Life Cycle Analysis of Transport Options

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Drivers for Transport Sector

- Urban Air Quality- Local Emissions and Health
- Climate Change- Low carbon
- Development, Income increase and mobility
- COVID – Health and Safety

Choices

- Modes- Non motorized- walking, cycle
- Motorised- Two wheeler – Petrol, Electric, Hydrogen

Three wheeler- petrol, LPG, CNG, Electric, Hydrogen,
Four Wheeler (Car)- petrol, LPG, CNG, Electric, Hydrogen,

Ethanol, Biodiesel, Hybrid…

Public Transport – Trains, Buses, Bus Rapid Transit. Metros, High Speed Train, Air craft, Ships, Water transport (multiple fuel options)

Hyperloop….

Freight – Tempos, LCVs, Trucks, Heavy duty tricks (Diesel, Hybrid, Electric, Hydrogen)

Choices of technology within an option – e.g Battery type

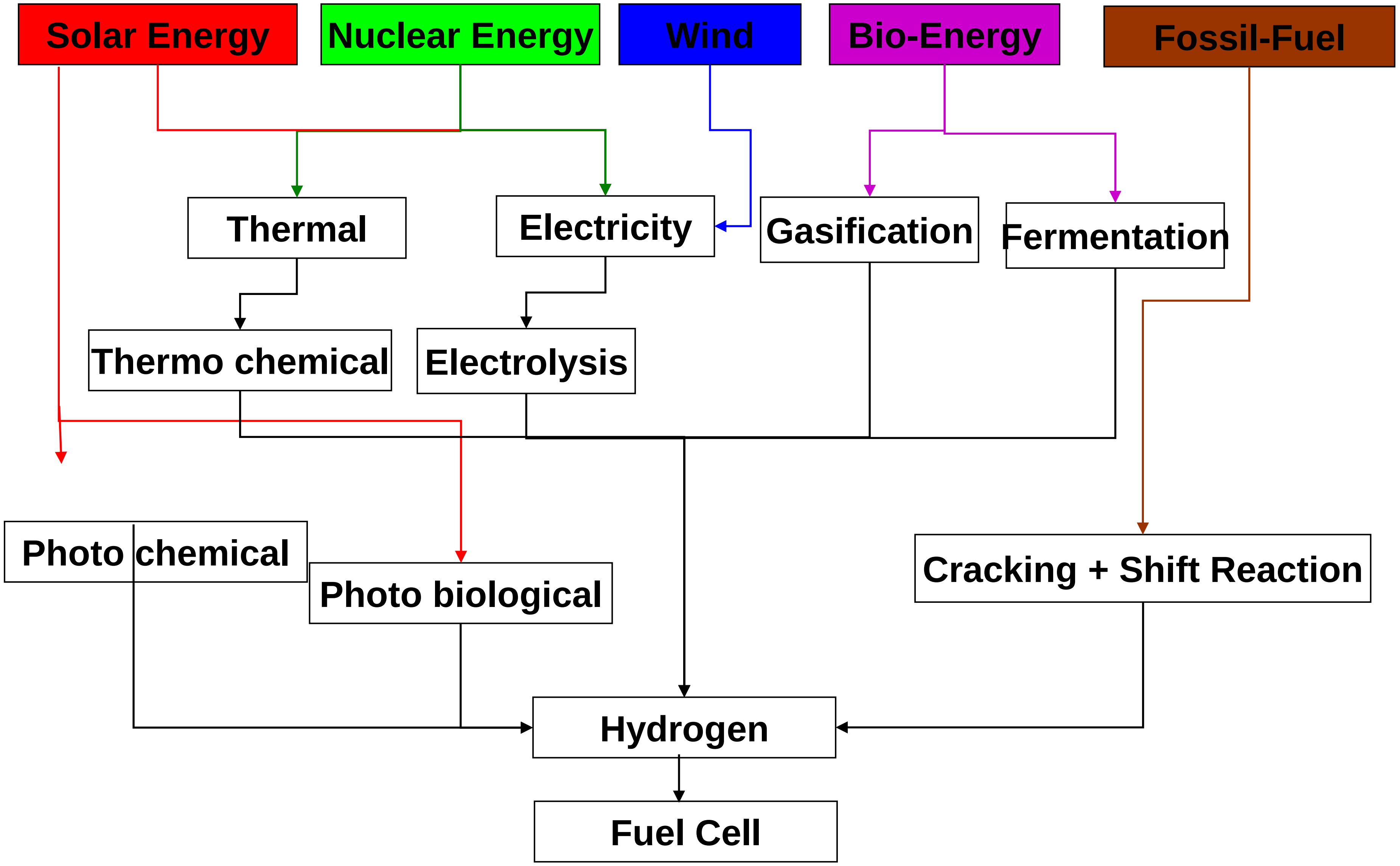
Criteria

- Cost- Capital cost
  - Operating Cost
  - Annualised life cycle cost/ p-km (or freight- km)
- Speed/ Travel time/ Total time (including waiting time)
- Convenience
- Emissions – Local
- Emissions – Global- GHG- CO_2 equivalent
- Energy efficiency, Operational energy, embodied energy,Life cycle energy
- Space taken
- Infrastructure

Life Cycle Analysis Examples

- Hydrogen fuel chain for passenger car
- Related LCA
  - LCA of Coal versus Gas based electricity
  - Energy and Carbon analysis for batteries (for micro-grids)
  - LCA trucks
  - Sustainability analysis of biofuels
  - Sustainability Analysis of Hyperloop

Hydrogen pathways



Solar Energy

Nuclear Energy

Wind

Bio-Energy

Fossil-Fuel

Thermal

Electricity

Gasification

Fermentation

Thermo chemical

Electrolysis

Photo chemical

Photo biological

Cracking + Shift Reaction

Hydrogen

Fuel Cell

Base case Fossil fuel based fuel chain

- Small-size passenger car (Maruti 800) manufactured by Maruti Udyog Limited
  - Petrol fuelled,
  - 37 bhp (27 kW) IC engine

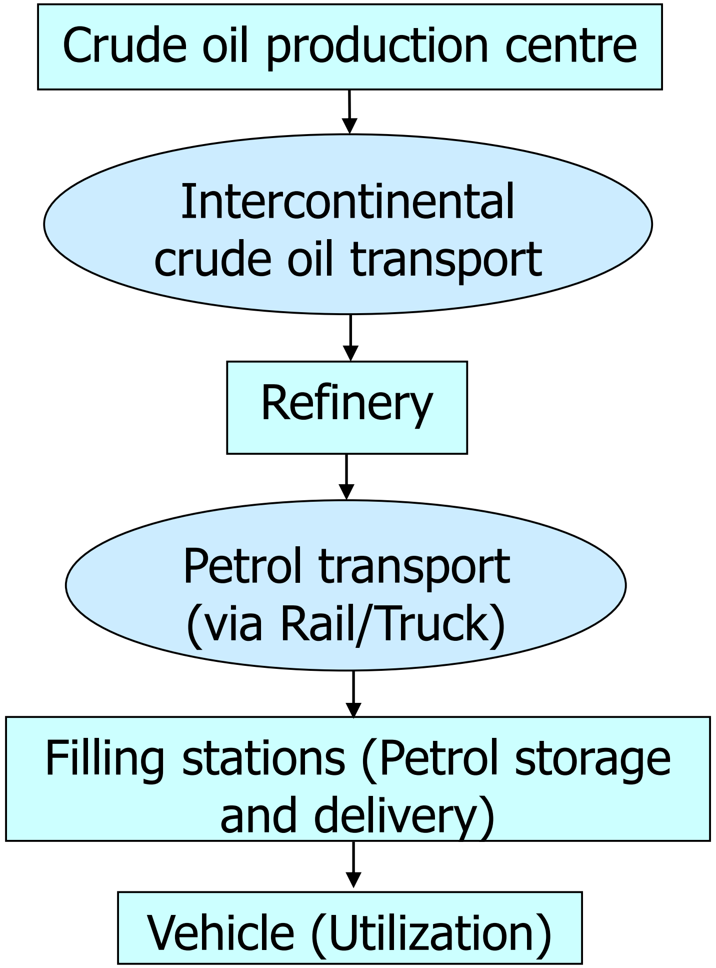
50% share in Indian passenger vehicle-market

560,000 units sold 2005-6

Study done in 2008

Fuel chains

Fossil fuel chain



Crude oil production centre

Intercontinental crude oil transport

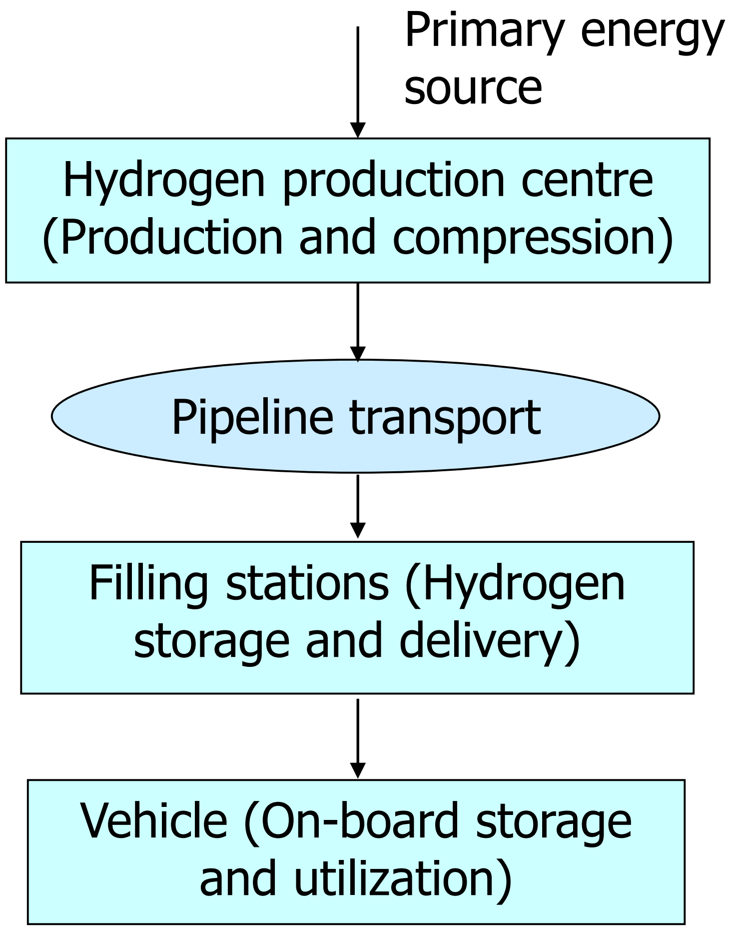
Refinery

Petrol transport (via Rail/Truck)

Filling stations (Petrol storage and delivery)

Vehicle (Utilization)

Hydrogen fuel chain



Primary energy source

Hydrogen production centre (Production and compression)

Pipeline transport

Filling stations (Hydrogen storage and delivery)

Vehicle (On-board storage and utilization)

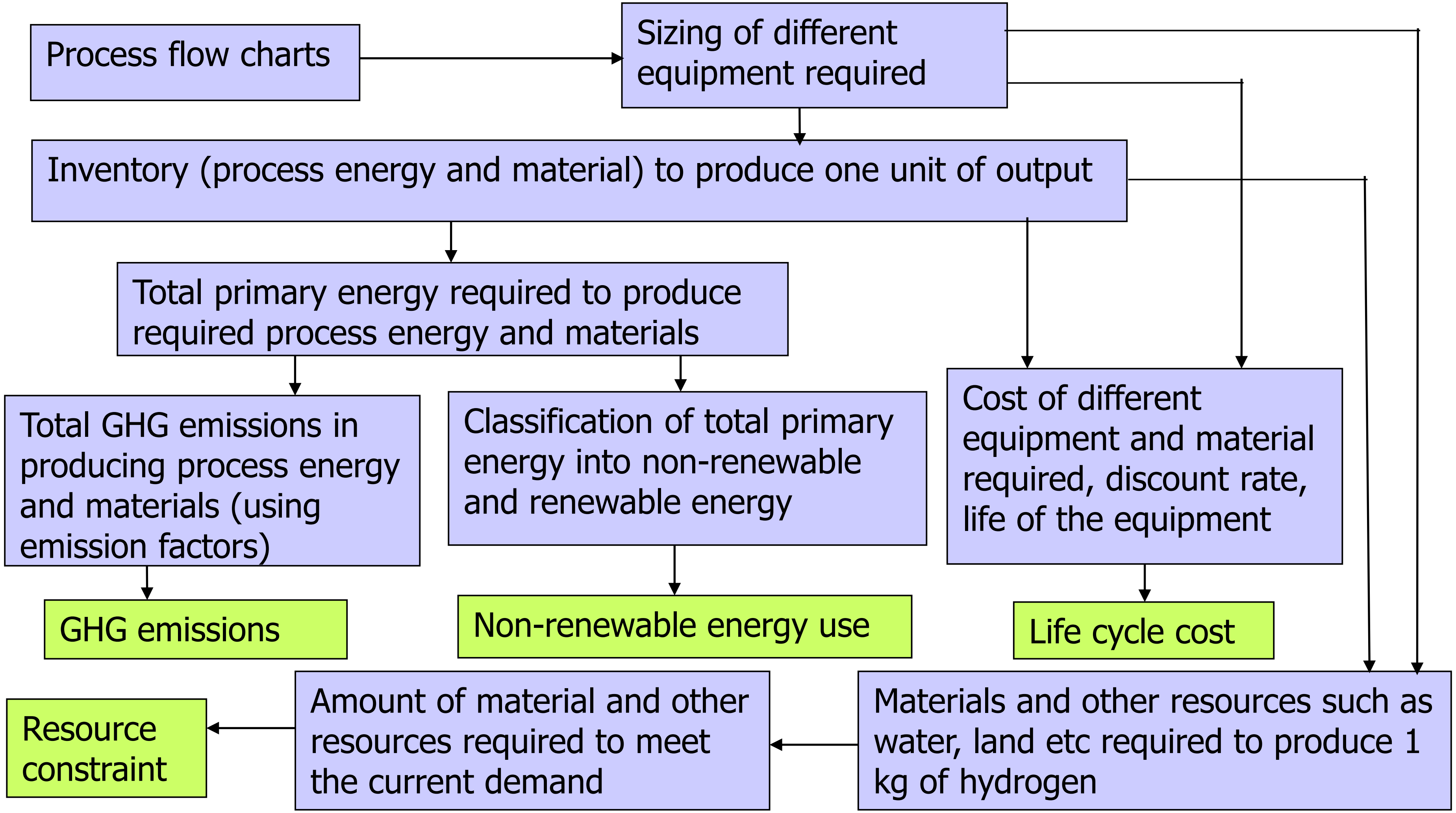
Comparison criteria

- Non-renewable energy consumption per km travel (MJ/km)
- Greenhouse gas emissions per km travel (g CO_2-eq/km)
- Cost per km travel (Rs./km)
  - Annualised life cycle costing (ALCC) method
  - Existing Indian prices.
  - If technology is not available commercially in India, international prices are used
- Resource constraints

Methodology

- Life cycle assessment (LCA)
  - All material and energy inputs to the process are identified
  - Total input energy required to extract, produce, and deliver a given energy output or end use
- Energy use and corresponding emissions during fabrication of PV, electrolyzer, wind machine etc. are also taken into account.

Methodology contd..



Process flow charts

Sizing of different equipment required

Inventory (process energy and material) to produce one unit of output

Total primary energy required to produce required process energy and materials

Total GHG emissions in producing process energy and materials (using emission factors)

Classification of total primary energy into non-renewable and renewable energy

Cost of different equipment and material required, discount rate, life of the equipment

GHG emissions

Non-renewable energy use

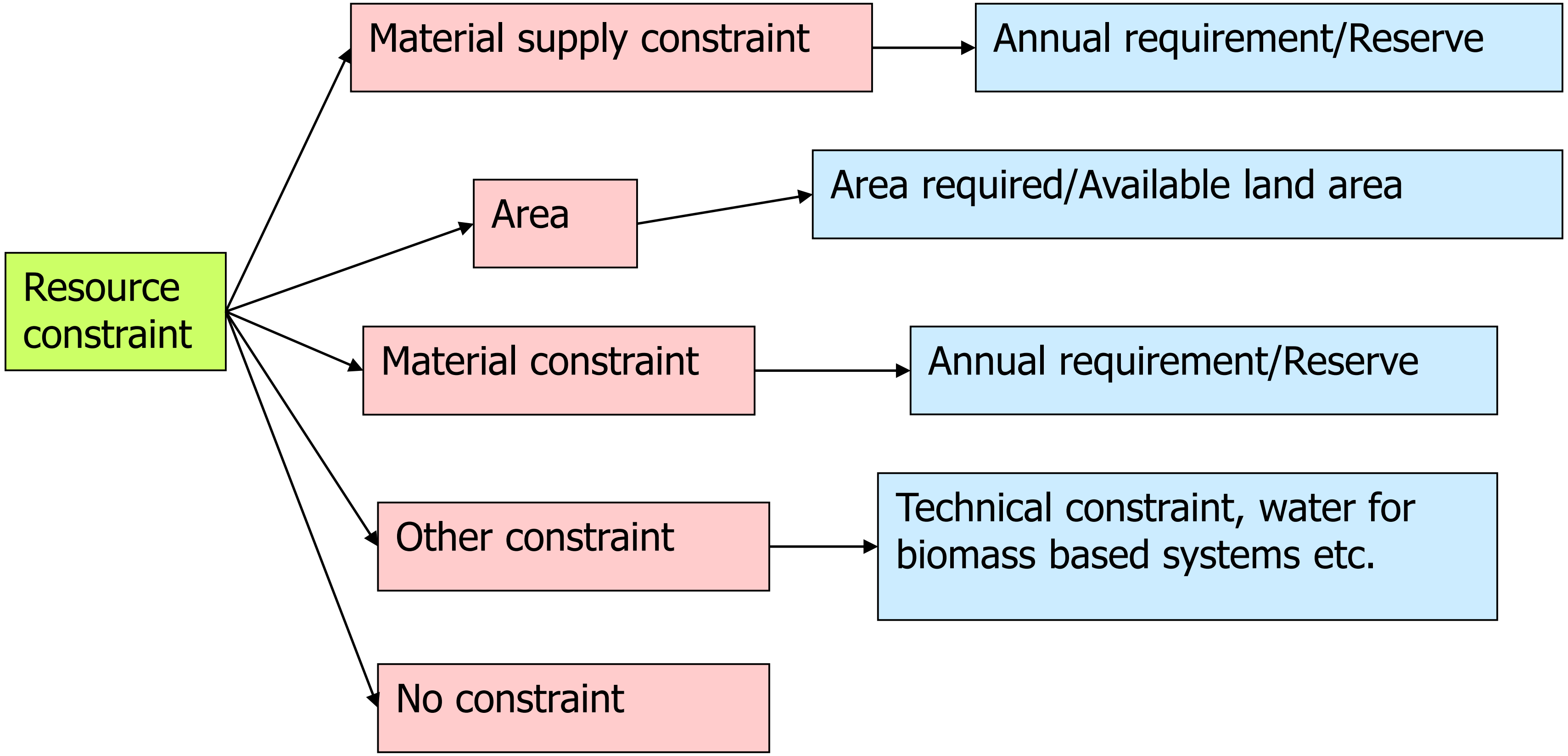
Life cycle cost

Resource constraint

Amount of material and other resources required to meet the current demand

Materials and other resources such as water, land etc required to produce 1 kg of hydrogen

Resource constraint



Resource constraint

Material supply constraint

Annual requirement/Reserve

Area

Area required/Available land area

Material constraint

Annual requirement/Reserve

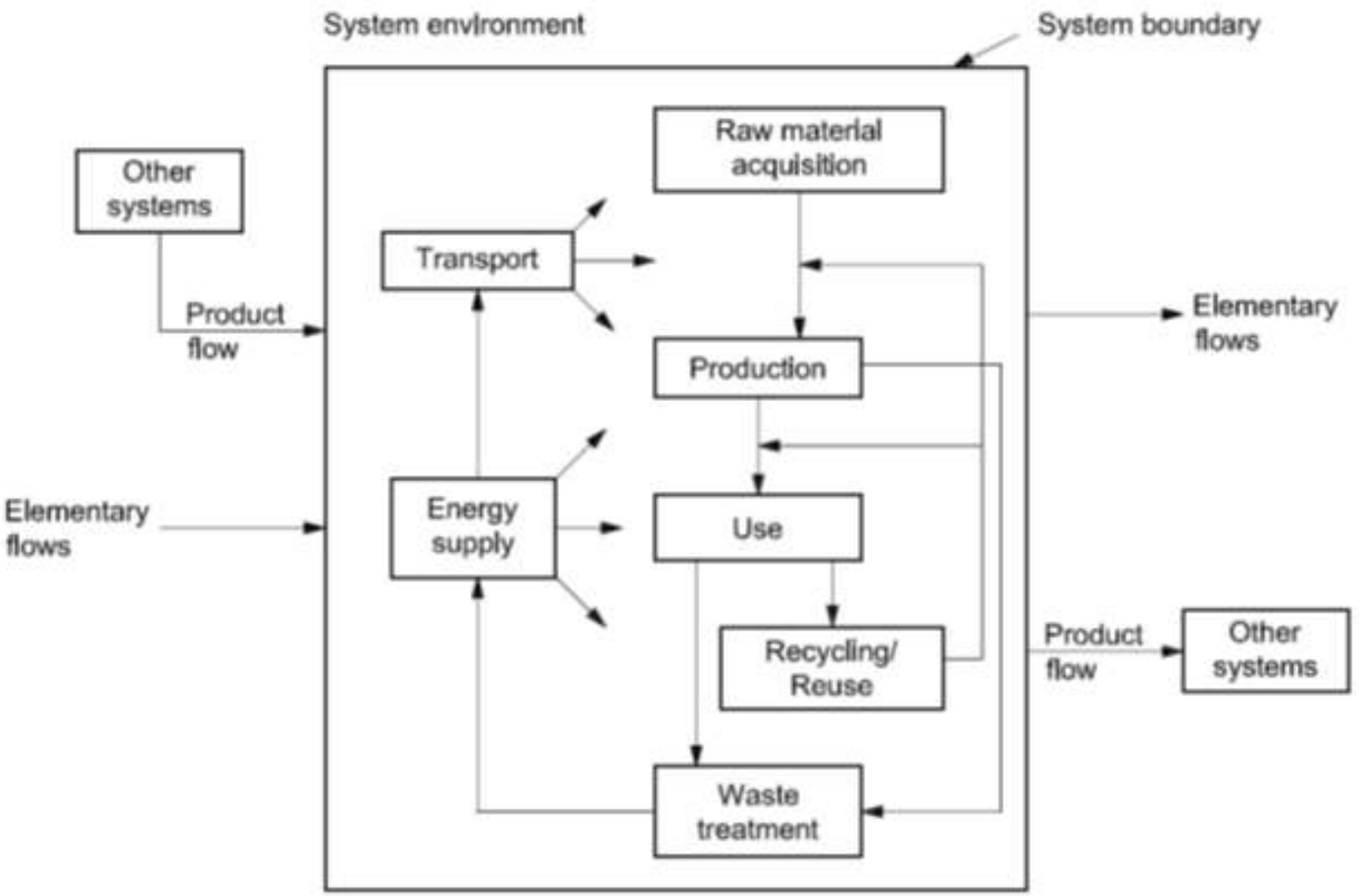
Other constraint

Technical constraint, water for biomass based systems etc.

No constraint

Source: Manish S, Indu R Pillai, and Rangan Banerjee, "Sustainability analysis of renewables for climate change mitigation," *Energy for Sustainable Development*, vol. 10, no. 4, pp. 25-36, 2006.

Life Cycle Analysis



ISO 14040

Define
functional units
Goals
System
boundaries

http://www.cscses.com/uploads/2016328/20160328110518251825.pdf

Vehicle Application

Weight (excl engine +tank) 550 kg

Passengers (max) 350 kg

Maruti

CR 0.01

CD 0.4

2m^2 front area

100 km travel /day

	Tank	Engine
Petrol	40 kg	60 kg
CNG	140 kg	60 kg
FC	130 kg	15 M +15 FC kg

Hydrogen fuel chain – different routes

Hydrogen Production

Steam methane reforming (SMR), Coal gasification, Water electrolysis, Renewable hydrogen (Photovoltaic-electrolysis, Wind power-electrolysis, Biomass gasification, Biological methods)

Transmission

Pipeline transport, transport via truck and rail

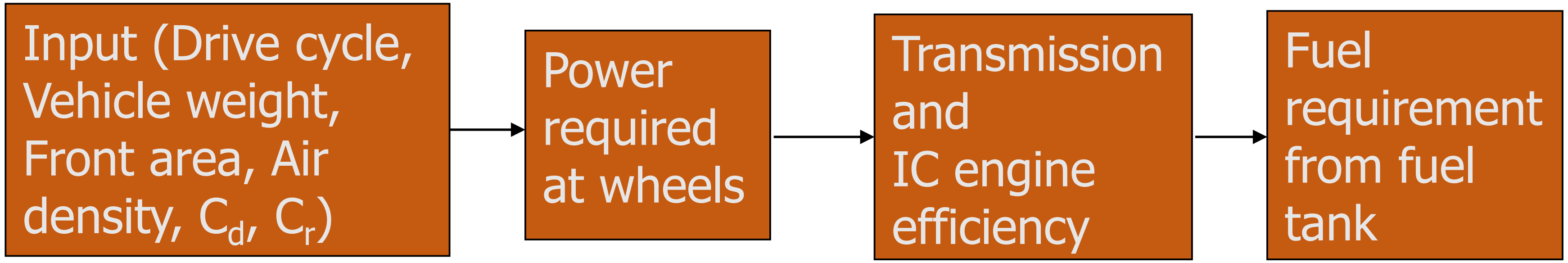
Storage

Compressed hydrogen storage, Metal hydrides, Liquid hydrogen storage, Complex chemical hydrides

Utilization

Fuel cells (PEMFC), IC engine

Energy analysis



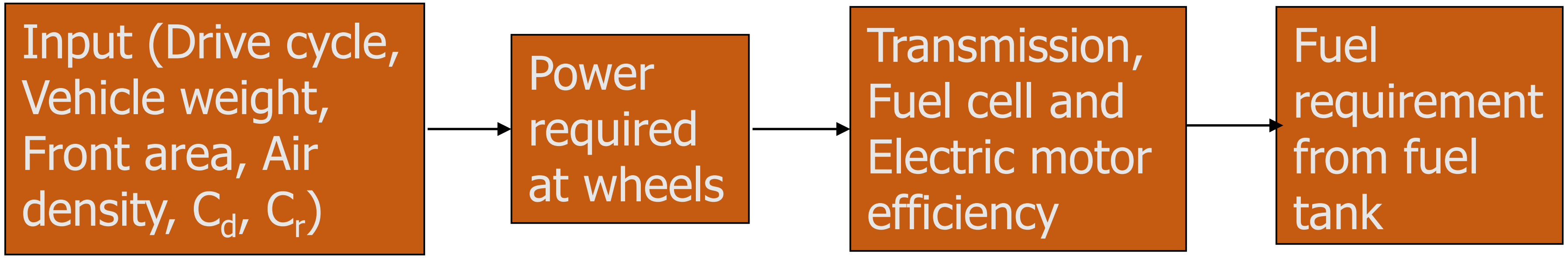
Input (Drive cycle, Vehicle weight, Front area, Air density, C_d, C_r)

Power required at wheels

Transmission and IC engine efficiency

Fuel requirement from fuel tank

IC engine vehicle



Input (Drive cycle, Vehicle weight, Front area, Air density, C_d, C_r)

Power required at wheels

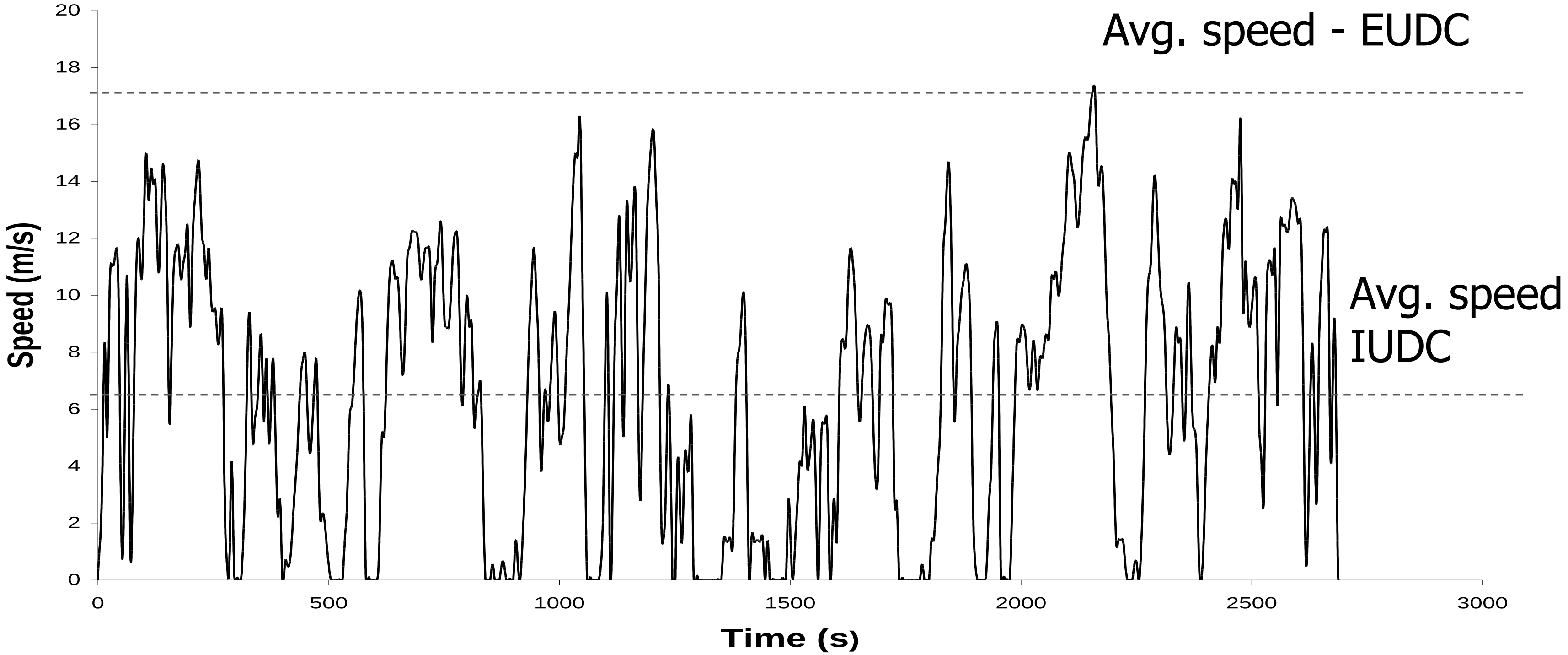
Transmission, Fuel cell and Electric motor efficiency

Fuel requirement from fuel tank

Fuel cell vehicle

Source: Manish S and Rangan Banerjee, "Techno-economic assessment of fuel cell vehicles for India," 16th World hydrogen energy conference, Lyon (France), 2006.

Indian urban drive cycle



***Indian urban drive cycle* :-**

Low average speed (23.4 km/h) and rapid accelerations (1.73 to -2.1 m/s^2)

***European urban drive cycle* :-**

Average speed (62.4 km/h) and accelerations from 0.83 to -1.4 m/s^2

Power required at wheels

- Three forces acts on the vehicle (Assumption:- vehicle is running on a straight road with a zero gradient). These are
  - Aerodynamic drag $\{F_{Drag}(t)\} = 0.5\rho A v(t)^2 C_d$
  - Frictional resistance $\{F_{Friction}(t)\} = mgC_r$
  - Inertial force $\{F_{Inertia}(t)\} = mf$ $\{f=dv(t)/dt\}$
- $F_{Total}(t)=F_{Drag}(t)+F_{Friction}(t)+F_{Inertia}(t)$
- $P_{Wheel}(t)=F_{Total}(t)\times v(t)$

Data used for base case vehicle

Parameter	*Value*
Air density (kg/m^3)	1.2
Coefficient of drag resistance	0.4
Coefficient of rolling resistance	0.01
Cargo weight (kg)	250
Frontal area (m^2)	2
Transmission efficiency	0.7
Transmission weight (kg)	114
IC engine weight (kg)	90
Fuel tank weight (kg)	40
Fuel capacity (kg)	24
Vehicle body weight (kg)	406
Total weight (kg)	900

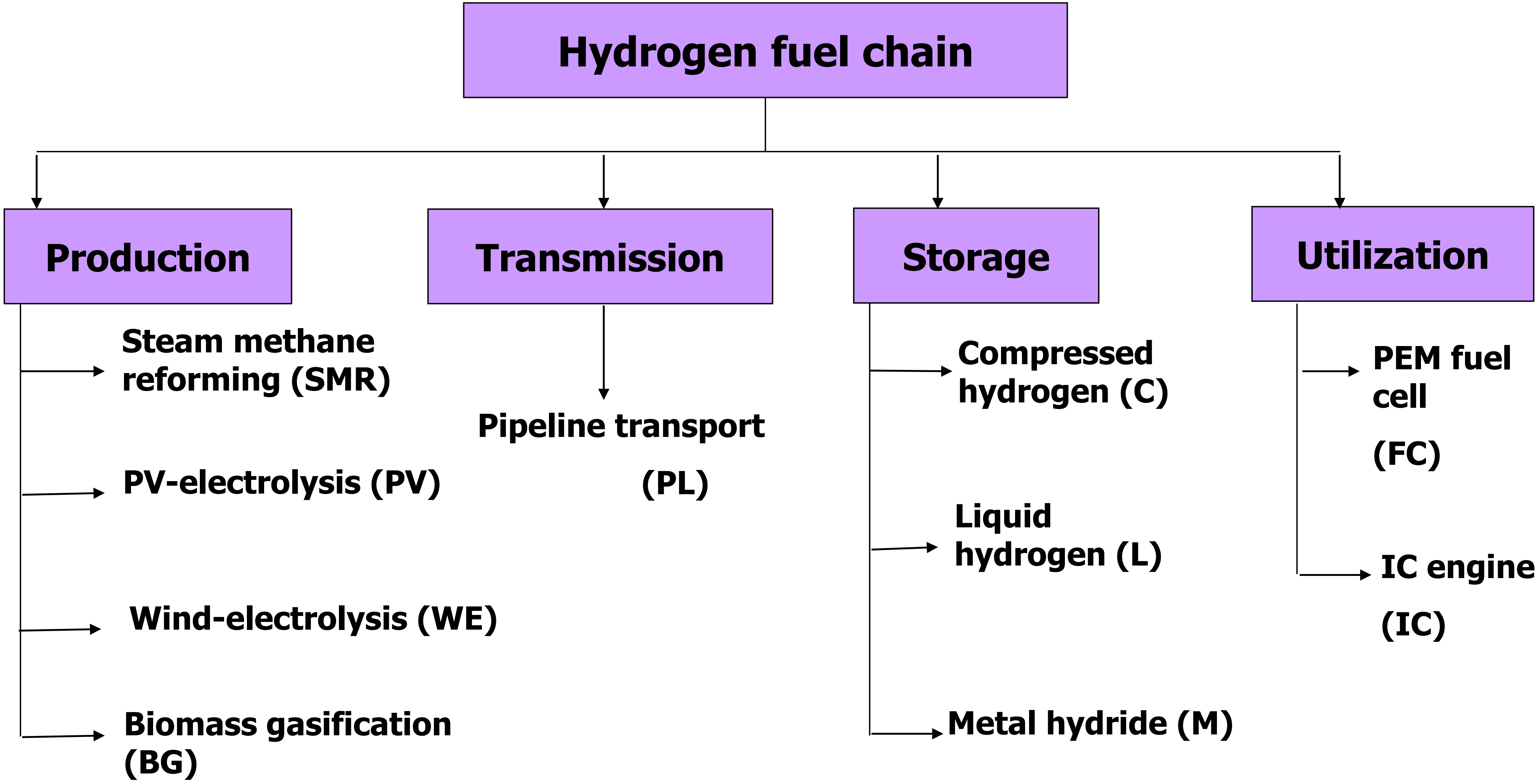
Result for base case vehicle

Parameter	*Value*
Driving range (km)	434
Cost (Rs/km)	2.8 (0.34)
Non-renewable energy use during operation (MJ/km)	2.6
GHG emissions (g/km)	180

Driving range of hydrogen vehicles should be at least half (~217 kms) for their public acceptance.

- Average daily travel Indian urban <100 kms.
- Vehicle to run for 2-3 days.

Hydrogen fuel chain – Options considered



Hydrogen fuel chain

Production

- Steam methane reforming (SMR)
- PV-electrolysis (PV)
- Wind-electrolysis (WE)
- Biomass gasification (BG)

Transmission

- Pipeline transport (PL)

Storage

- Compressed hydrogen (C)
- Liquid hydrogen (L)
- Metal hydride (M)

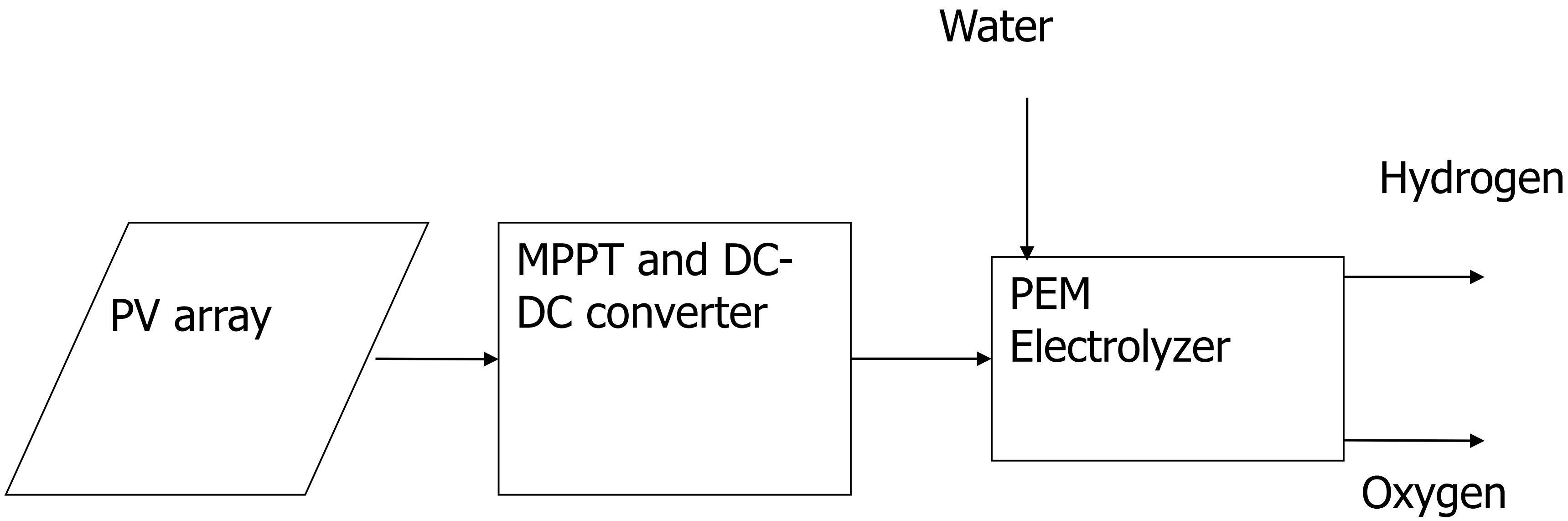
Utilization

- PEM fuel cell (FC)
- IC engine (IC)

Hydrogen production – Steam Methane Reforming (SMR)

- Feedstock - Natural Gas
- SMR: $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$
- Life of plant 20 years
- Existing NG price Rs 8/Nm^3,
- Price of Hydrogen Rs 48/ kg 4.3 Rs/Nm^3 or 400 Rs/GJ

PV-Electrolyzer System



Water

PV array

MPPT and DC-DC converter

PEM Electrolyzer

Hydrogen

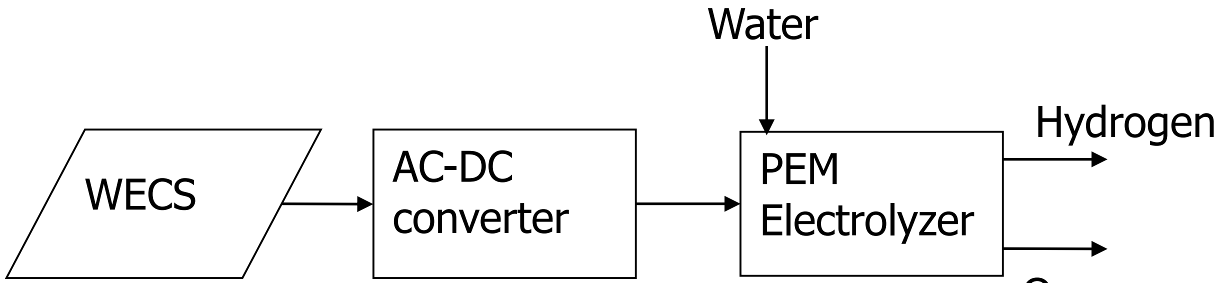
Oxygen

- HYSOLAR (Saudi Arabia) 350 kW Alkaline electrolyser 65 m^3/h peak (German-Saudi) ~5.8 kg/hr

PV-Hydrogen

- 100 kg hydrogen/ day
- Electrolyzer efficiency 70%
- Annual capacity factor 20%
- Module area 8800 m^2
- 1300 kW_p PV, 1200 kW electrolyzer

Wind-Electrolyzer



WECS

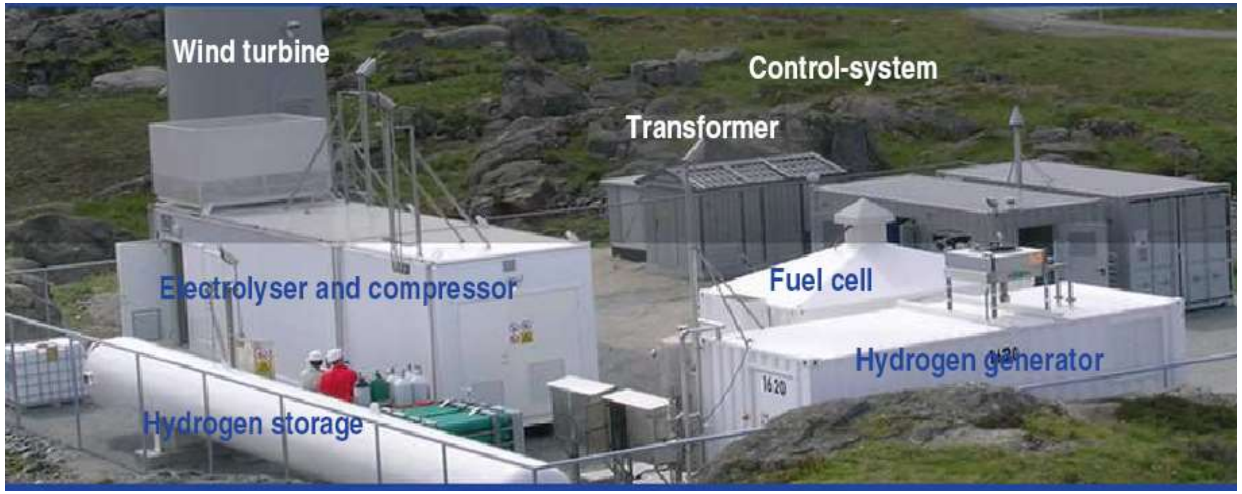
AC-DC converter

Water

PEM Electrolyzer

Hydrogen

Oxygen



Utsira Plant

10 Nm^3/h (~0.9kg/h)

48 kW electrolyzer

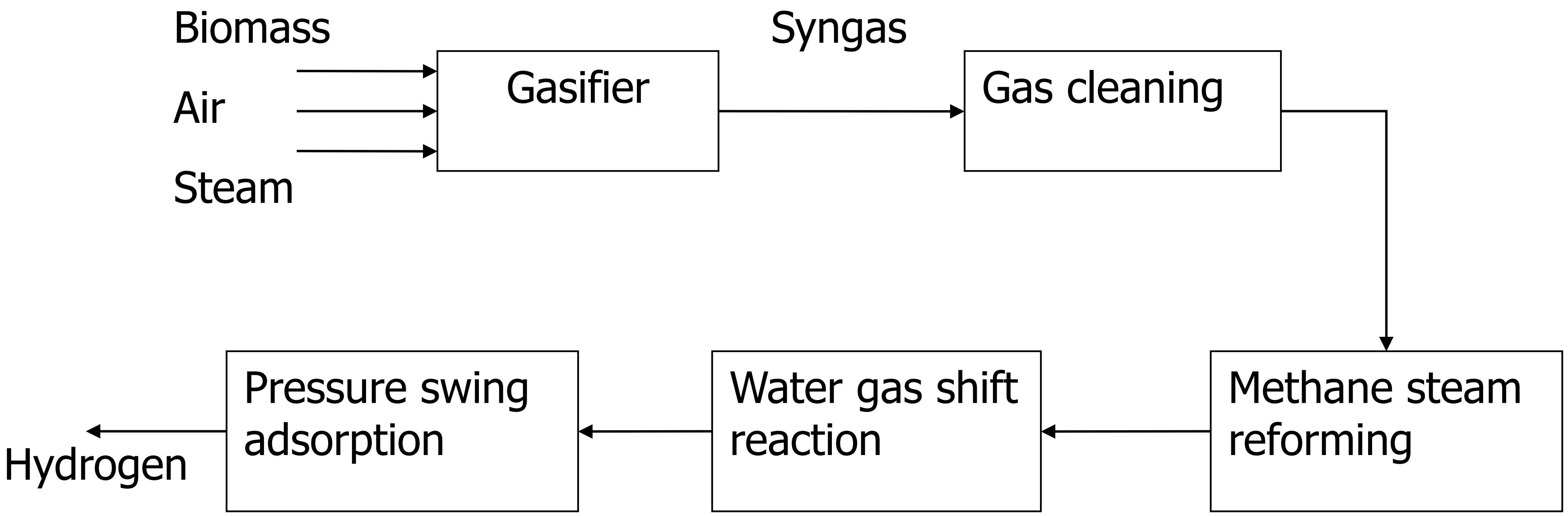
Two wind turbines 600 kW (peak) each

Source: Norsk Hydro

Wind-Electrolyzer

- 100 kg hydrogen/ day
- Electrolyzer efficiency 70%
- Annual capacity factor 30%
- 880 kW (peak), 784 kW electrolyzer

Biomass gasifier-reformer



Many configurations possible – atmospheric, pressurised, air blown, oxygen blown

No large scale systems

Comparison of hydrogen production methods

Indicator	**Unit**	**SMR**	**PV-electrolysis**	**WECS-electrol.**	**Biomass Gasification**
Non-renewable energy use	MJ/kg	182	67.5	12.4	67.7
GHG emission	kg/kg	12.8	3.75	0.98	5.4
Life cycle cost*	**Rs/kg**	48	1220	400	44.7

*At 10% discount rate

Average load factors; PV-0.2, WECS-0.3, Biomass gasification-0.65

Hydrogen transmission

- Can be transported as a compressed gas, a cryogenic liquid (and organic liquid) or as a solid metal hydride.
- Via pipeline, trucks, rail etc.
- Compressed hydrogen via pipeline
  - US, Canada and Europe
  - Typical operating pressures 1-2 MPa
  - Flow rates 300-8900 kg/h

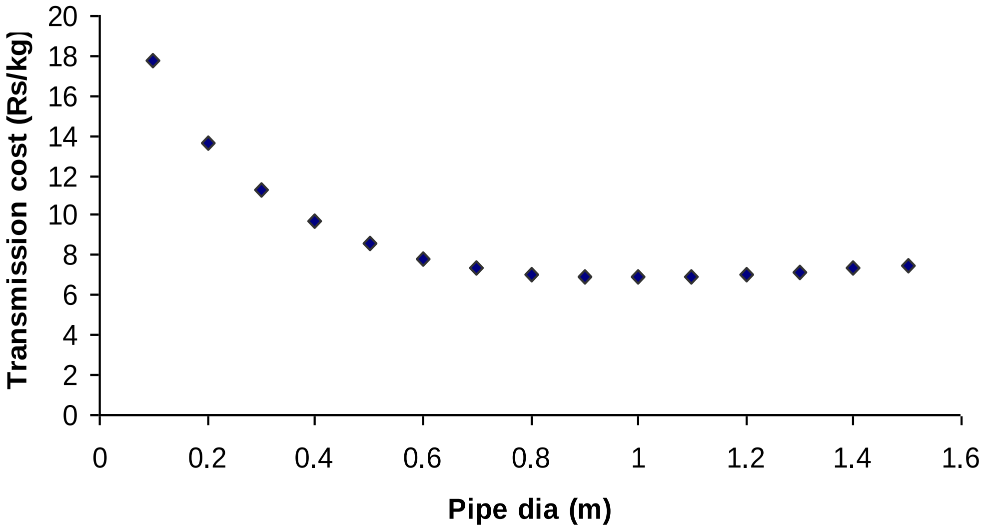
Hydrogen transmission- contd..

- 210 km long 0.25 m diameter pipeline in operation in Germany since 1939 carrying 8900 kg/h at 2 MPa
- The longest pipeline (400 km, from Northern France to Belgium) owned by Air Liquide.
- In US, total 720 km pipeline along Gulf coast and Great lakes.

Results for transmission process

For 1 million kg/day, transmission distance 100 km, supply pressure 10 bar

Parameter	**Value**	**Unit**
Optimum pipe diameter	1	m
Transmission cost	6.93	Rs/kg
GHG emissions	0.99	kg/kg



Transmission cost vs. pipe diameter

Hydrogen on-board storage and utilization

- Demo hydrogen vehicles : Daimler-Benz, Honda, Toyota, Ford, BMW, General Motors, Daimler-Chrysler, Mazda
- On-board storage: compressed gas, liquid hydrogen, metal hydride, organic liquid
- Energy conversion device: internal combustion engine, fuel cell

Vehicles with compressed hydrogen storage

Name of the vehicle/Company	**Energy conversion device**	**Net power output**	**Storage system**	**Range of Vehicle (km)**
NEBUS (bus) (Daimler-Benz)	Fuel cells 10 stacks of 25kW	190 kW	150 litre cylinders at 300 bar	250
Zebus (bus) (Ballard power systems)	Fuel cells	205 kW	Compressed hydrogen	360
FCX (Car) (Honda)	Fuel Cells	100 kW	171 litre at 350 bar	570
FCHV-4 (car) (Toyota)	PEM fuel cell + Battery	80 kW	350 bar	250
Model U (Ford motor co.)	Internal combustion Engine	113 kW @4500rpm	7 kg @690 bar	---
NECAR 2 (Daimler Benz)	Fuel cell	50 kW	Compressed gas	---

Vehicles with liquid hydrogen storage

Name of the vehicle/Company	**Energy conversion device**	**Net power output**	**Storage system**	**Range of Vehicle (km)**
BMW 750-hl (BMW Corporation)	Hybrid, 12 cylinder combustion engine	---	140 liters, cryo storage at -253^{0}C	400
Hydrogen 3 (General motors)	Fuel cell	60 kW	4.6 kg Liquid Hydrogen at -253^{o}C	400
Necar4 (Daimler Chrysler)	Fuel cell	70 kW	---	450

Vehicles with organic liquid storage

Name of the vehicle/Company	**Energy conversion device**	**Net power output**	**Storage system**
NECAR 5 (Daimler Chrysler)	Fuel cell	75 kW	Methanol (On board reformer)
FC5 (Ford Motor company)	Fuel cell	65kW	--do--
Mazda Premacy (Ford Motor company)	Fuel cell	65kW	--do--
FCX-V2 (Honda Motor company)	Fuel cell	60kW	--do--

Vehicles with metal hydride storage system

Name of the vehicle/Company	**Energy conversion device**	**Net power output**	**Storage system**
HRX2 (Mazda Motor Corporation)	Wankel Rotory Engine	65kW	TiFe
FCX-V1 (Honda Motor company)	Fuel cell	60kW	$LaNi_5$

On-board storage + utilization

Option		**Cost (Rs/km)**	**GHG g/km**	**Non-renewable energy use (MJ/km)**	**H_2 use MJ/km**
On-board storage	**Energy conversion device**				
Compressed H_2	Fuel cell	21.03	17.8	0.24	0.83
Liquid H_2	Fuel cell	21.06	17.8	0.24	0.80
Metal hydride	Fuel cell	21.92	26.9	0.36	0.88
Compressed H_2	IC engine	1.23	0*	0*	2.47
Liquid H_2	IC engine	1.35	0*	0*	2.32
Metal hydride	IC engine	4.17	32	0.42	2.74

*Energy use and emissions in base case vehicle manufacturing neglected

Results for hydrogen storage (at filling stations)

Parameter	**Compressed hydrogen**	**Liquid hydrogen**	**Metal hydride**	**Unit**
Delivery and storage cost	8.75	42.6	33.7	Rs/kg
GHG emissions	1.24	7.2	0.28	kg/kg
Non-renewable energy use	12.72	74	3.84	MJ/kg

Comparison of routes

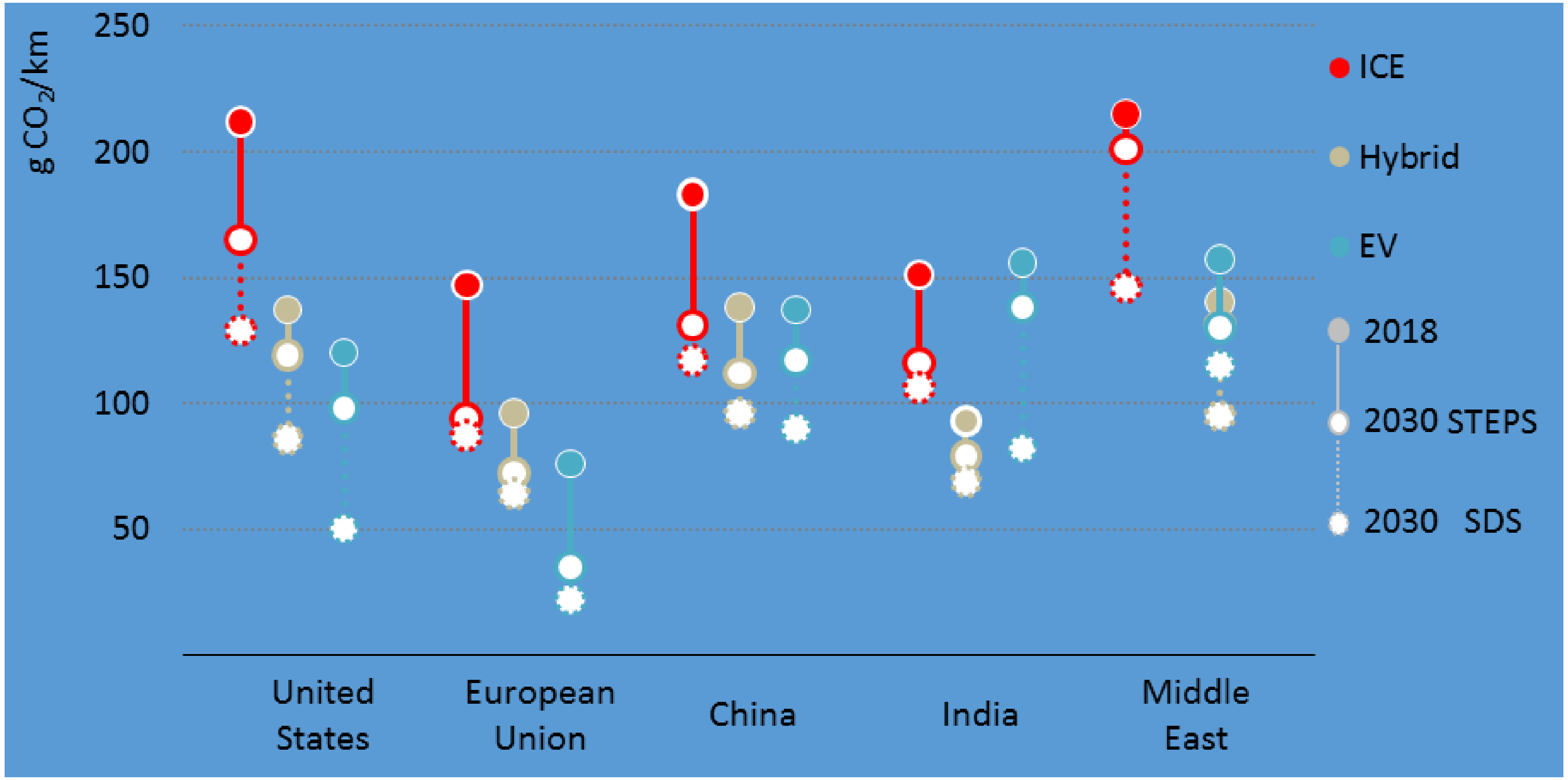
Base case 2.5 Rs/km 180 g/km

Route	**SMR – PL-C-IC**	**SMR-PL-C-FC**	**PV- PL-C-FC**	**W-PL-C-FC**	**BG-PL-C-IC**	**BG-PL-C-FC**
Specific Fuel consumption (g/km)	20.8	6.9	6.9	6.9	20.8	6.9
ALCC Cost Rs/ km	2.5	21.5	29.6	25.3	2.5-4	20.4
GHG emissions CO_2/km	310	122	59.1	43.4	157.8	70.8

Conclusions (Hydrogen Vehicles)

- Renewable hydrogen based fuel chains viable based on GHG emission and non-renewable energy use criteria
- Cost (Rs/km) higher (for photovoltaics, electrolyzer and fuel-cell based system) than existing petrol based fuel chain.
- IC engine vehicles lower cost but higher energy consumption than fuel cell vehicles.
- Hydrogen fuel chain based on SMR process (with compressed hydrogen storage and IC engine) is economically viable. However this fuel chain has higher GHG emissions.

Carbon emissions of different car powertrains by region

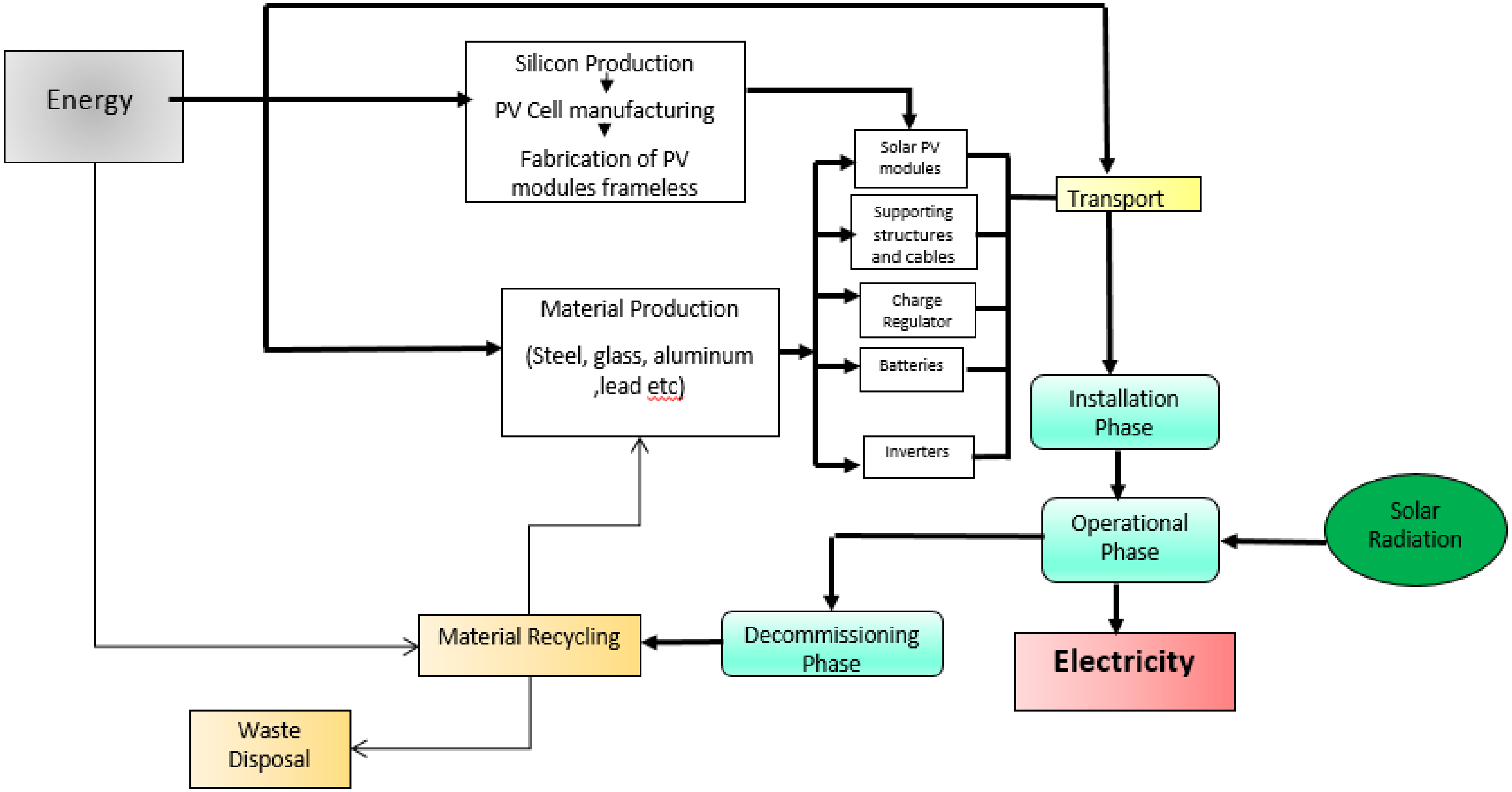


Elec
CO2/kWh
US 0.45
NY 0.21
India
Maharashtra
0.88
TN 0.82

The relative carbon footprint of ICE versus electric cars strongly depends on the power sector mix

Source: World Energy Outlook 2019 IEA
Used with permission

Life Cycle Energy Analysis Flow diagram



Comparison of different Battery options

Battery Technology	Cycle Life @ 80% DoD (Manufacture)	Maximum Service Life in years (Manufacturer)	Life in years calculated assuming 1 cycle /day	Efficiency [#1]	Specific Energy (Wh/kg)	Weight of battery cell (kg)	Energy Rating of battery (Wh)
VRLA	700[#1]-1800[#2]	10[#2]	2-5	84%	32	157	5024
Li ion	5000-7000[#1]	15[#4]	13-15	92%	91	19	1729
NiCd	1000-1500[#1]	10[#1]	3-4	80%	40	69	2745
NiMH	1500-2000[#1]	8[#1]	4-6	85%	55	10	360
NaS	5625 (4500[#3] @ 100% DoD)	15[#3]	15	90%	150	5.5	825
LiS	1400@80% [#5] DoD	5	3.5	97%	152	0.138	20.97

#1. Carl Johan Rydh, Energy analysis of batteries in photovoltaic systems. Part I:. *Energy Conservation and Management, 46*, 1980-2000, 2005
#2. Tubular gel 2V VRLA battery Technical Manual, http://www.exide4u.com/solatron-tubular-gel-vrla-2v-cell
#3. NGK Insulators NaS Battery, https://www.ngk.co.jp/nas/specs/
#4. Castillo, "Grid-scale energy storage applications in renewable energy integration: A survey", 2014
#5 http://oxisenergy.com/wp-content/uploads/2016/10/OXIS-Li-S-Long-Life-Cell-v4.01.pdf

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#3. NGK Insulators NaS Battery, https://www.ngk.co.jp/nas/specs/
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#5 http://oxisenergy.com/wp-content/uploads/2016/10/OXIS-Li-S-Long-Life-Cell-v4.01.pdf

Comparison of PV-Battery

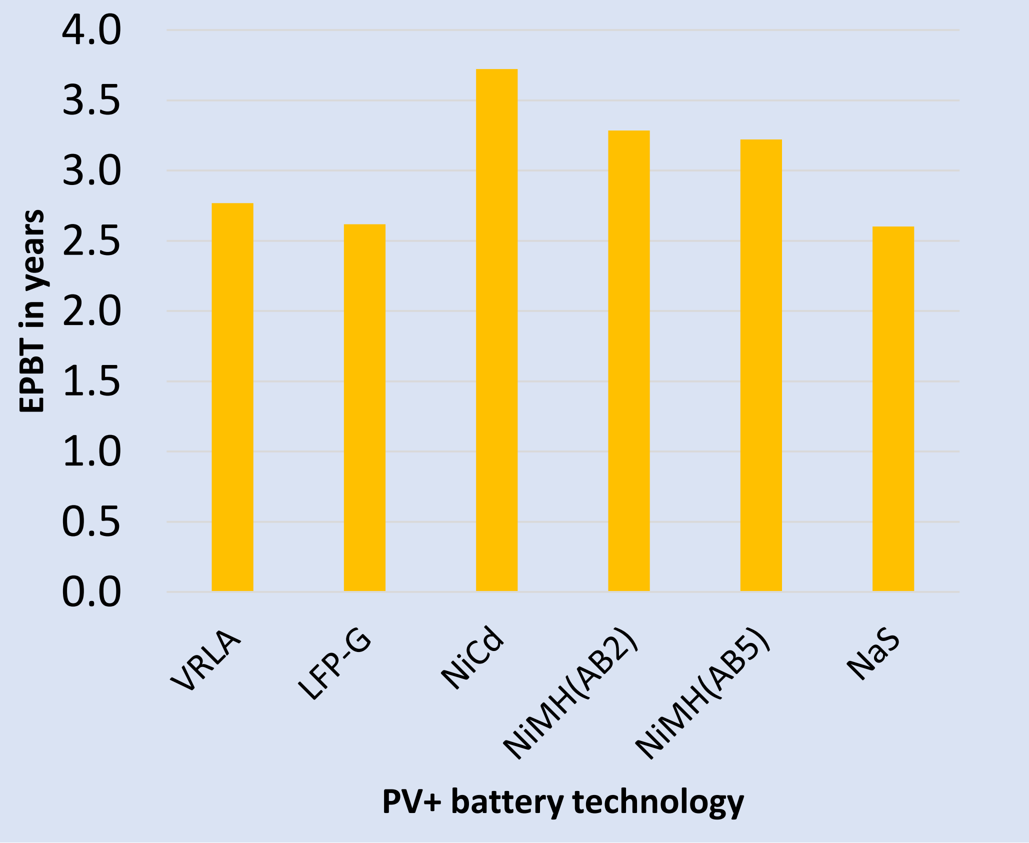
PV+battery configuration	Energy Pay Back Time(years)	Net Energy Ratio	Energy Pay back (% of cycle life)	Emission Factor ($kgCO_2$/kWh of output)
VRLA	2.75	4.63	20.10	0.26
LFP-G	2.62	6.55	6.88	0.14
NiMH(AB_2)	3.44	2.52	36.92	0.42
NiMH(AB_5)	3.4	2.63	34.12	0.42
NaS	4.3	3.9	7.58	0.67
NiCd	2.69	4.2	64.12	0.091
LiS	3.38	2.8	67.56	0.31

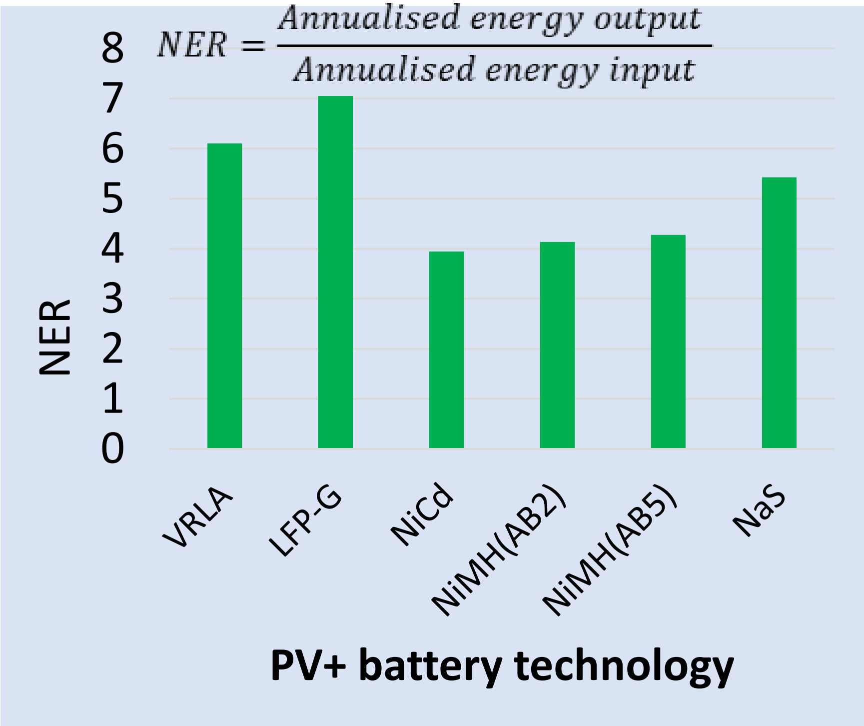
$$\text{EPBT} = \frac{\text{LifeTime Energy Input to the system}}{\text{Annual Energy Output}}$$

$$\text{NER} = \frac{\text{Annualised energy output}}{\text{Annualised energy input}}$$

Das et al., CTEP, Springer, 2017

Comparison of Energy Pay Back Time & Net Energy Ratio





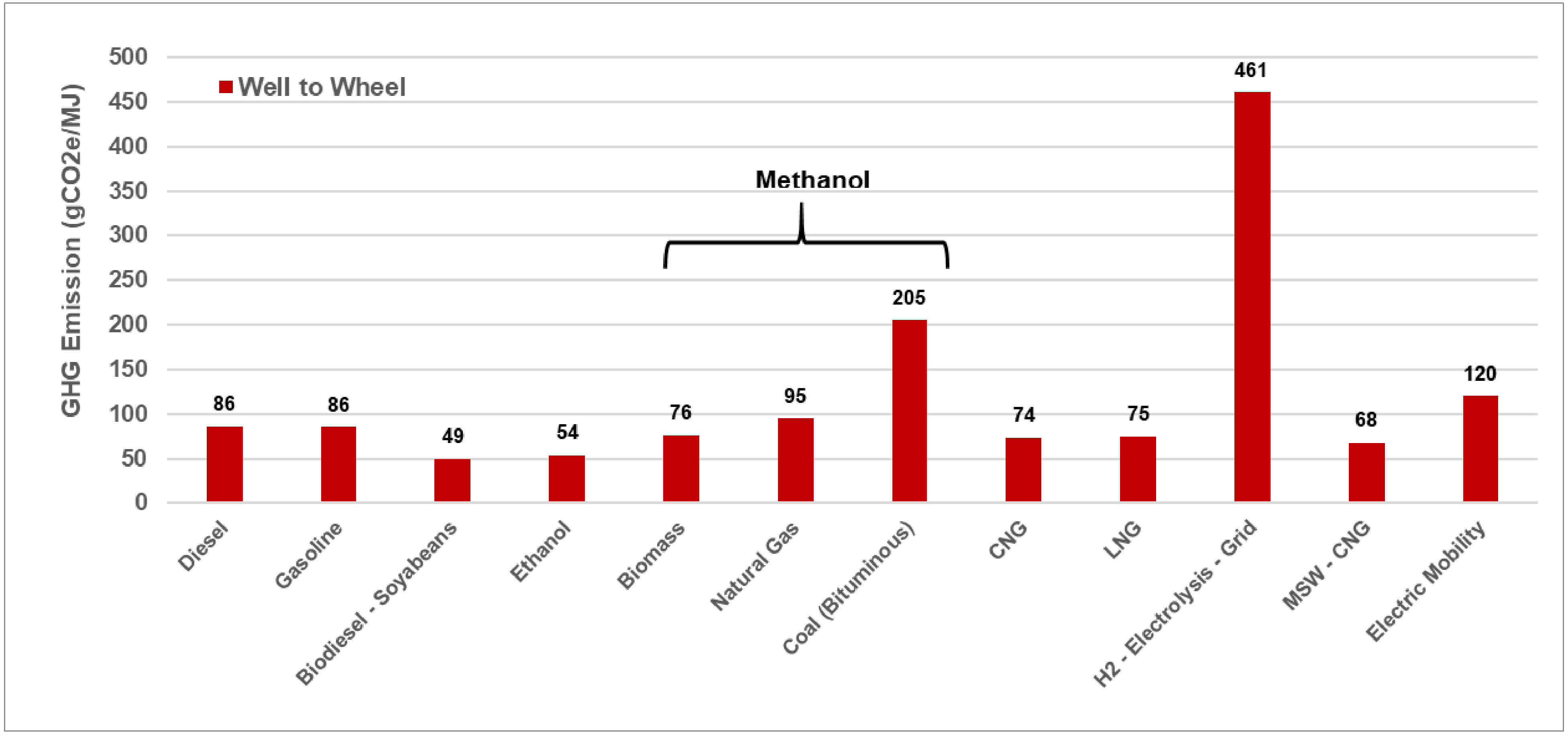
$$NER = \frac{Annualised\ energy\ output}{Annualised\ energy\ input}$$

Energy Analysis – Hydrogen Storage

Comparison of different storage options for 1 km ride

	Compressed tank	Cryogenic tank	FeTi hydride	Mg hydride
H2 consumption (gms)	6.24	6.4	8.04	9.7
Direct energy required to travel (kJ)	749	768	965.4	1164
Energy required to produce and store H2 (kJ)	1260.7	2172.7	1473.7	1777
Energy required to produce tank(kJ)	34.2	15.6	177.3	60
Total energy required (kJ)	2043.9	2956.3	2616.4	3001.5

Well to Wheel (WTW) GHG Emissions for Fuels



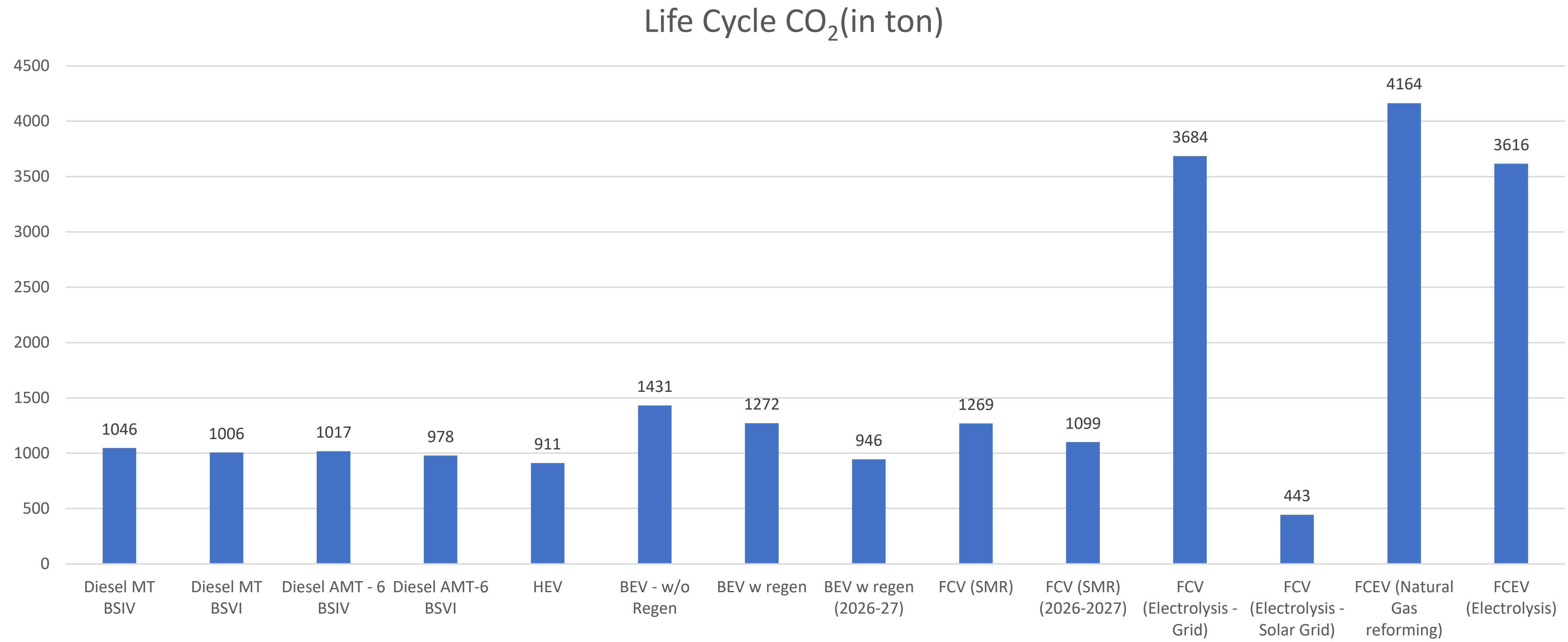
Options for Heavy Duty Trucks-Industry Study

- Natural Gas and Bio fuels have the least GHG foot print
- For Electric Mobility – GHG footprint will get attractive when Renewable mix increases

Note: India electricity mix is dominated by coal-based thermal power plants resulting in higher WTW GHG emissions

Source: EU WTT – 2014, India and EU Electricity Mix – Above numbers are adjusted for Indian Electricity mix where applicable

Life Cycle CO_2



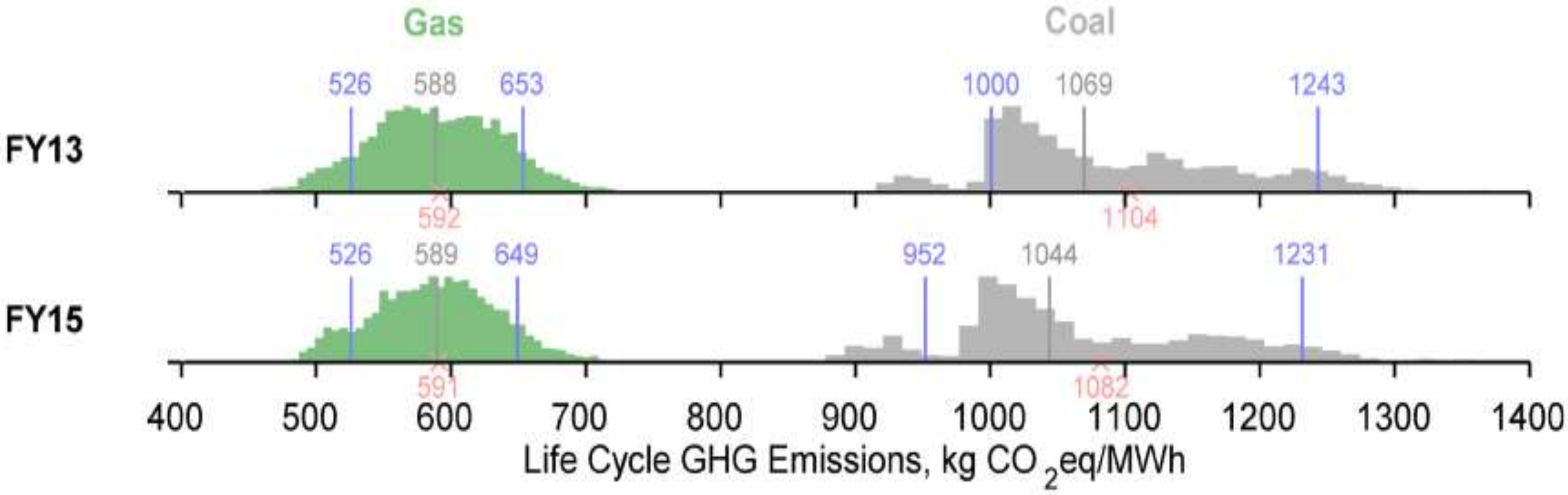
Options for Heavy Duty Trucks- Industry Study

Life Cycle of CO2 is considered with,

Annual Run km	100000
Years	10
Lifecycle Kms	1000000

Route used for simulation:
Pune – Bangalore – Pune
BSVI commercial Vehicle

GHG Emissions of Power plants



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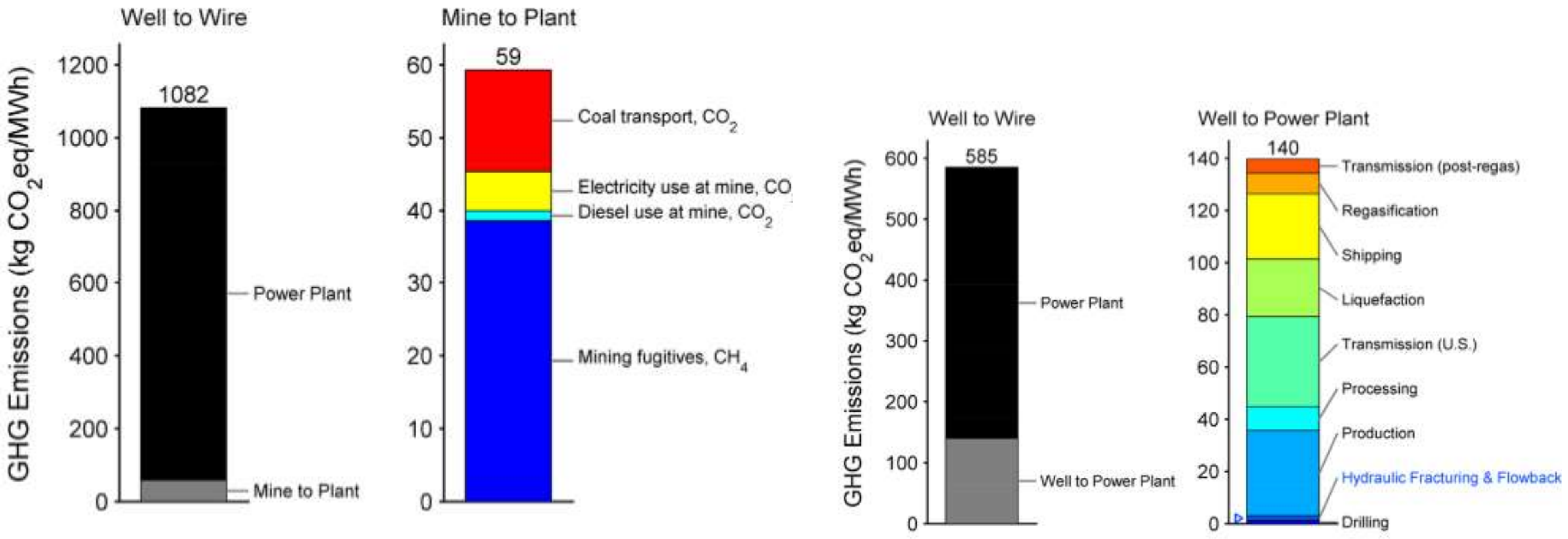
Coal and Gas power plant GHG emissions



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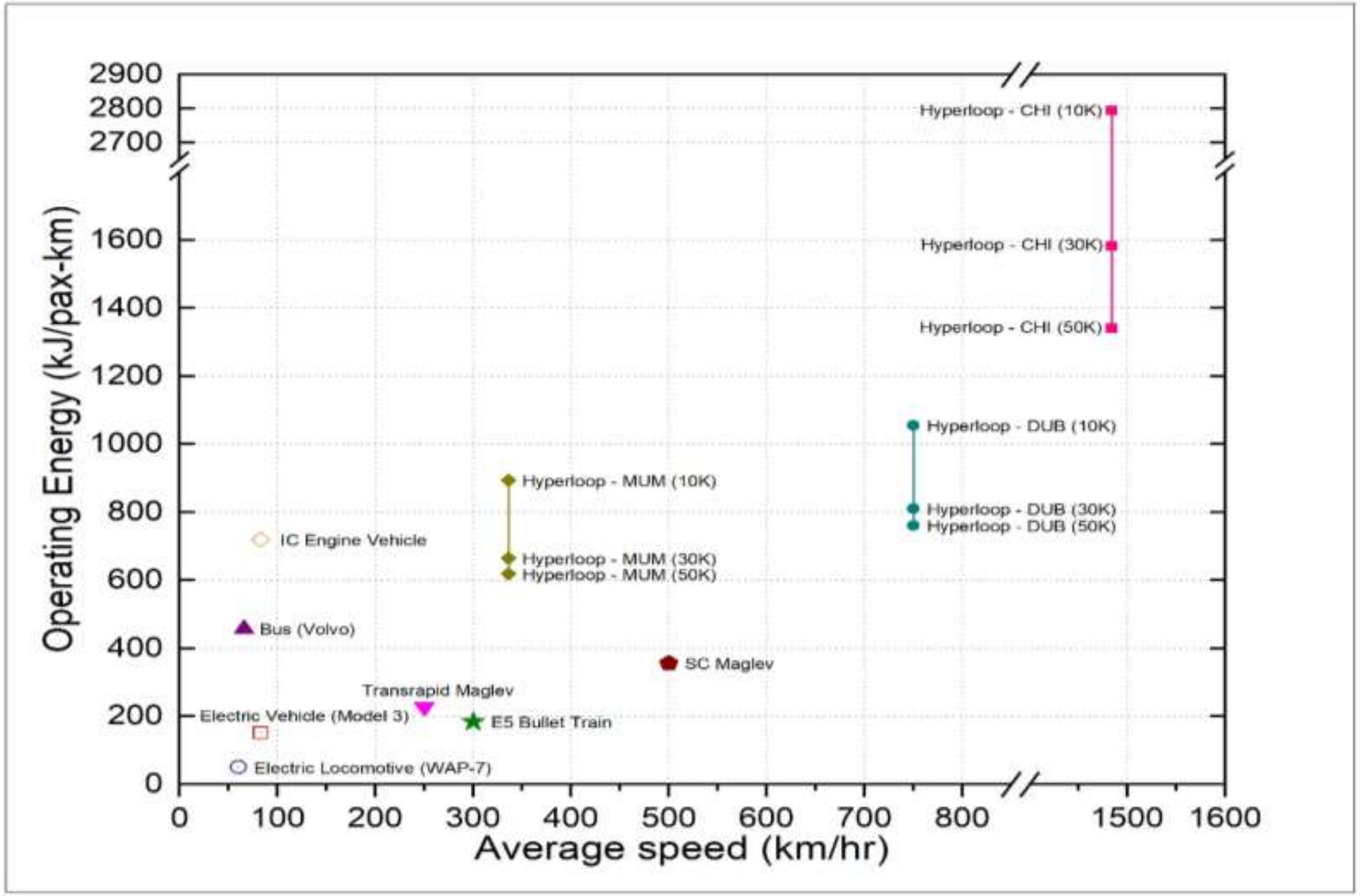
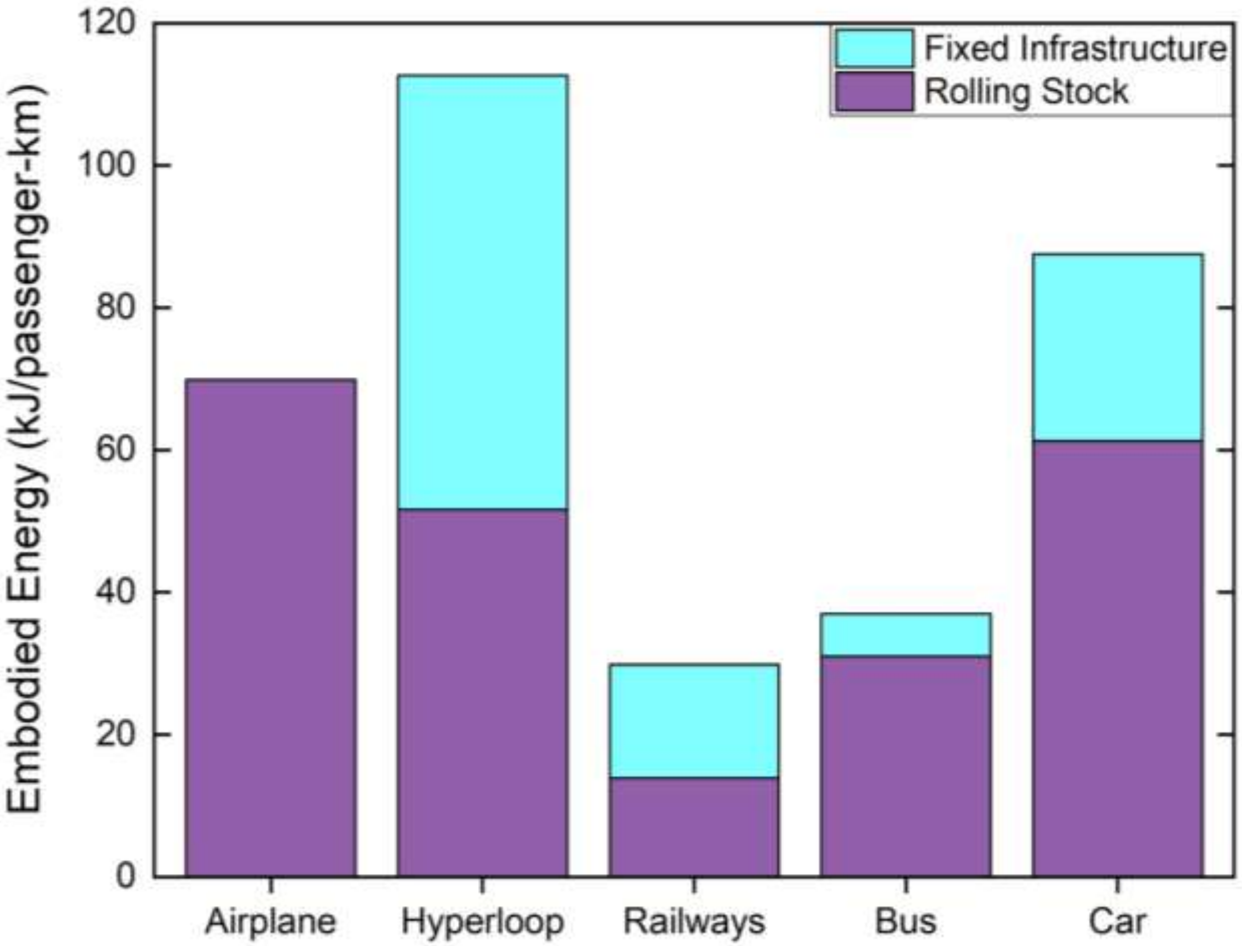
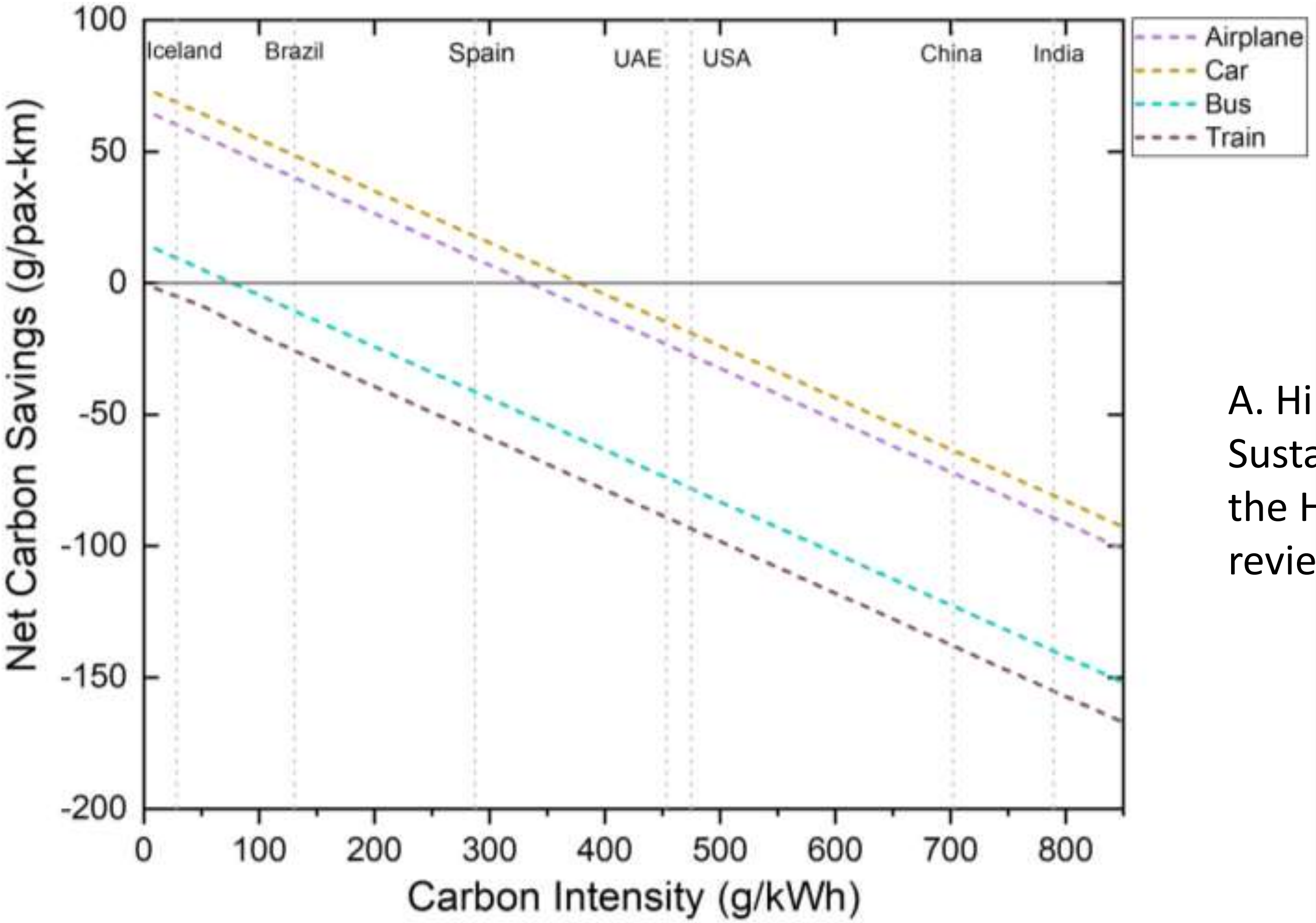
Operating Energy comparisona



Embodied Energy alternative transport



Hyperloop- Carbon Savings



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Conclusions

- Life cycle Analysis- Energy and carbon – can identify viability and sustainability of options
- Screening of new technologies
- Replacement of energy and carbon intensive materials, processes
- Sensitivity to grid mix - Electricity versus hydrogen
- Cost, LCA,- Energy, Carbon, Land ,Water – multi criteria
- Overall impact on sustainability, economy, employment

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