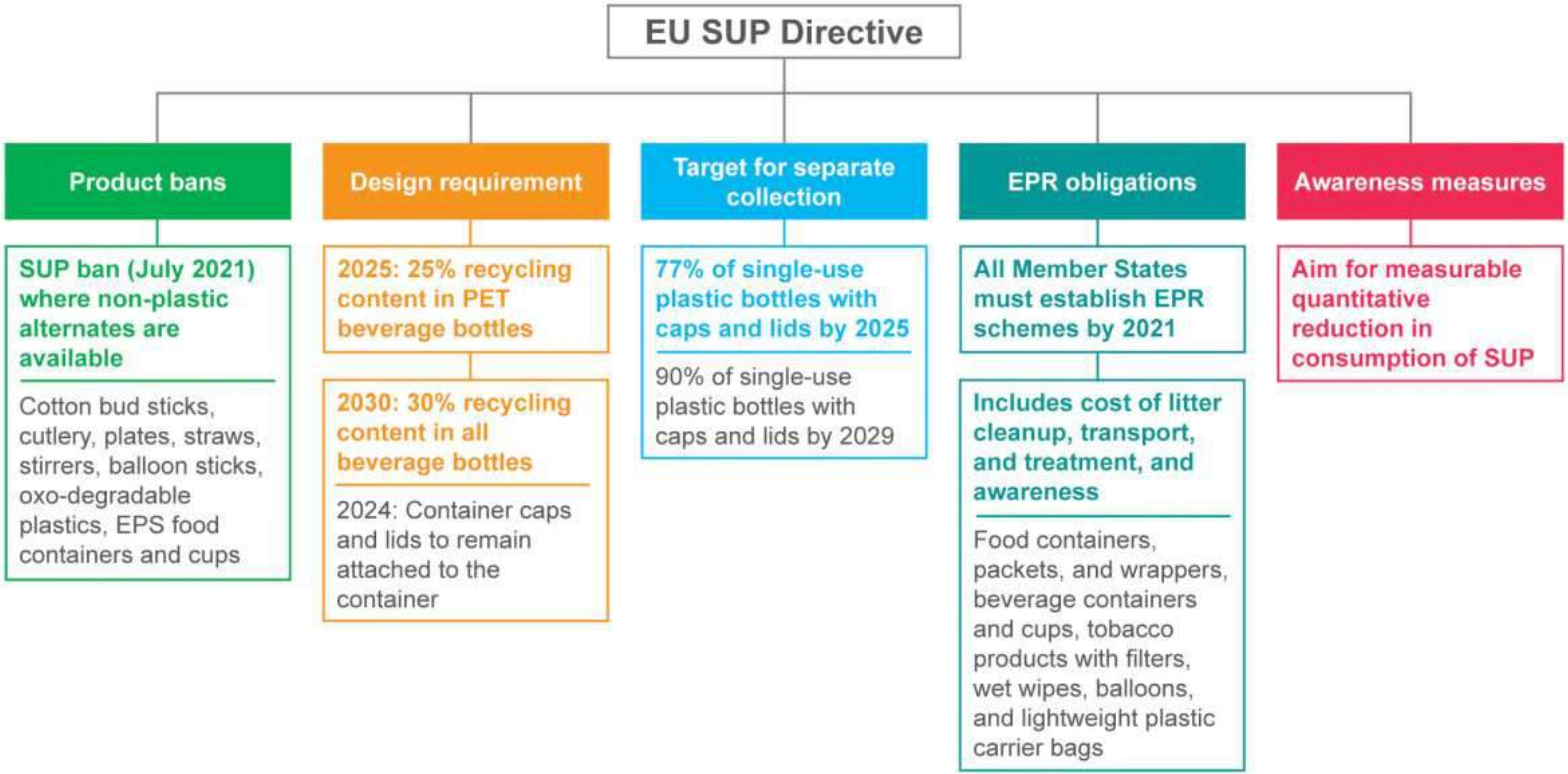
Type 7: other nonrecyclable plastics and all thermoset plastics (e.g., acrylics, nylons, polycarbonates, acrylonitrile butadiene styrene [ABS], and polylactic acid).

Single Use Plastic (SUP): Should it be banned?

Europe

ITEM	ACTION
Balloon sticks	Ban
Cutlery, plates & straws	Ban
Cotton swab sticks	Ban
Drink bottles	Allowed only if caps remain attached
Drink cups	Reduce use
Food containers	Reduce use
Cigarette butts	Awareness, cleanup efforts
Bags	Awareness, cleanup efforts
Snack bags & wrappers	Awareness, cleanup efforts
Wet wipes & sanitary items	Awareness, cleanup efforts

European Single-Use Plastics (SUP) Ban: At a glance



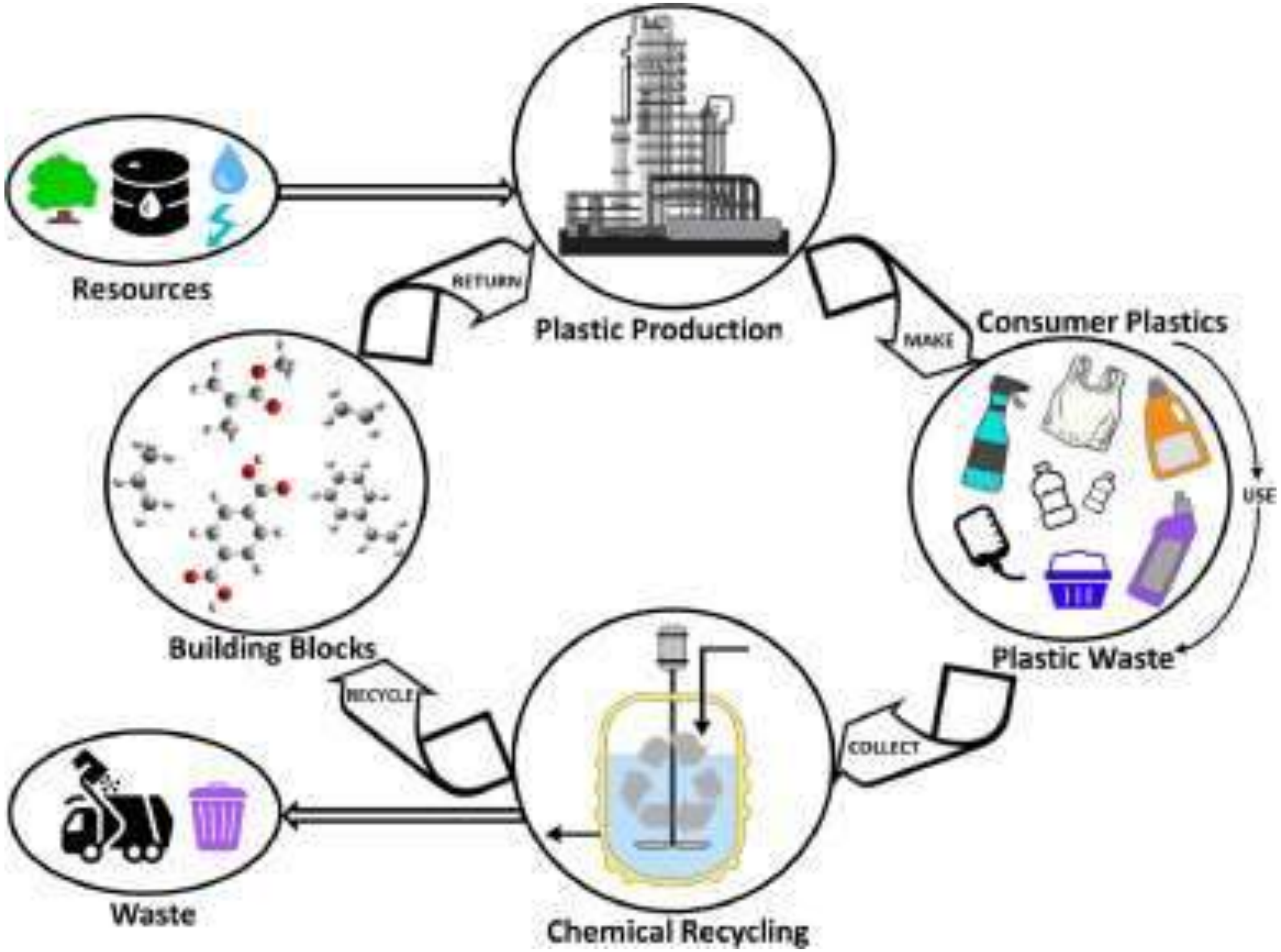
Source: IHS Markit

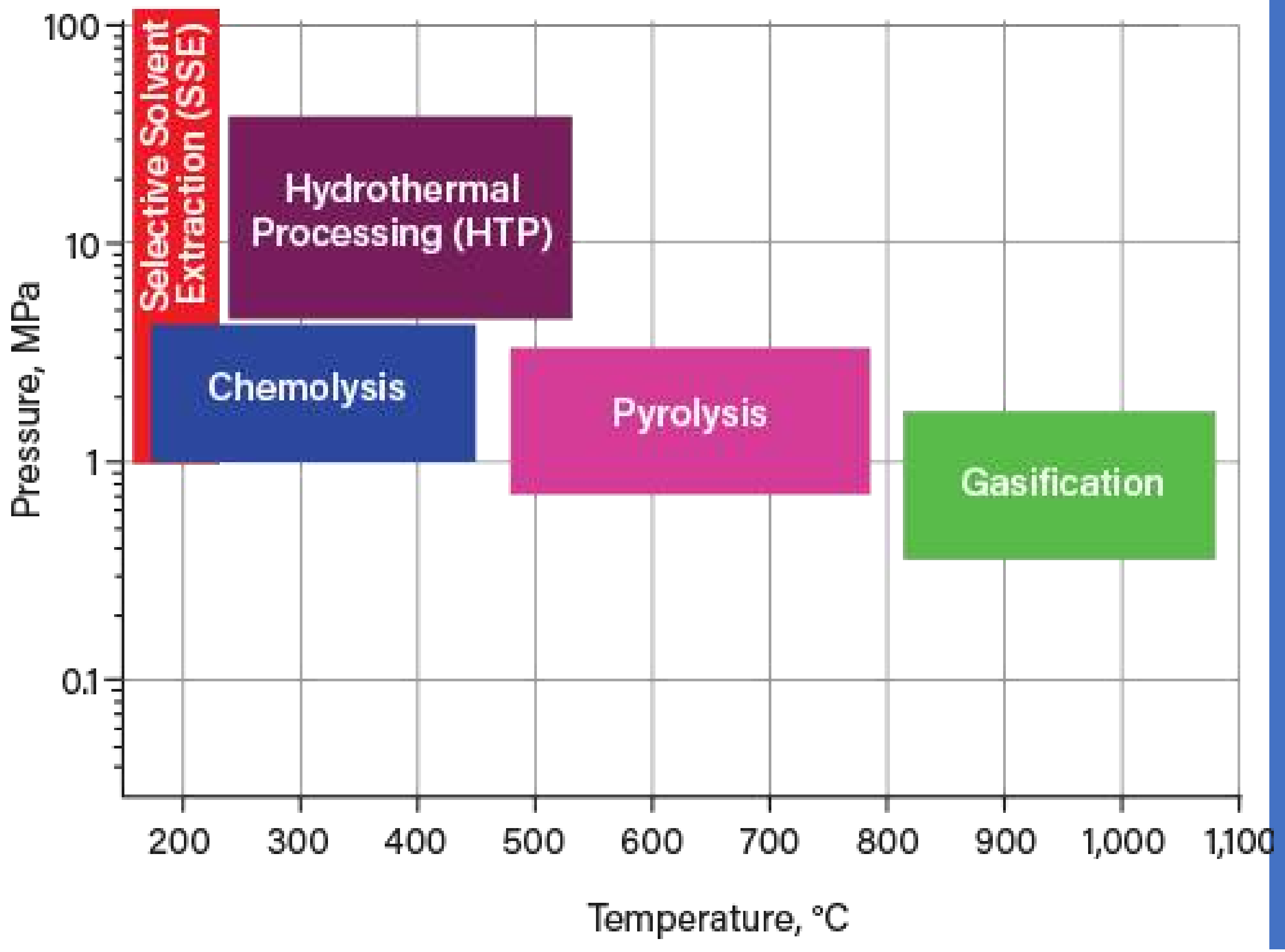
Ban is not the solution

- If one technology creates societal problems due to irresponsible usage by citizens, another technology should solve it. Legislation is then secondary.
- SUP can be recycled using Chemical Processes

Sorting at source whether paper or plastic. Consumers should pay some refundable deposit. Plastic boy collects it and charges 5% as collection fee and refunds the deposit digitally.

Chemical Recycling of Plastics



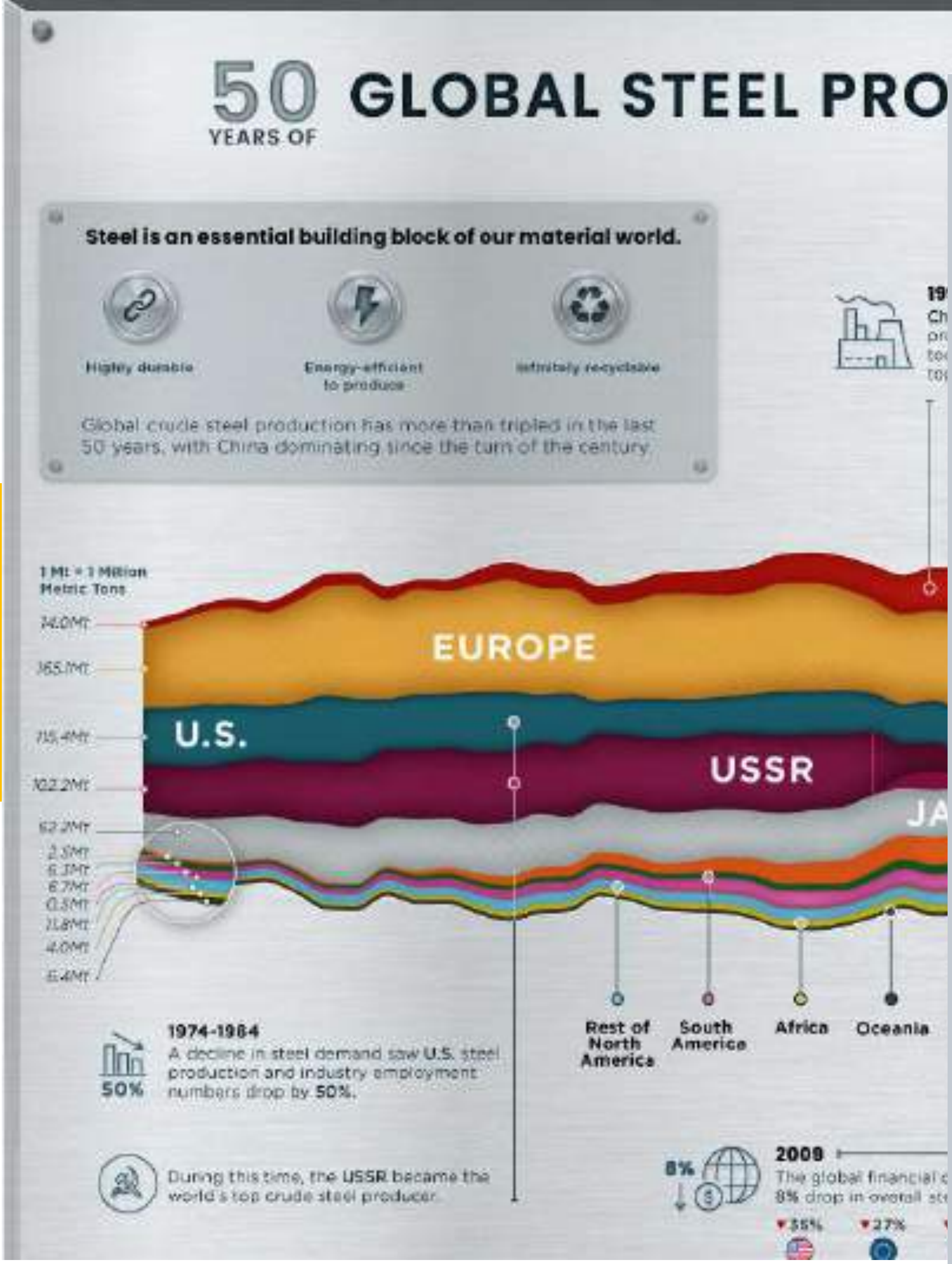


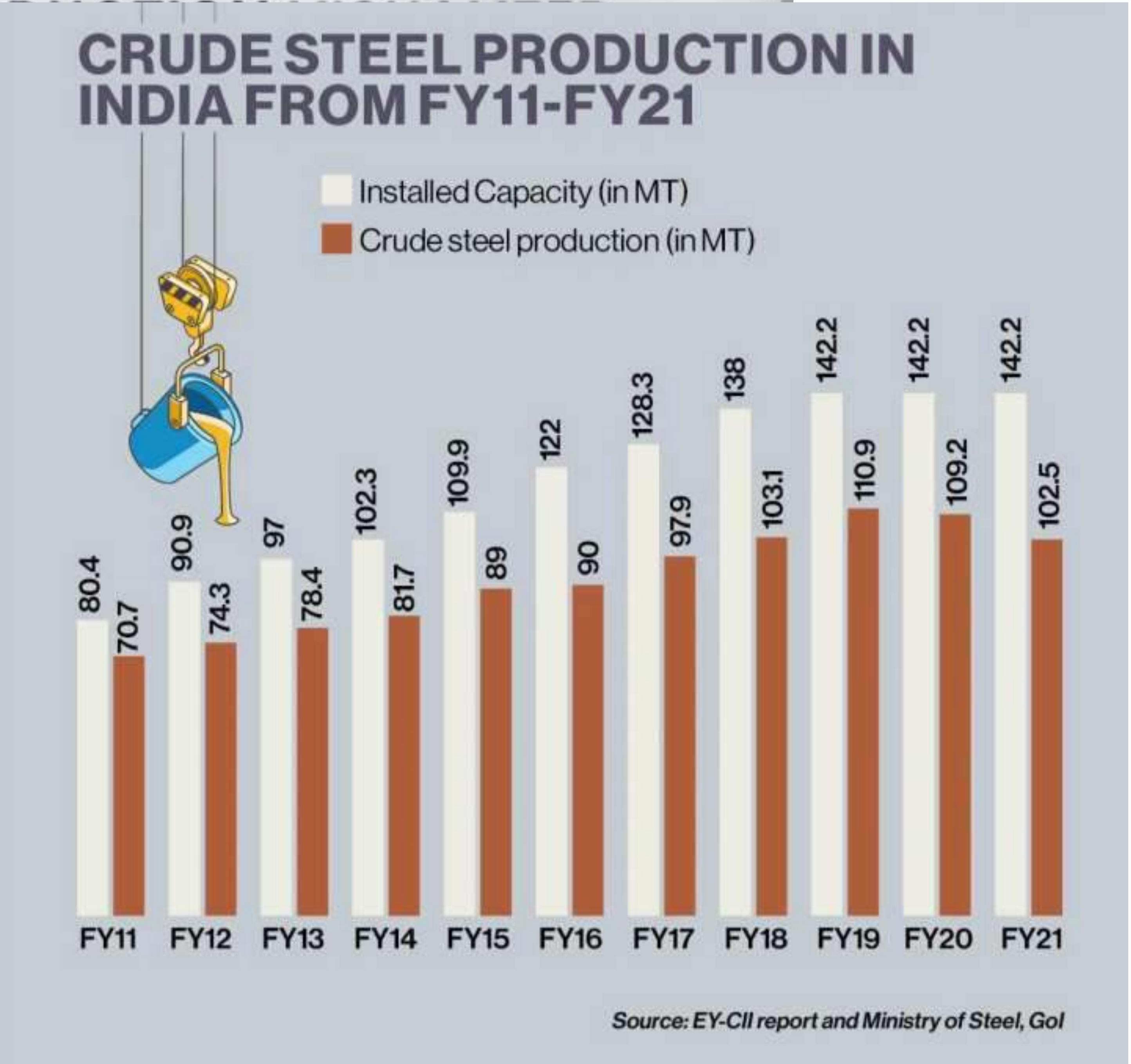
Waste Plastic Chemical Recycling Techniques

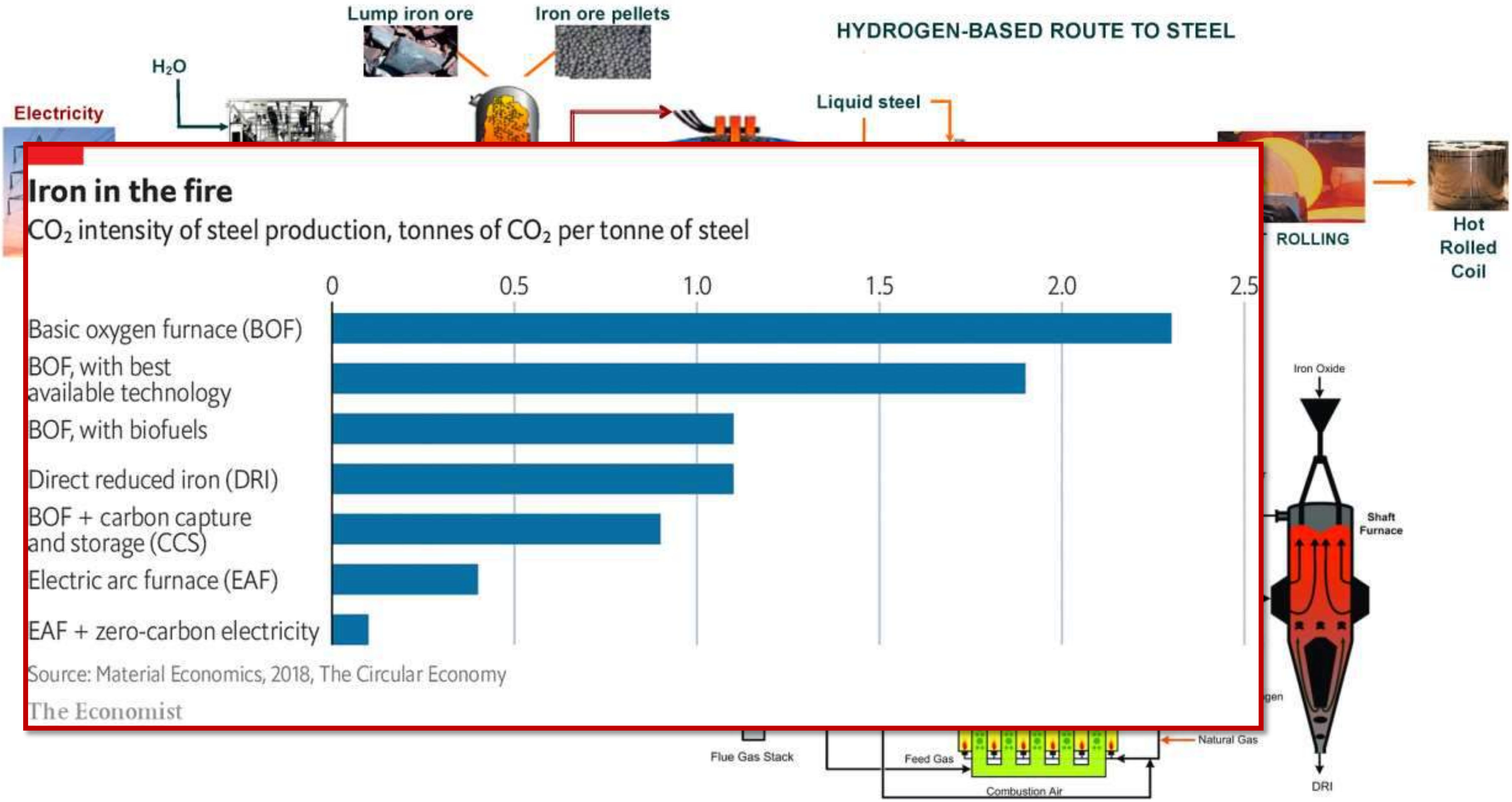
- Chemolysis and thermolysis
    - Thermosets
    - Feedstock recycling
    - Depolymerization
    - Energy recovery
- Recycling polyurethanes
- Designing for recycling
- Material reduction
- Part re-use

Plastic Waste

- PVC → Cl (+H_2)→HCl
- PET→O (+H_2)→H_2O
- Polyamides→N (+H_2)→NH_3
- Rubber →S (+H_2)→ H_2S


50 YEARS OF
GLOBAL STEEL PRO
Steel is an essential building block of our material world.
Highly durable
Energy-efficient to produce
Infinitely recyclable
Global crude steel production has more than tripled in the last 50 years, with China dominating since the turn of the century.
1 MT = 1 Million Metric Tons
EUROPE
U.S.
USSR
Rest of North America
South America
Africa
Oceania
1974-1984
A decline in steel demand saw U.S. steel production and industry employment numbers drop by 50%.
50%
During this time, the USSR became the world's top crude steel producer.
8%
2009

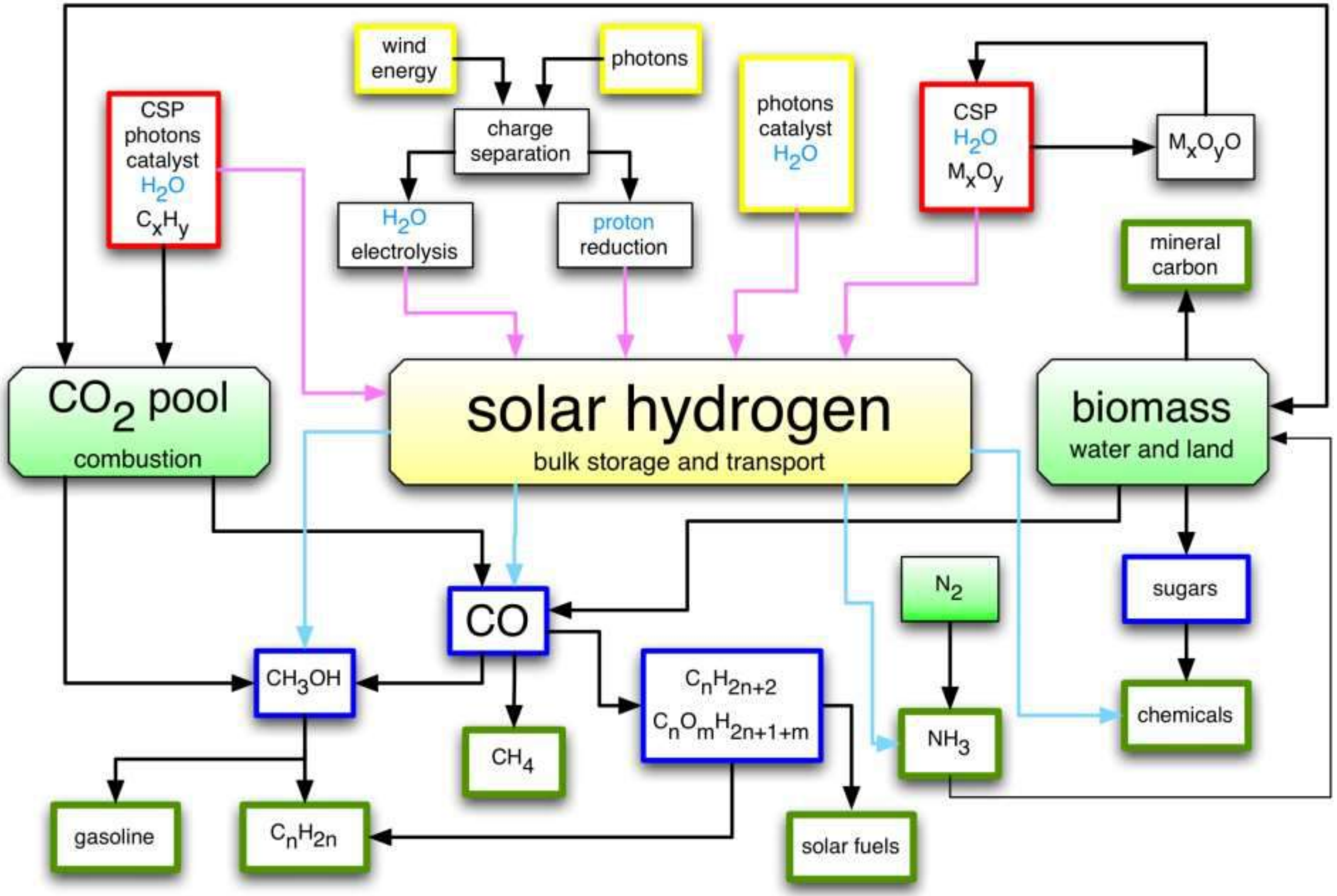

CRUDE STEEL PRODUCTION IN INDIA FROM FY11-FY21
Installed Capacity (in MT)
Crude steel production (in MT)
FY11 80.4 70.7
FY12 90.9 74.3
FY13 97 78.4
FY14 102.3 81.7
FY15 109.9 89
FY16 122 90
FY17 128.3 97.9
FY18 138 103.1
FY19 142.2 110.9
FY20 142.2 109.2
FY21 142.2 102.5
Source: EY-CII report and Ministry of Steel, GoI



HYDROGEN-BASED ROUTE TO STEEL
Lump iron ore
Iron ore pellets
H₂O
Electricity
Liquid steel
ROLLING
Hot Rolled Coil
Iron in the fire
CO₂ intensity of steel production, tonnes of CO₂ per tonne of steel
0
0.5
1.0
1.5
2.0
2.5
Basic oxygen furnace (BOF)
BOF, with best available technology
BOF, with biofuels
Direct reduced iron (DRI)
BOF + carbon capture and storage (CCS)
Electric arc furnace (EAF)
EAF + zero-carbon electricity
Source: Material Economics, 2018, The Circular Economy
The Economist
Iron Oxide
Shaft Furnace
Natural Gas
Flue Gas Stack
Feed Gas
Combustion Air
DRI

Hydrogen Production Technologies

Thermochemical	• Natural gas steam reforming, 95% • Biomass gasification and pyrolysis • High temperature water splitting • Reforming of renewable liquid fuels
Electrolytic	• PEM electrolyzers • Alkaline electrolyzers, 5% • Solid oxide electrolyzers
Photolytic	• Photobiological • Photoelectrochemical



http://www.solarify.eu/2012/05/02/opportunities-and-challenges-of-regenerative-energy-the-pivotal-role-of-chemistry/

Technology Maturity

Technology	Feed stock	Efficiency	Maturity
Steam reforming	Hydrocarbons	70–85%[a]	Commercial
Partial oxidation	Hydrocarbons	60–75%[a]	Commercial
Autothermal reforming	Hydrocarbons	60–75%[a]	Near term
Plasma reforming	Hydrocarbons	9–85%[b]	Long term
Aqueous phase reforming	Carbohydrates	35–55%[a]	Med. term
Ammonia reforming	Ammonia	NA	Near term
Biomass gasification	Biomass	35–50%[a]	Commercial
Photolysis	Sunlight + water	0.5%[c]	Long term
Dark fermentation	Biomass	60–80%[d]	Long term
Photo fermentation	Biomass + sunlight	0.1%[e]	Long term
Microbial electrolysis cells	Biomass + electricity	78%[f]	Long term
Alkaline electrolyzer	H_2O + electricity	50–60%[g]	Commercial
PEM electrolyzer	H_2O + electricity	55–70%[g]	Near term
Solid oxide electrolysis cells	H_2O + electricity + heat	40–60%[h]	Med. Term
Thermochemical water splitting	H_2O + heat	NA	Long term
Photoelectrochemical water splitting	H_2O + sunlight	12.4%[i]	Long term

Process	Energy source	Feedstock	Capital cost (M$)	Hydrogen cost ($/kg)
1. SMR with CCS	Standard fossil fuels	Natural gas	226.4	2.27
2. SMR without CCS	Standard fossil fuels	Natural gas	180.7	2.08
3. CC with CCS	Standard fossil fuels	Coal	545.6	1.63
4. CG without CCS	Standard fossil fuels	Coal	435.9	1.34
5. ATR of methane with CCS	Standard fossil fuels	Natural gas	183.8	1.48
6. Methane pyrolysis	Internally generated steam	Natural gas	–	1.59–1.70
7. Biomass pyrolysis	Internally generated steam	Woody biomass	53.4–3.1	1.25–2.20
8. Biomass gasification	Internally generated steam	Woody biomass	149.3–6.4	1.77–2.05
9. Direct bio-photolysis	Solar	Water + algae	50 $\$/m^2$	2.13
10. Indirect bio-photolysis	Solar	Water + algae	135 $\$/m^2$	1.42
11. Dark fermentation	–	Organic biomass	–	2.57

Process	Energy source	Feedstock	Capital cost (M$)	Hydrogen cost ($/kg)
12. Photo-fermentation	Solar	Organic biomass	–	2.83
13. Solar PV electrolysis	Solar	Water	12–54.5	5.78–23.27
14. Solar thermal electrolysis	Solar	Water	421–22.1	5.10–10.49
15. Wind electrolysis	Wind	Water	504.8–499.6	5.89–6.03
16. Nuclear electrolysis	Nuclear	Water	–	4.15–7.00
17. Nuclear thermolysis	Nuclear	Water	39.6–2107.6	2.17–2.63
18.Solar thermolysis	Solar	Water	5.7–16	7.98–8.40
19. Photo-electrolysis	Solar	Water	–	10.36
20. ICT-OEC Process	**Solar +Thermochemical**	**Water**		**0.95**

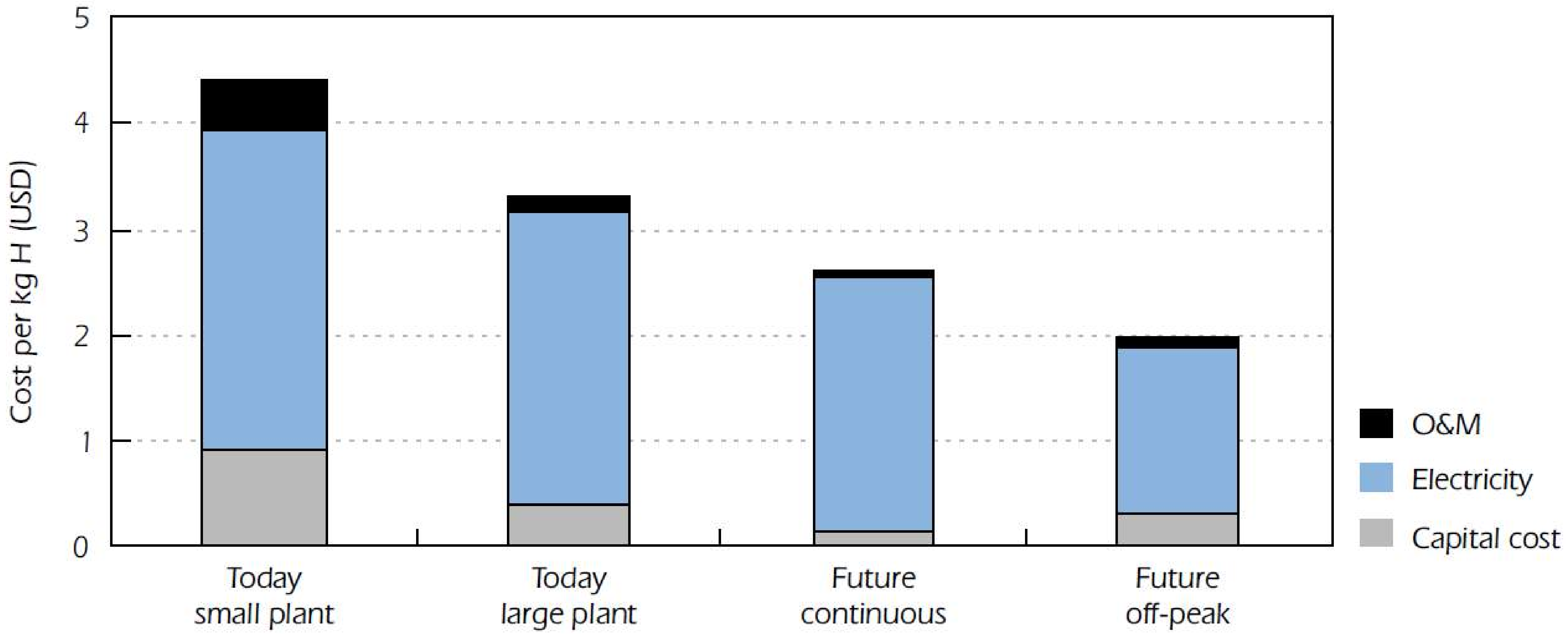
Source : Muhammet Kayfeci, ... Mutlucan Bayat, in Solar Hydrogen Production, 2019

Cost of Hydrogen

- Electrolyser costs: 1100 US$/kW (2020) to 550 USD/kW (2030), 220 USD/kW (2040).
- Alternatives to electrolysers is thermochemical processes: Cu-Cl and I-S cycles
- Costs of CCS increases the costs of steam reforming of natural gas from 990 USD/kWh to 1850/kWh.
- Low-carbon fossil-based hydrogen: Cost in 2030 from 2.5-3.0 USD in the EU,
- Green hydrogen: USD 1.3-2.9/kg.
- Target for solar electricity is to be cost competitive with the current fossil-fueled system.
- If the cost of installed PV power can be reduced from the present cost of about USD 5/W installed to about USD1/W installed, the cost of solar electricity is predicted to reach USD 0.10/kWh.

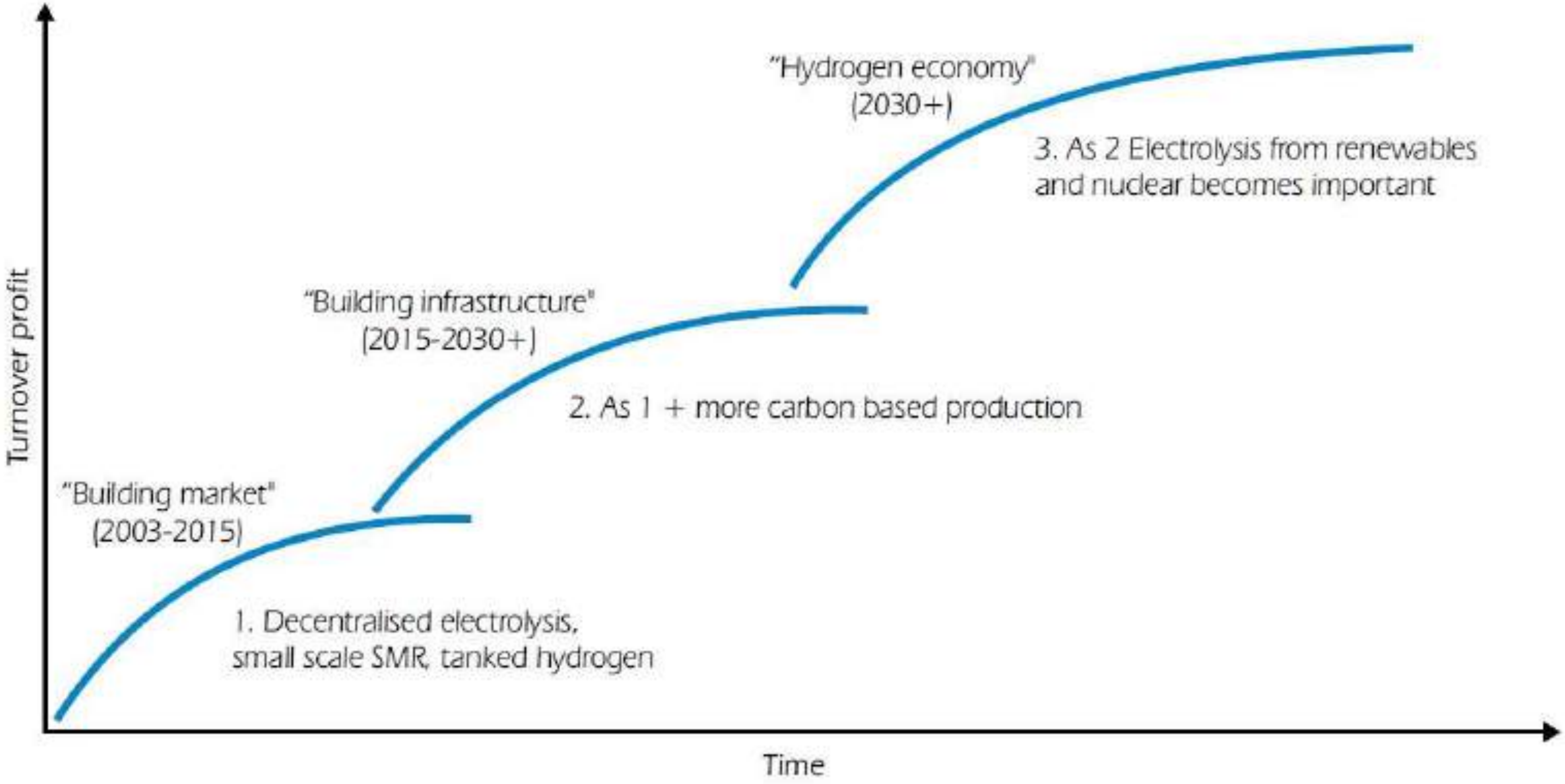
Source: International Energy Agency, IEA (2019), IHC, BNEF

Future cost of electrolytic H_2



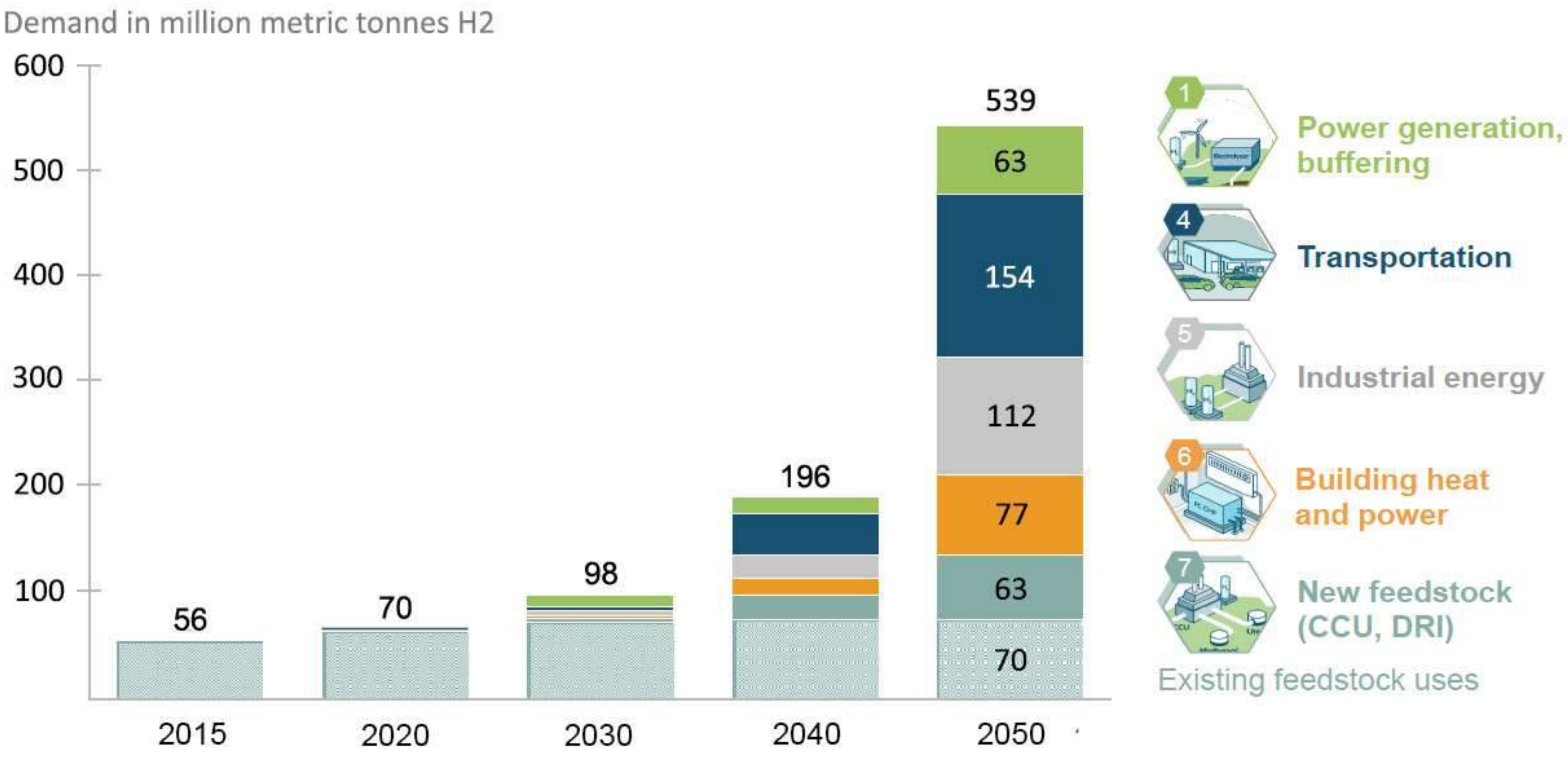
Source: US DoE.

Long Term Perspective of H_2 Economy



Source: Hydro.

Hydrogen demand could increase 10-fold by 2050

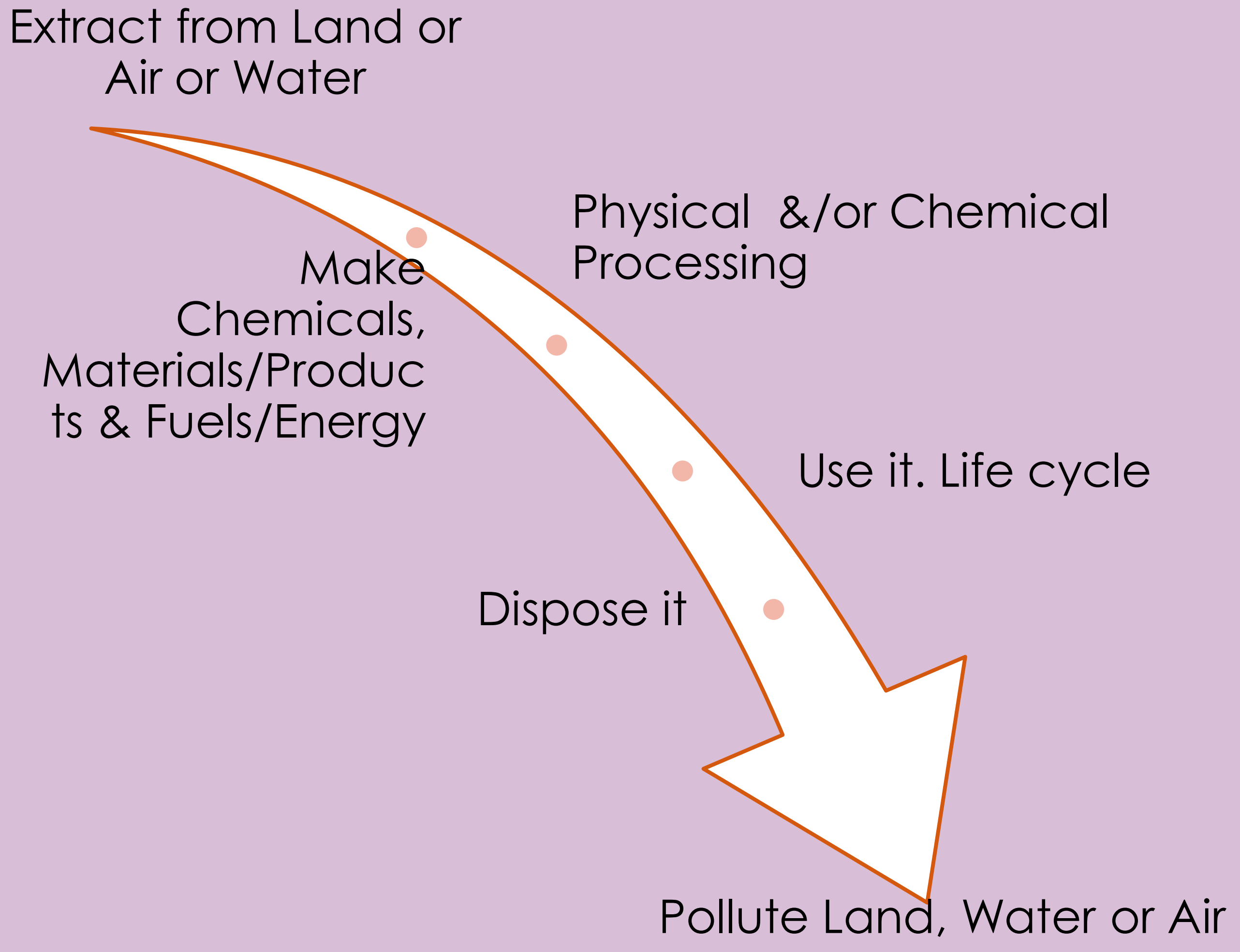


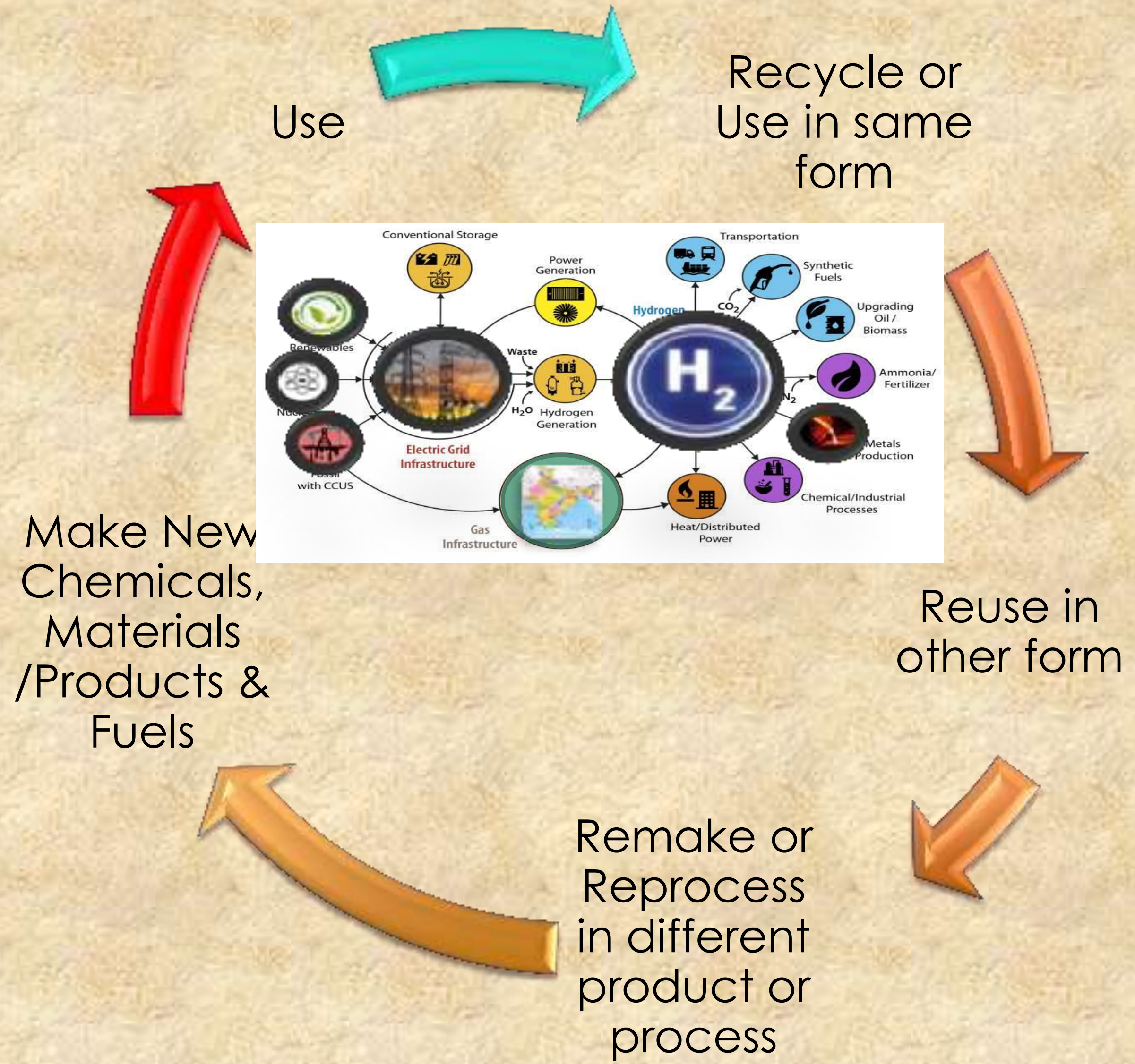
Adapted from *Scaling Up*, Hydrogen Council, 2017. Orginal units in EJ converted to tonnes H2; 1 EJ = 7,000,000 tonnes H2.

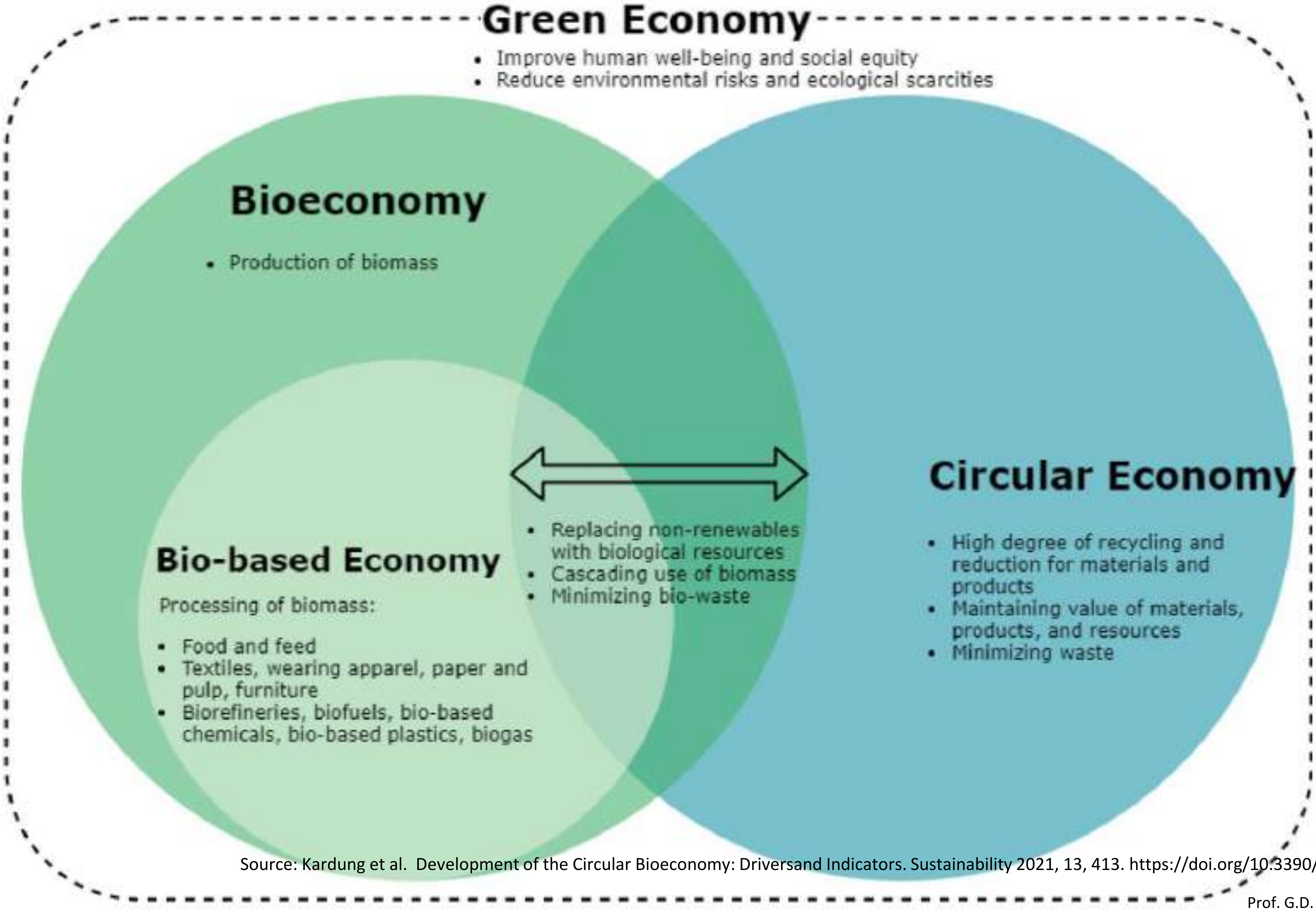
When can we create a zero-waste society

2030 or 2050

Role of Hydrogen in Circular Economy

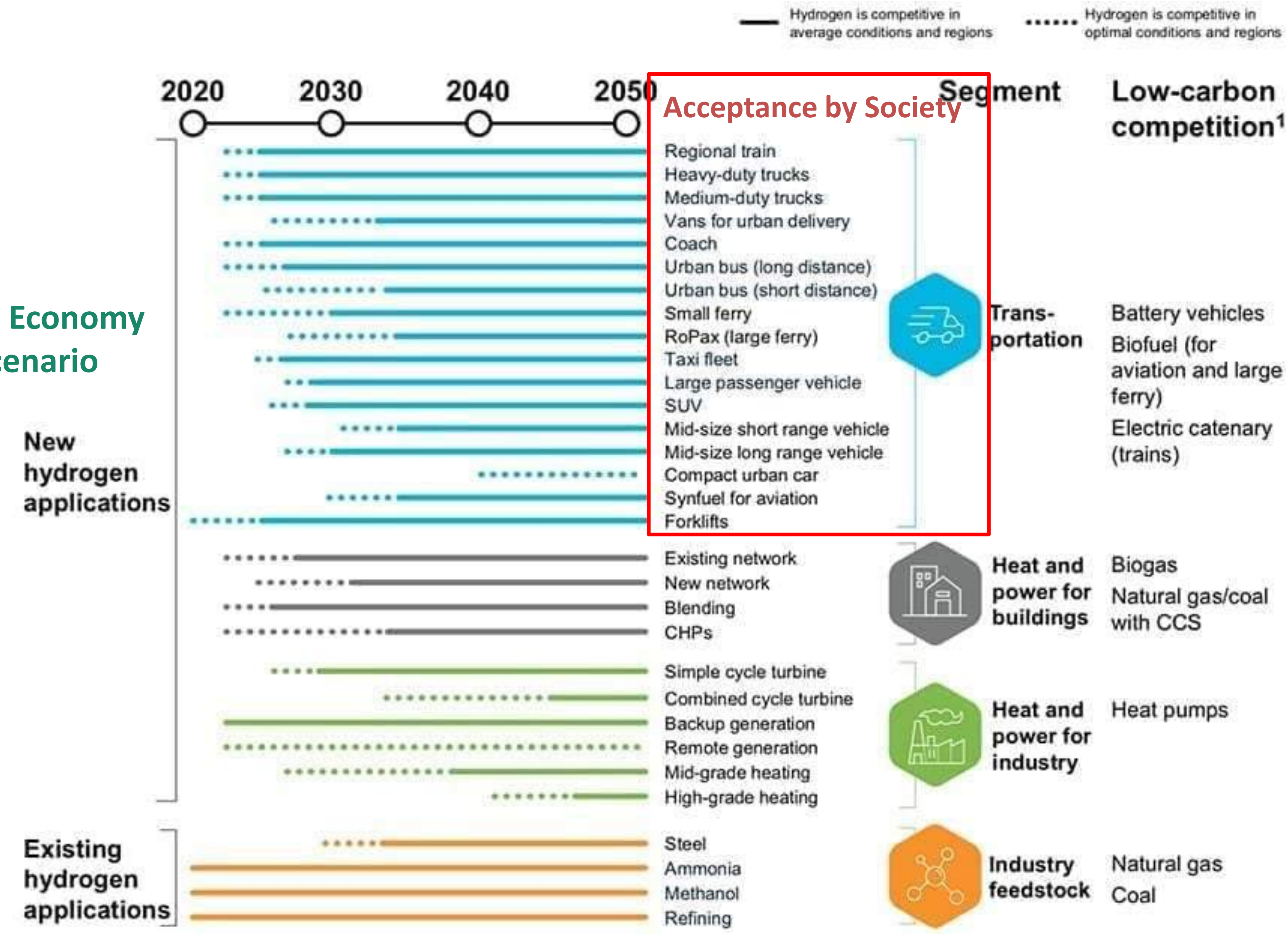






Source: Kardung et al. Development of the Circular Bioeconomy: Driversand Indicators. Sustainability 2021, 13, 413. https://doi.org/10.3390/ su13010413

Hydrogen Economy & 2050 Scenario



Hydrogen Safety

By their nature, all fuels have some degree of danger associated with them. The safe use of any fuel focuses on preventing situations where the three combustion factors—ignition source (spark or heat), oxidant (air), and fuel—are present.

A number of hydrogen's properties make it safer to handle and use than the fuels commonly used today. For example, hydrogen is non-toxic. In addition, because hydrogen is much lighter than air, it dissipates rapidly when it is released, allowing for relatively rapid dispersal of the fuel in case of a leak.

Testing of hydrogen systems—tank leak tests, garage leak simulations, and hydrogen tank drop tests—shows that hydrogen can be produced, stored, and dispensed safely.

Green hydrogen is safer than conventional fuels

- While no fuel is 100 percent safe, green hydrogen has been shown to be *safer* than conventional fuels in a multitude of aspects.

Each work has to pass through three stages: Ridicule, Opposition and then Acceptance

Swami Vivekanand

Way Forward

Green Hydrogen will be the saviour of the world.

CO_2 should not be liability but an asset to convert.

Agricultural waste as biorefineries and blue hydrogen sources

Hydrogen economy can be elegantly intertwined to make many chemicals from waste carbon sources including biomass and C1 off-gases.

Govt of India should adopt hydrogen economy to meet the demands of the Paris Agreement.

ICT-OEC Hydrogen Production Technology is very promising at <USD~1.00

That is the only way to meet the goals of the Paris Agreement 2015.

We can MAKE IT.

Thank you all

- R.T. Mody Distinguished Professor Endowment
- Tata Chemicals Darbari Seth Distinguished Professor of Leadership & Innovation
- J.C. Bose National Fellowship, Dept of Sc and Tech, GOI
- National Science Chair (Mode I), SERB, DST, GoI
- ONGC Energy Centre

US NAE Election on 8th Feb. 2022
National Science Chair March 2022

Ph Ds 107

Patents 115

Masters 134

Papers 507

PDFs 47