Lecture – 22A & 22B

Energy Resources, Economics and Environment

Net Energy Analysis

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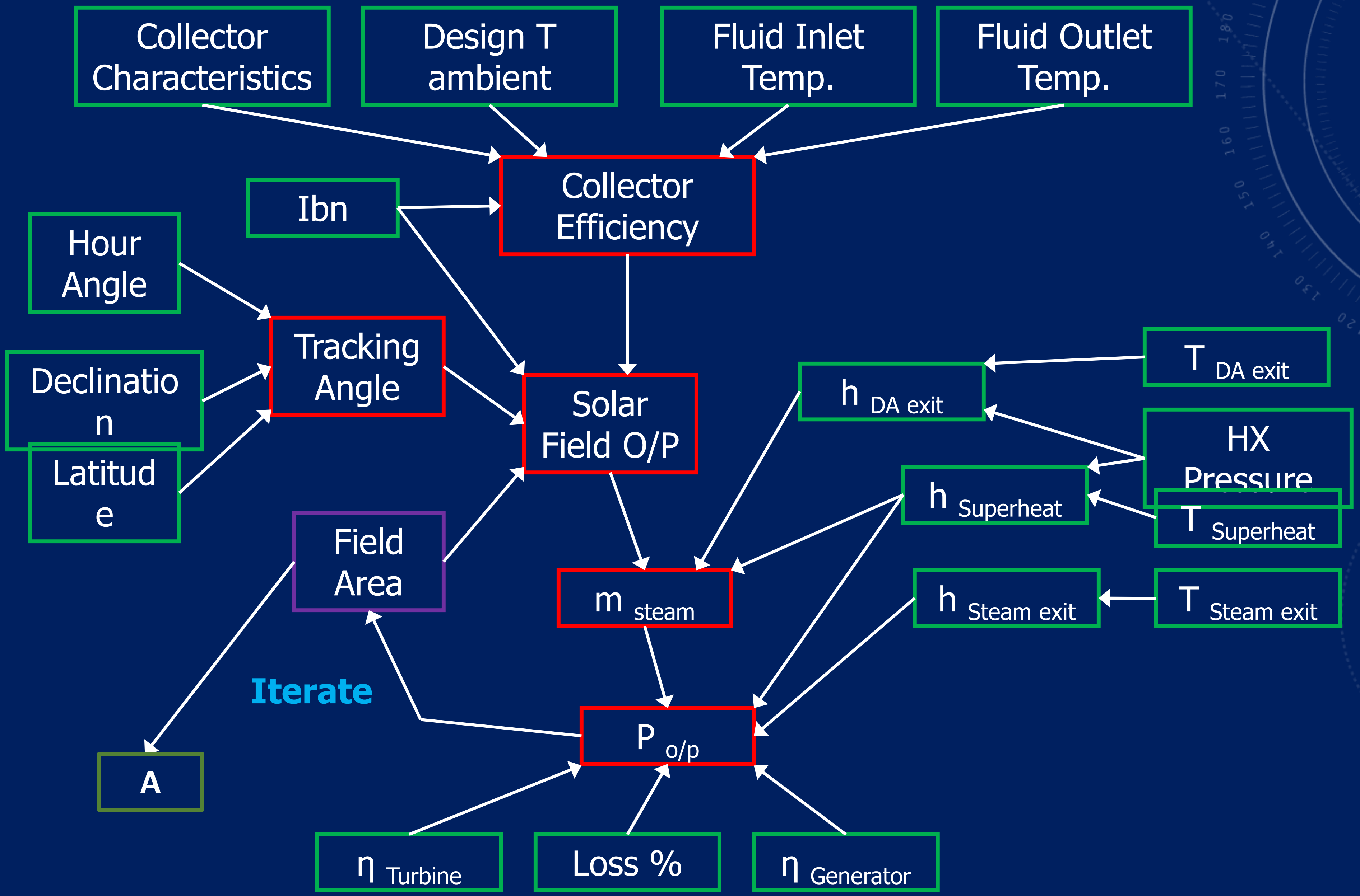
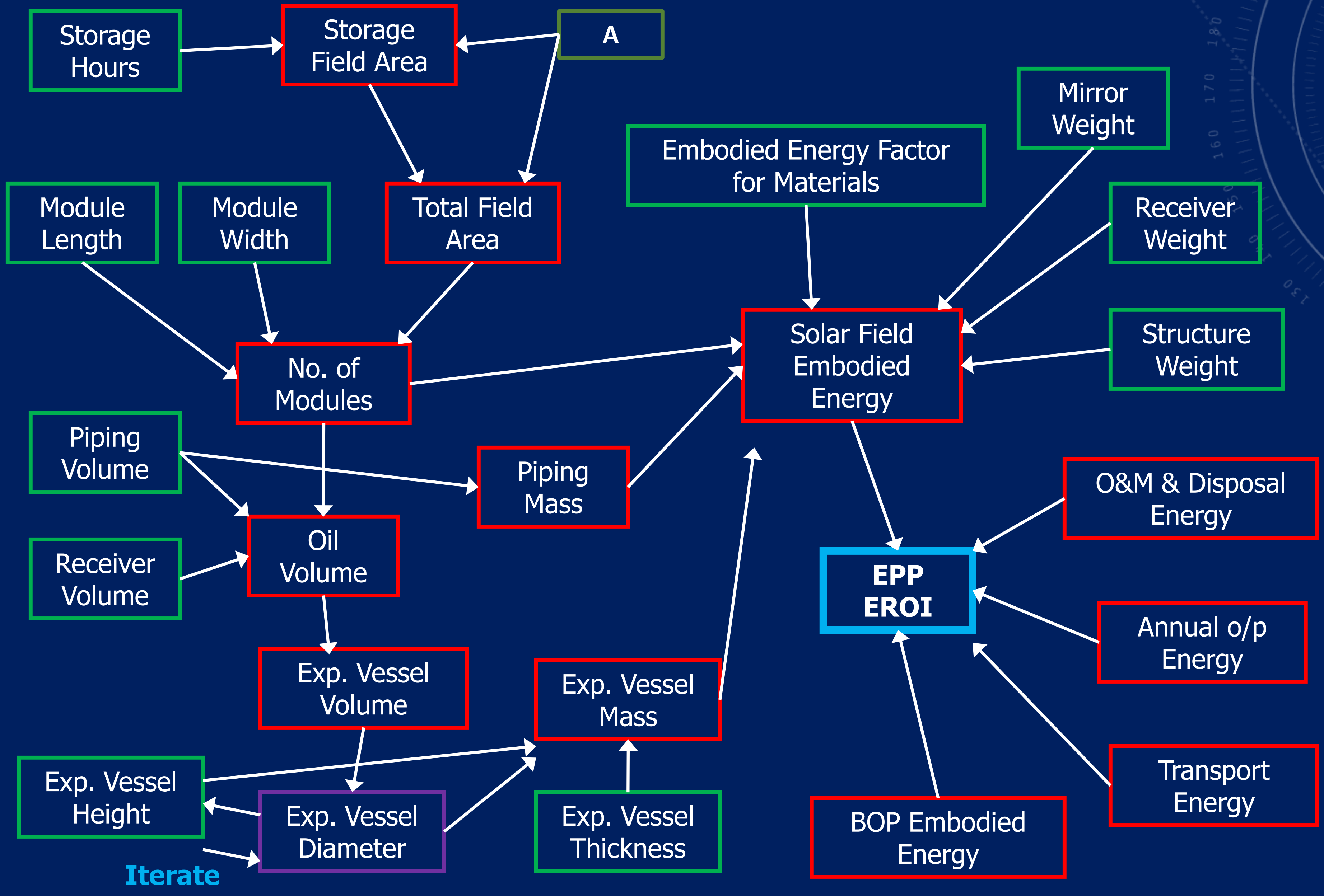
Energy Analysis – Hydrogen Storage

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

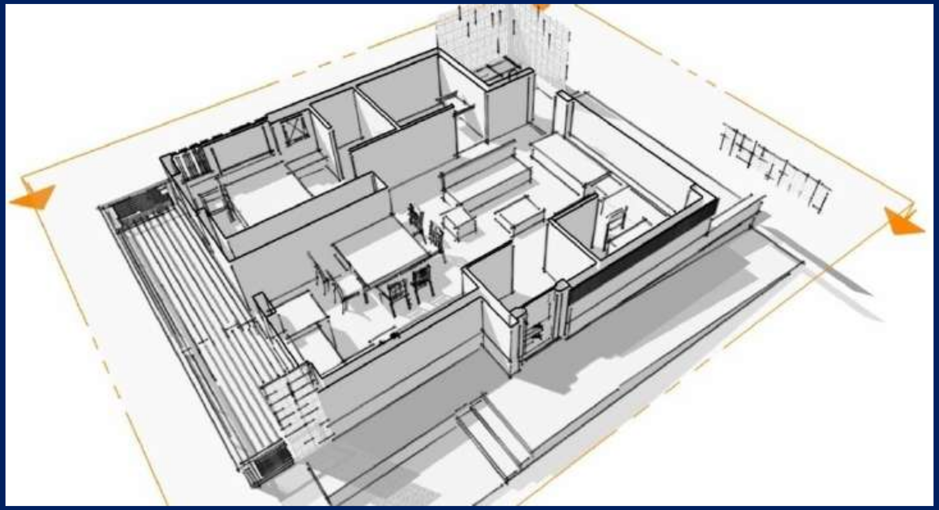
Solar Thermal Power – Energy Analysis

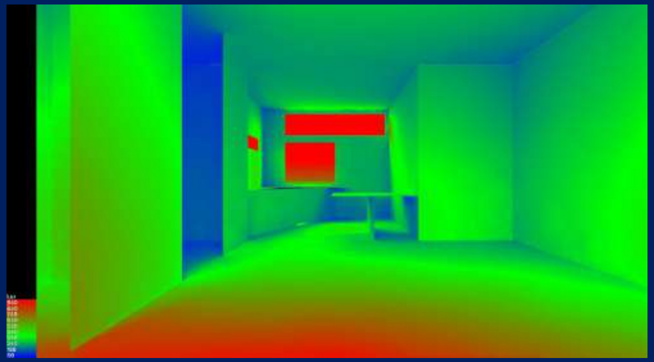


Solar Thermal Power – Energy Analysis (Contd)

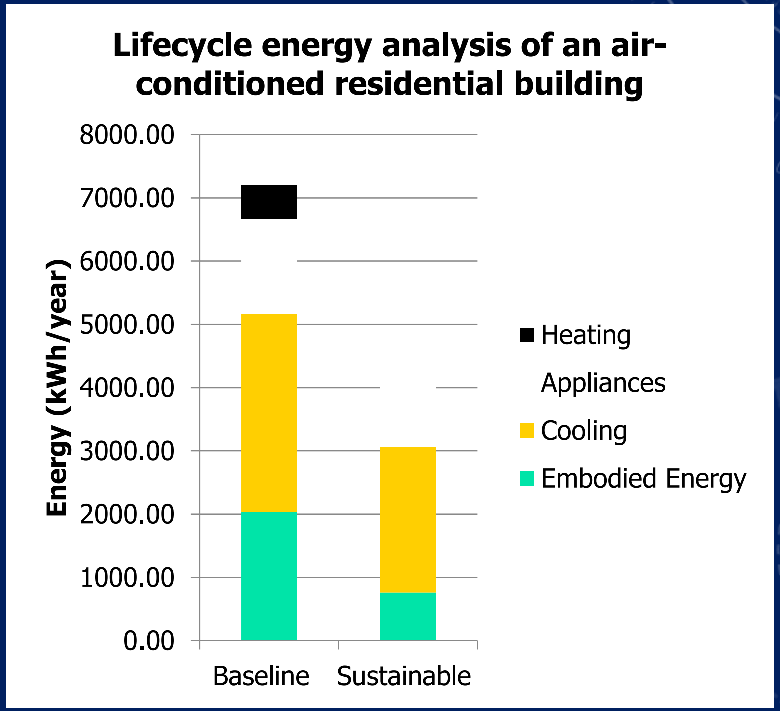


Energy Analysis Of Buildings

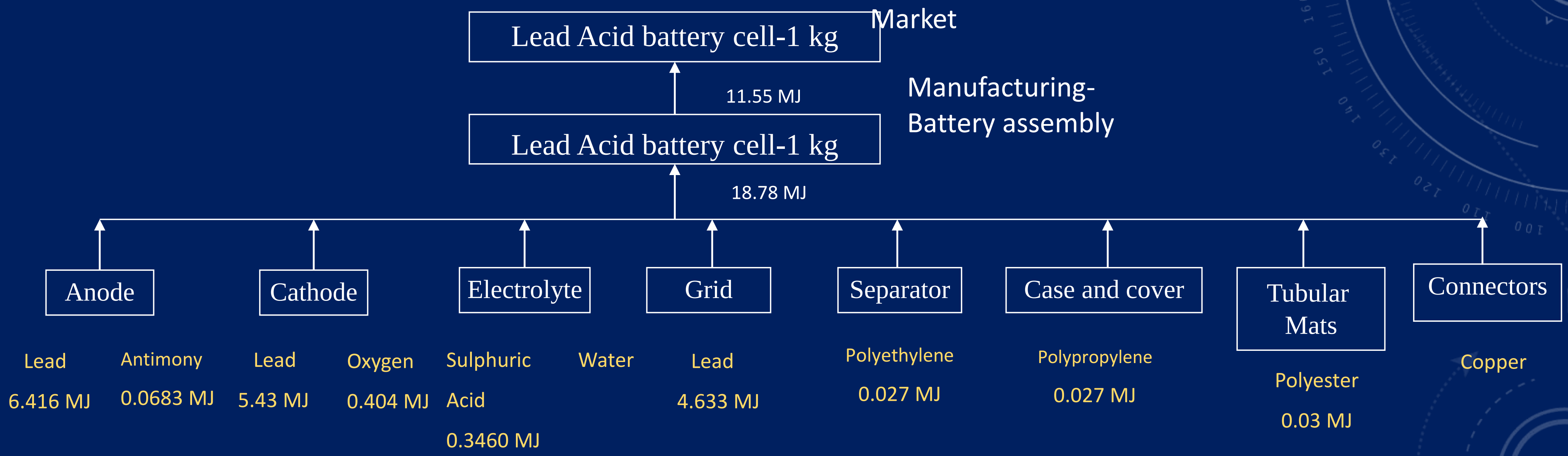




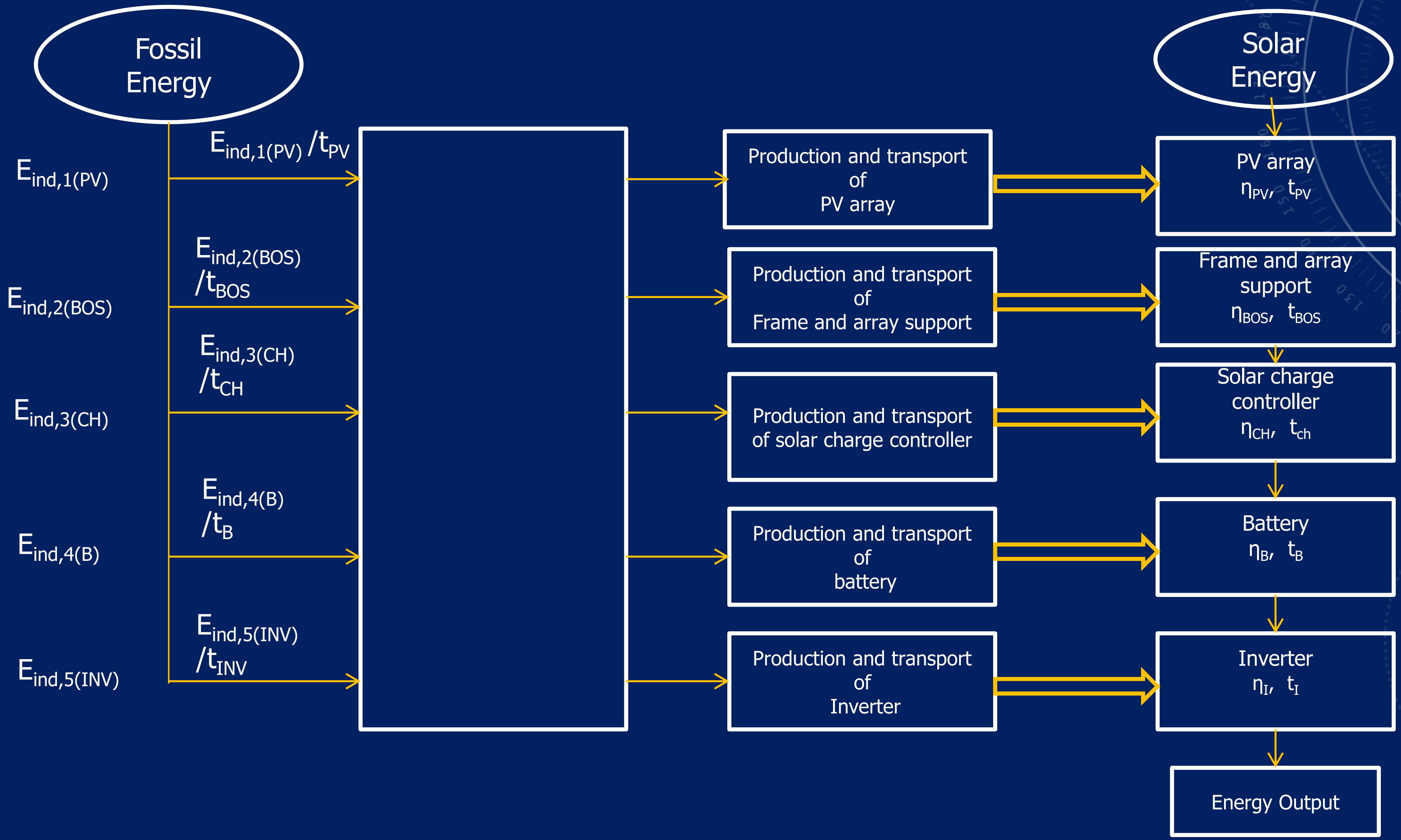
Daylighting Simulation



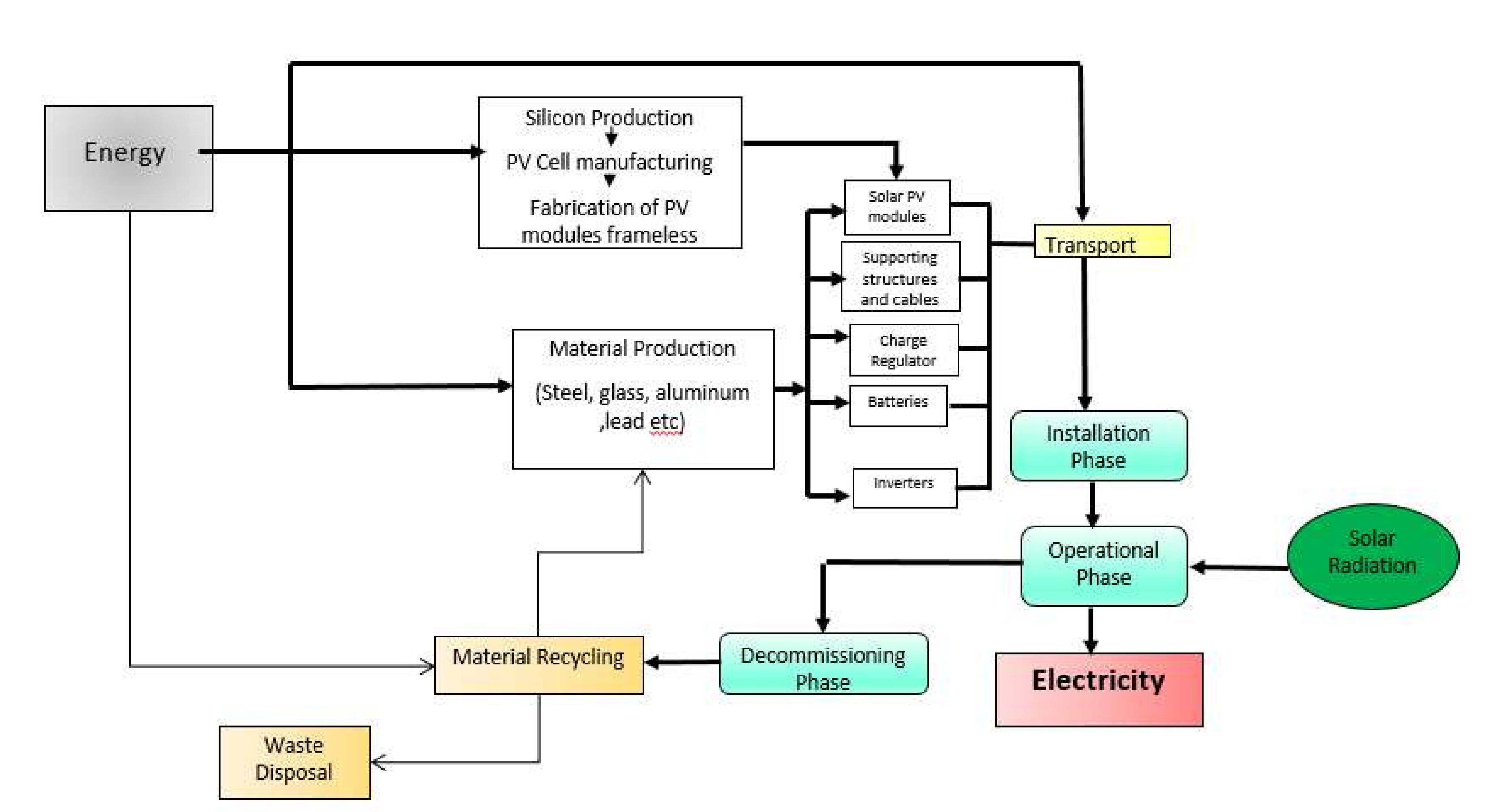
Cradle to Gate model structure of a lead acid battery



Material	Embodied Energy(MJ/kg)
Virgin Lead	39.01
Recycled Lead	25.8
Virgin Aluminium	160.5
Recycled Aluminium	31.8


Fossil Energy
Solar Energy
$E_{ind,1(PV)}$
$E_{ind,1(PV)}/t_{PV}$
$E_{ind,2(BOS)}$
$E_{ind,2(BOS)}/t_{BOS}$
$E_{ind,3(CH)}$
$E_{ind,3(CH)}/t_{CH}$
$E_{ind,4(B)}$
$E_{ind,4(B)}/t_{B}$
$E_{ind,5(INV)}$
$E_{ind,5(INV)}/t_{INV}$
Production and transport of PV array
Production and transport of Frame and array support
Production and transport of solar charge controller
Production and transport of battery
Production and transport of Inverter
PV array η_{PV}, t_{PV}
Frame and array support η_{BOS}, t_{BOS}
Solar charge controller η_{CH}, t_{ch}
Battery η_{B}, t_{B}
Inverter η_{I}, t_{I}
Energy Output

Life Cycle Energy Analysis Flow diagram



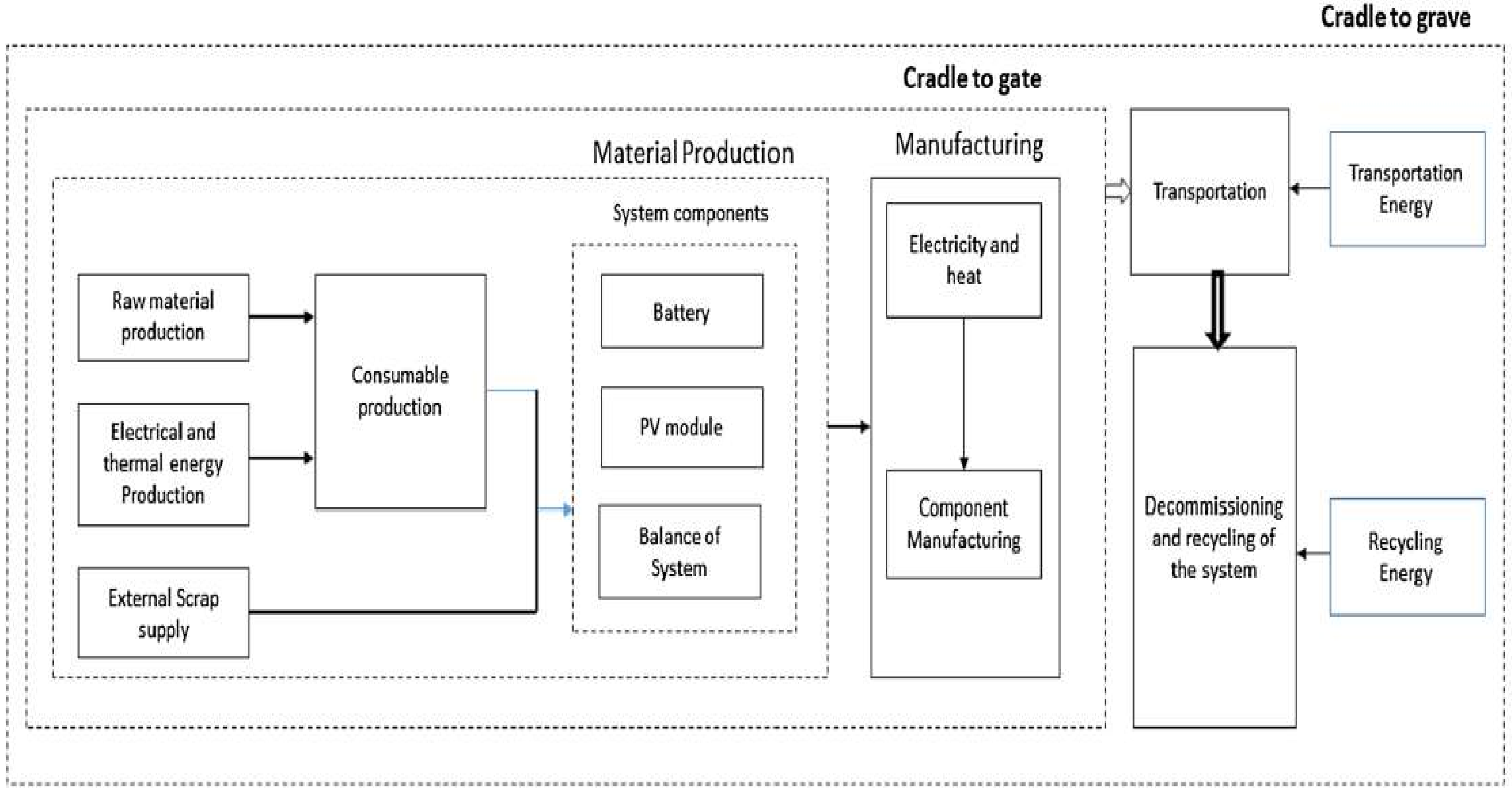


Fig. 4 Life cycle energy and environmental analysis boundary of the proposed microgrid

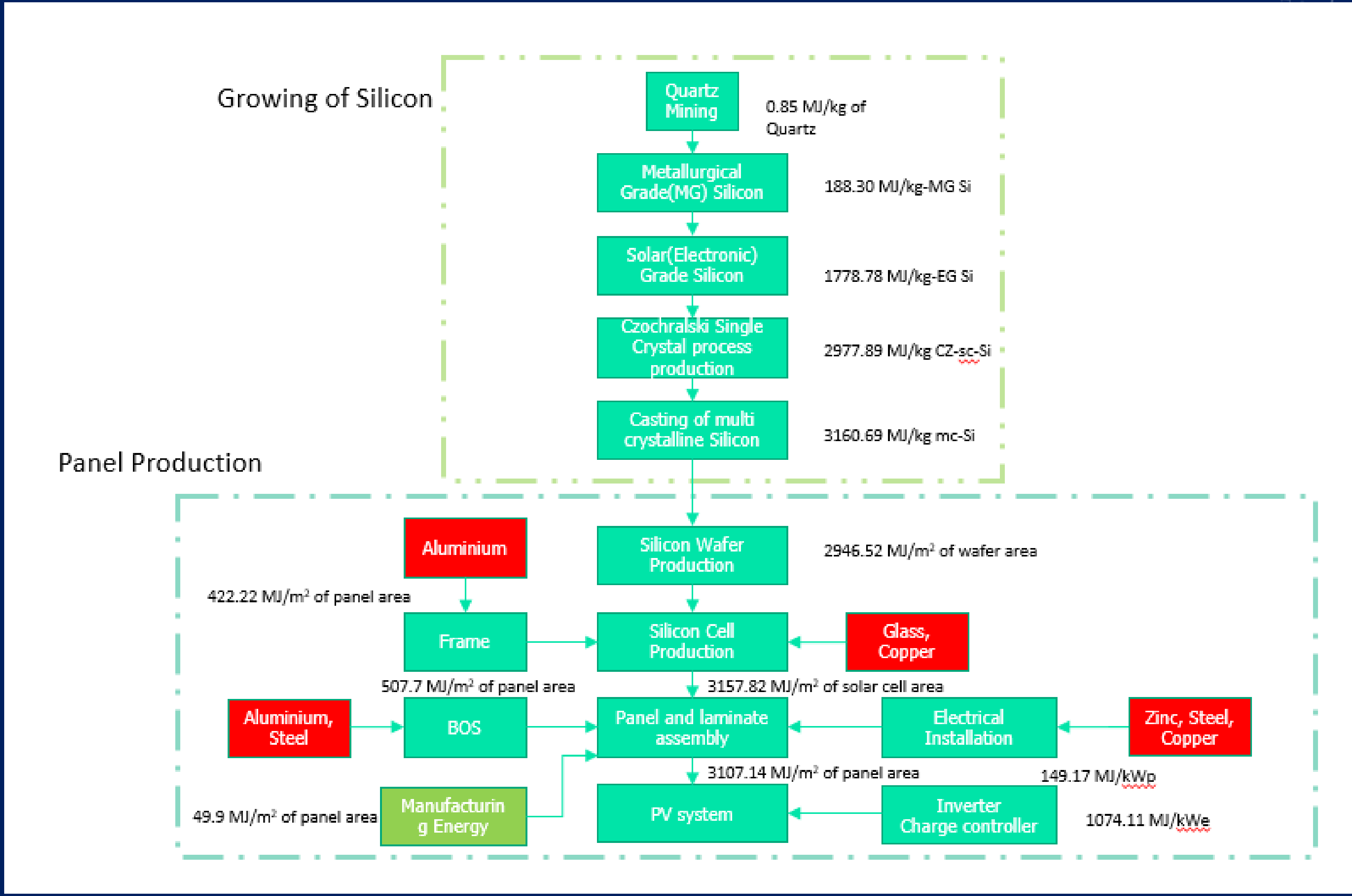
Table 3 Embodied energy of Pb and Al in Indian conditions and comparison with existing literature values

Material	Source	Production energy (MJ/kg)	References
Pb	Ore	22.3	Sullivan et al. (2011)
Pb	Ore	27.2	Larcher and Tarascon (2014)
Pb	Ore	28.7	Alsema (2000a)
Pb	Ore	31.2	Gaines and Singh (1995)
Pb	Ore	39.1	This work
Pb	Scrap	4.2	Sullivan et al. (2011)
Pb	Scrap	5.3	Larcher and Tarascon (2014)
Pb	Scrap	11.2	Alsema (2000a)
Pb	Scrap	7.2	Gaines and Singh (1995)
Pb	Scrap	24.74	This work
PbO	Pb	12.7	Gaines and Singh (1995)
PbO	Pb (scrap)	19.94	This work
Al	Ore	204	Sullivan et al. (2011)
Al	Ore	160.54	This work
Al	Scrap	31.8	This work

Table 5 Battery embodied energy values in Indian context

Battery configuration	Material production energy E_{mp}		Manufacturing energy E_{mnf}		Recycling energy E_{rec}		Transportation Energy–E_{tr} for finished product import		$E_{tot} = E_{ctg} + E_{rec} + E_{tr}$ (MJ_{pf}/Wh)
	MJ_{pf}/kg (Recycled materials)	MJ_{pf}/Wh (Recycled materials)	MJ_{pf}/kg	MJ_{pf}/Wh	MJ_{pf}/kg	MJ_{pf}/Wh	(MJ_{pf}/kg)	(MJ_{pf}/Wh)	
VRLA	21.87	0.681	11.6	0.39	2.4	0.08	–	–	1.14
LFP–G	96.27	1.05	30	0.33	3.6	0.04	2.9	0.03	1.46
Nickel metal hydride (AB_2)	41.99	0.76	75	1.36	19.6	0.36	0.99	0.02	2.5
Nickel–metal hydride (AB_5)	33.12	0.60	75	1.36	19.6	0.36	0.99	0.018	2.34
Nickel cadmium	64.72	1.58	46	1.15	4.85	0.12	0.99	0.025	2.88
Sodium sulphur	128.31	0.86	56	0.38	–	–	1.34	0.009	1.24
Lithium sulphur	242.06	1.59	172	1.13	51.2	0.34	1.61	0.01	3.07

Energy Flow diagram of the PV panel for India



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

PV Battery Grid Backup System Components

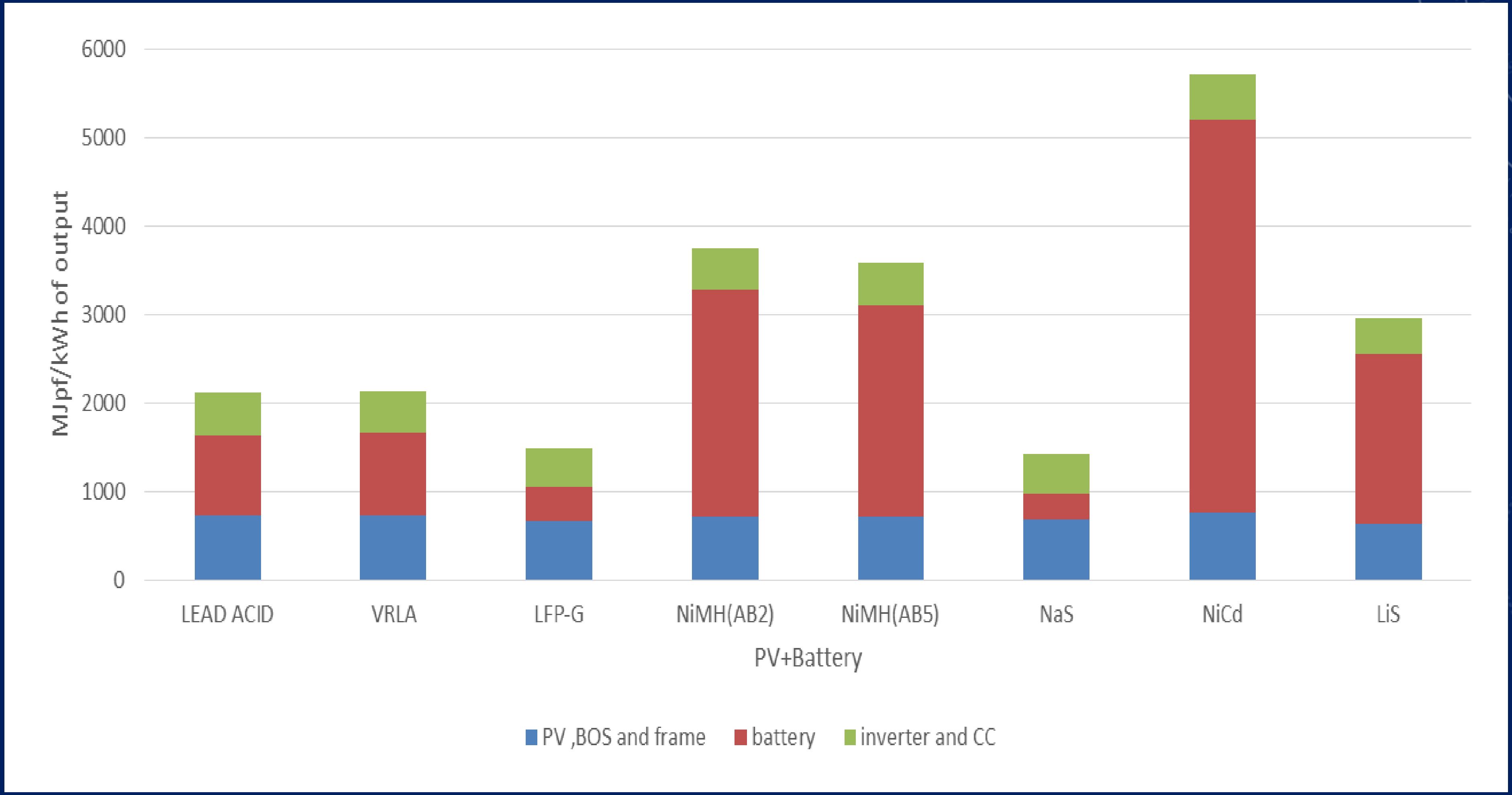
Component	Specifications							
104 x250 Wp PV Polycrystalline module	Mass = 2620.8 kg							
	Recyclable mass of the frame = 192.42 kg							
	Sensing Area=153.34 m^2							
	Frame area =21.38 m^2							
	Efficiency =15.4 %							
1 x solar battery charger	30 kW,Eff=97%							
1 x Inverter	50 kW,208 V AC,28 A ,Eff=96.3%							
Array support	Roof top							
Battery	Pb-Acid	VRLA	Li Ion	NiMH(AB2)	NiMH(AB5)	NiCd	NaS	LiS
Storage Capacity(kWh)	150	149.88	136.8	148.11	148.11	139.89	157.37	129.8

Component	Material Production Energy	Manufacturing Energy of PV panel, frame and BOS (MJ_{pf}/m^2)	Material Production Energy (MJ_{pf} /kW_e)	Recycled Material Production Energy (MJ_{pf} /Wh)	Virgin Material Production Energy (MJ_{pf} /Wh)	Manufacturing Energy (MJ_{pf} /Wh)	Recycling Energy (MJ_{pf} /Wh)	Transportation Energy (MJ_{pf} /Wh)
PV system (polyc-Si)	3107.14MJ_{pf}/m^2 of sensing area	49.9 m^2 of panel area						0.34 (MJ_{pf} /kg)
Frame	422.22 MJ_{pf}/m^2 of panel area							
Balance of System(BOS)	507.7 MJ_{pf}/m^2 of panel area							
Electrical Installation	149.17 MJ_{pf}/kWp							
Charge controller			1074.11					
BATTERY								
VRLA				0.681	1.12	0.385	0.075	-
LFP-G				1.05	1.088	0.33	0.04	0.031
NiMH (AB2)				0.763	1.55	1.36	0.36	0.018
NiMH (AB5)				0.602	1.498	1.36	0.36	0.018
NiCd				1.58	3.205	1.15	0.121	-
NaS@300 °C				0.855	1.04	0.373	-	0.0089
LiS				-	1.59	1.13	0.34	-
Inverter			1074.11					

Energy requirement comparison(expressed per mass)

	Energy Density(Wh/kg)	Weight of a battery cell(kg)	Cycle life(80% DOD)	Emp(MJ/kg)	Emnf(MJ/kg)	Erec(MJ/kg)
LEAD ACID	30	3.14	500	18.78	11.55	2.4
VRLA	32	157	700-1800	21.8	11.55	2.4
LFP-G	91	19	5000-7000	96.27	30	3.6
NiMH(AB2)	55	10	1500-2000	41.99	75	19.6
NiMH(AB5)	55	10	1500-2000	33.12	75	19.6
NaS(@ 300 °C)	150	5.5	5625	128.32	56	0
NiCd	40	69	1000-1500	64.8	46	4.85
LiS	152	0.138	1400	242.06	172	51.2

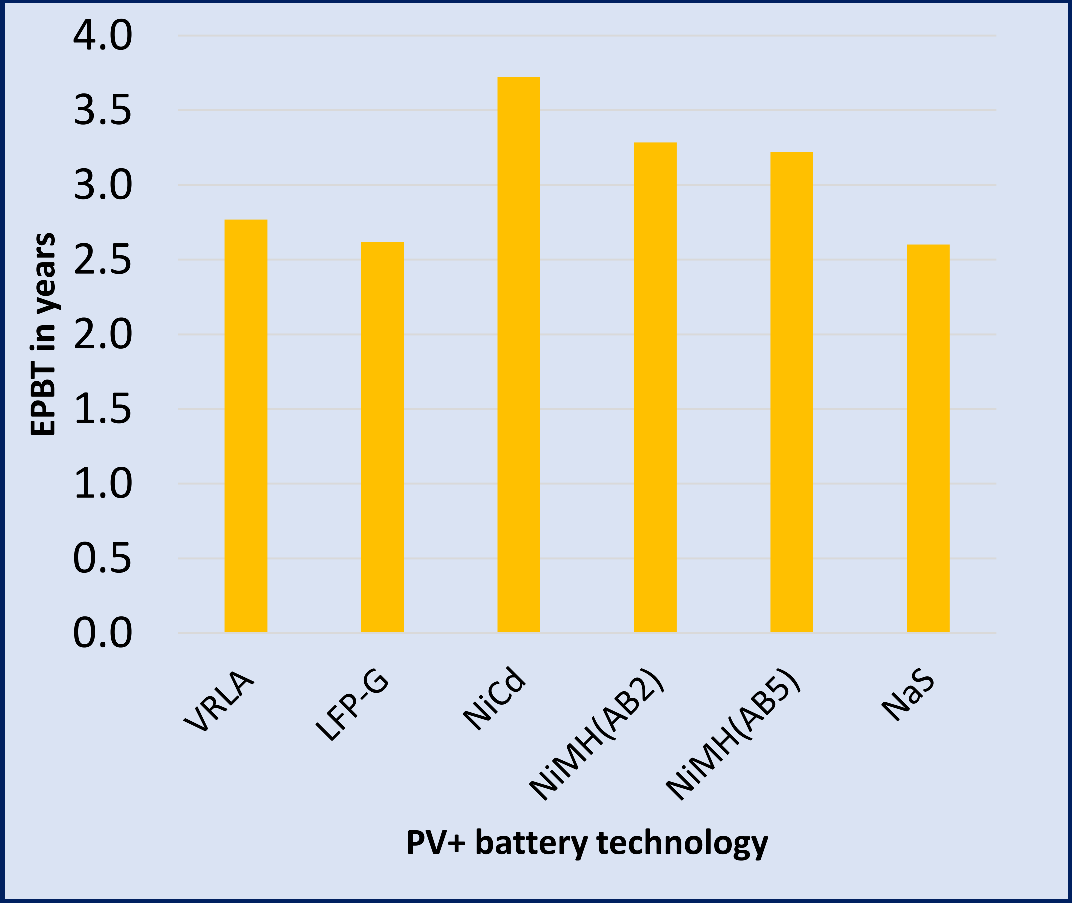
Embodied energy per unit generation of the system



Energy requirement for different components

Component	Material Production Energy (MJ_{pf}/m^2)	Material Production Energy (MJ_{pf}/kW_e)	Recycled Material Production Energy (MJ_{pf}/Wh)	Virgin Material Production Energy (MJ_{pf}/Wh)	Manufacturing Energy (MJ_{pf}/Wh)	Transportation Energy (MJ_{pf}/Wh)
PV system (mc-Si)	4200					
Balance of System(BOS)	2300					
Charge controller		1000				
BATTERY OPTIONS						
VRLA			0.68	1.12	0.39	-
LFP-G			1.05	1.09	0.33	0.07
NiMH (AB_2)			0.76	1.55	1.36	0.03
NiMH (AB_5)			0.60	1.5	1.36	0.03
NiCd			1.58	3.21	1.15	-
NaS			0.86	1.04	0	0.02
Inverter		1000				

Comparison of Energy Pay Back Time & Net Energy Ratio



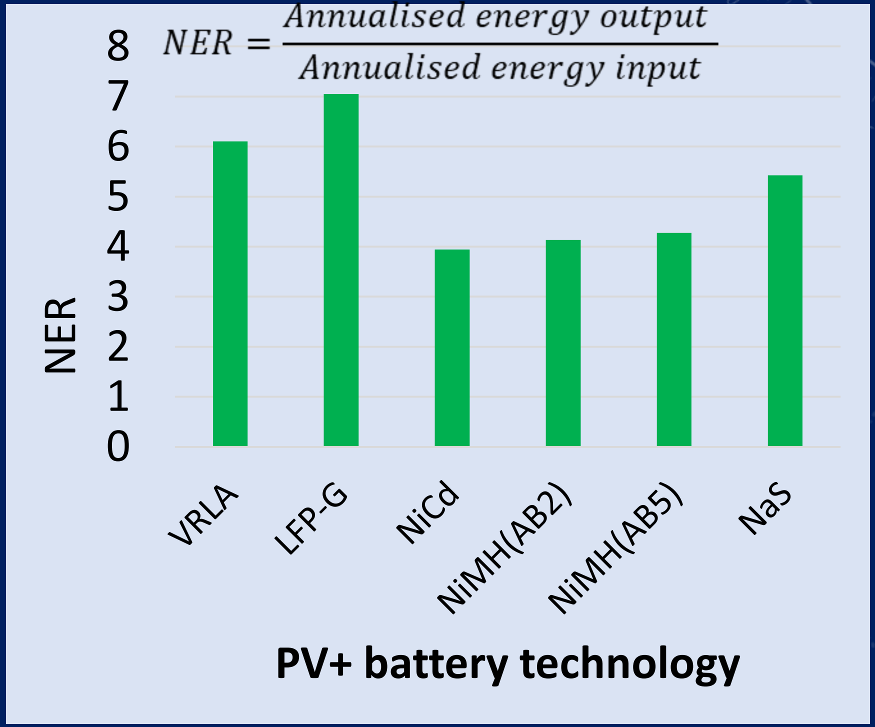


Table 6 Embodied carbon of batteries in Indian conditions

Battery	Material production	Manufacturing	Recycling	Transportation
	kgCO_2/storage capacity (Wh)			
VRLA	0.18	0.04	0.02	–
LFP–G	0.21	0.05	0.01	0.002
NiMH (AB_2)	0.09	0.25	0.02	0.001
NiMH (AB_5)	0.09	0.25	0.02	0.001
NiCd	0.03	0.07	0.0025	0.001
NaS	0.11	0.32	–	0.0024
LiS	0.26	0.11	0.0044	7.89×10^{-4}

Renewable Hydrogen

- Current methods of hydrogen production
  - Steam methane reforming (SMR)
  - Coal gasification
  - Electrolysis
- Based on fossil fuels, Not sustainable
- Need for hydrogen production from renewable energy sources like wind, solar, biomass etc.

Biological methods of hydrogen production

- Operates at ambient temperature and pressure – expected to be less energy intensive.
- Variety of feedstocks as carbon source like sugars, lignocellulosic material, wastewater etc.
- Several reactions – substrate, bacteria

$$C_6H_{12}O_6 + 2H_2O \longrightarrow 4H_2 + 2CO_2 + 2CH_3COOH$$

Available online at www.sciencedirect.com

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International Journal of Hydrogen Energy 33 (2008) 279–286

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Comparison of biohydrogen production processes

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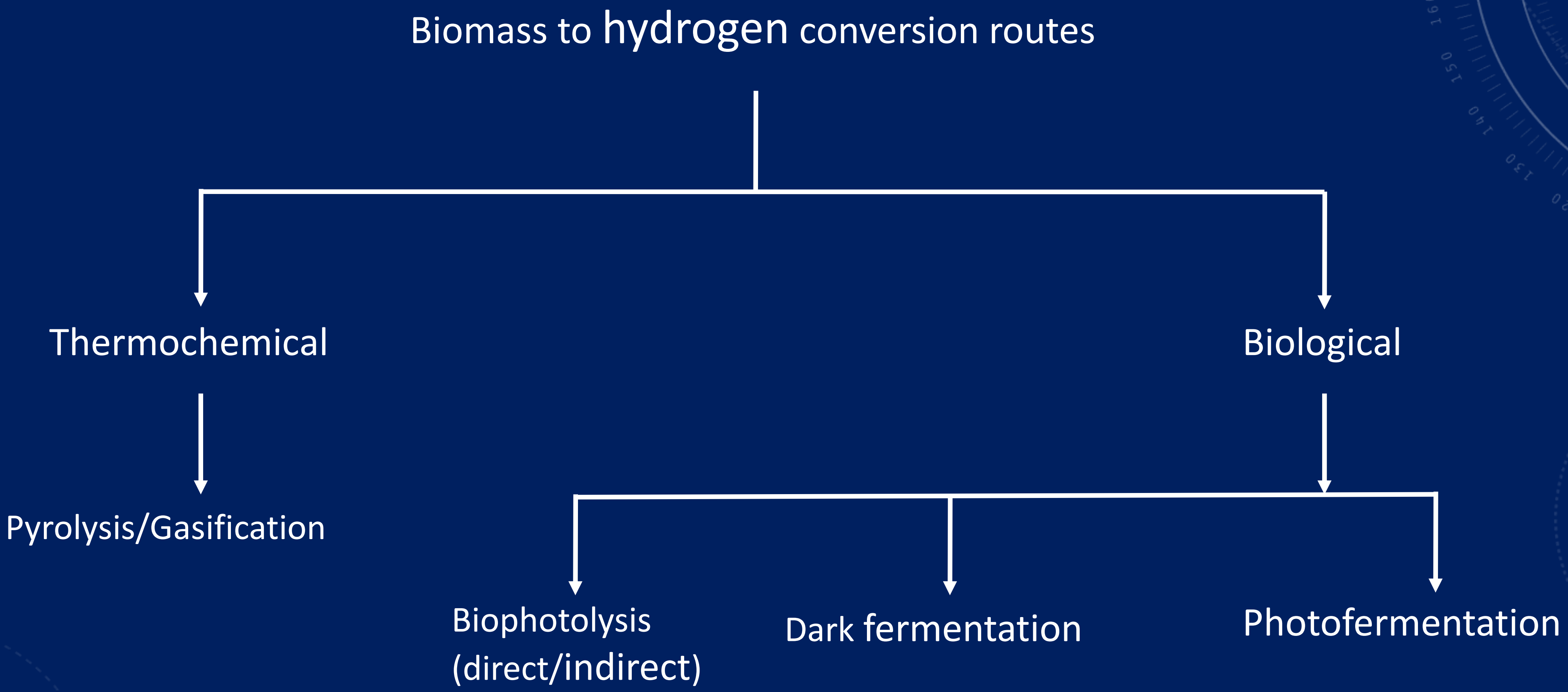
Biohydrogen - Issues

- Production at commercial level is not reported.
- Pretreatment methods and hydrogen production depends on feedstock
  - Which feedstock is viable, which is not?
- Analysis of different feedstocks/processes is necessary before scaling up the process.

Biomass to Hydrogen Conversion



Processes compared

- #1 Dark Fermentation
- #2 Photo Fermentation
- #3 Two- stage fermentation process
- #4 Biocatalysed Electrolysis

Input feedstock – Sugarcane juice

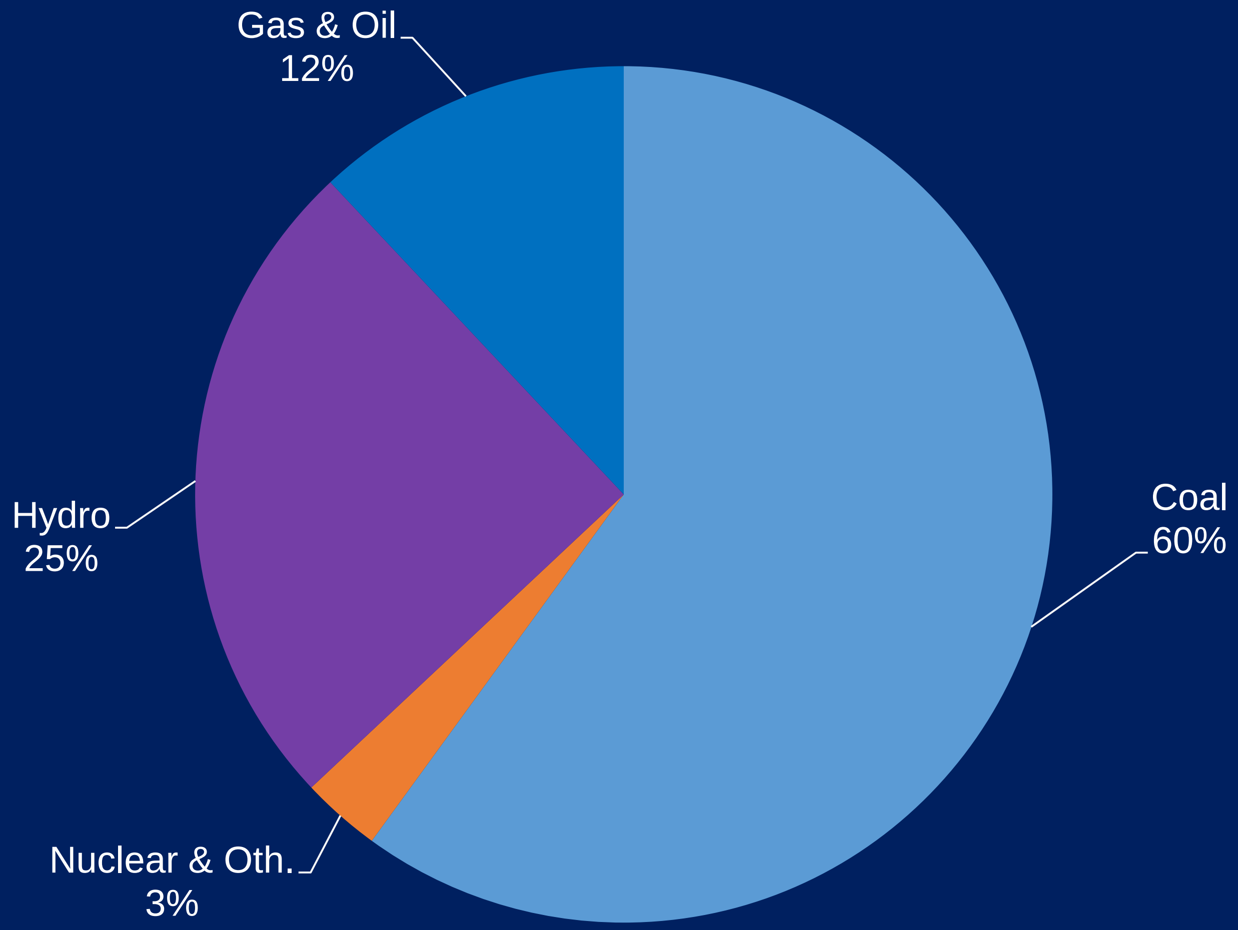
Net energy analysis

- Functional unit – 1 kg hydrogen at 25^{o}C temperature and 1 atm pressure.
- Base case – steam methane reforming
- Criteria
  - Net energy ratio (output/non-renewable energy input) NER> 1
  - Greenhouse gases (GHG) emissions (kg CO_2 eq / kg H_2)
  - Energy Efficiency
- LCA software SimaPro 6

Impact Assessment

- SimaPro 6 Life Cycle Analysis (LCA) software
- Assumptions
  - Heat derived from diesel with 90% combustion efficiency
  - Indian electricity mix (60% coal, 12% gas and oil, 25% hydropower, 3% nuclear)
  - 100% carbon closure for biomass derived CO_2
  - Methane (Natural gas), Ligneous residue (Bagasse)

Electricity Supply Mix



Steam methane reforming

Parameter	Value	Unit (/kg H_2)
Resource consumption		
Natural gas (in ground), input	3.64	kg
Coal (in ground), input	159.2	g
Iron (Fe, ore), input	10.3	g
Iron scrap, input	11.2	g
Limestone ($CaCO_3$, in ground)	16.0	g
Oil (in ground)	16.4	g
Average air emissions		
Benzene	1.4	g
Carbon dioxide	10.62	kg
Carbon monoxide	5.7	g
Methane	59.8	g
Nitrogen oxides (as NO_2)	12.3	g
Nitrous oxide (N_2O)	0.04	g
Non-methane hydrocarbons (NMHCs)	16.8	g
Particulates	2.0	g
Sulfur oxides (as SO_2)	9.5	g

#2 Photo fermentation

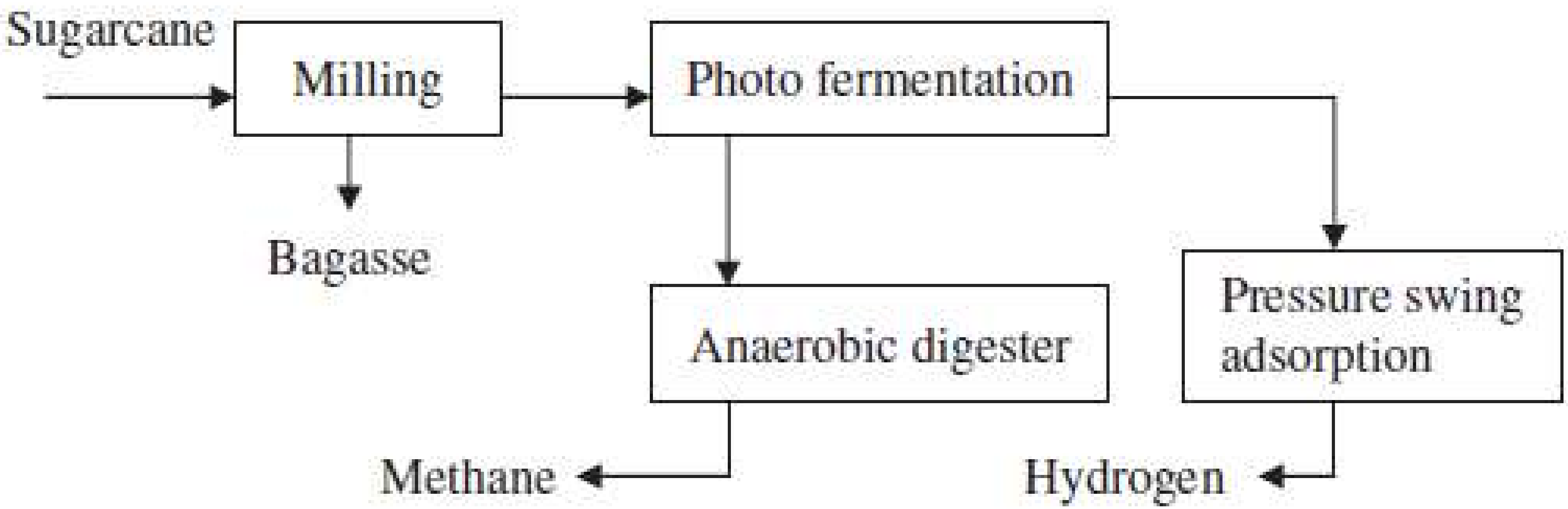
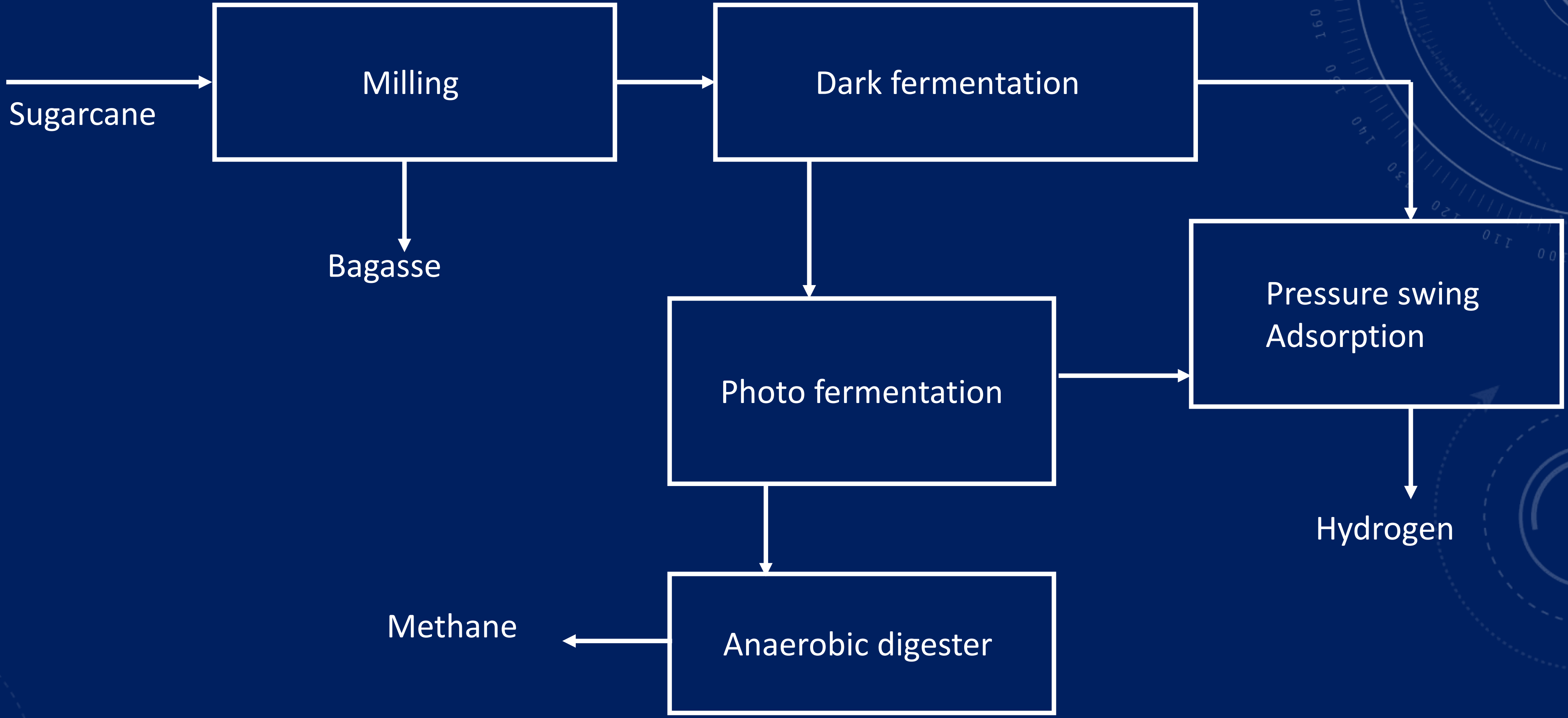
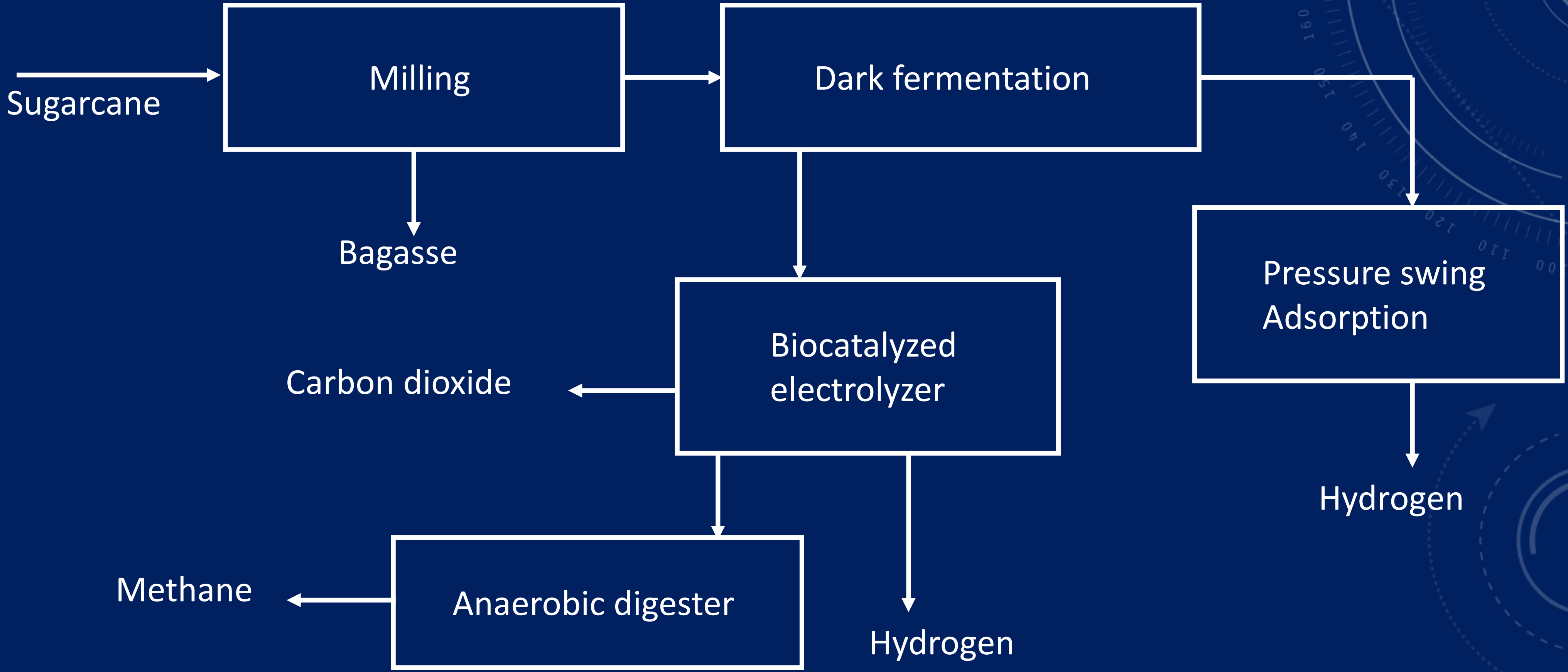


Fig. 3. Photo-fermentation process.

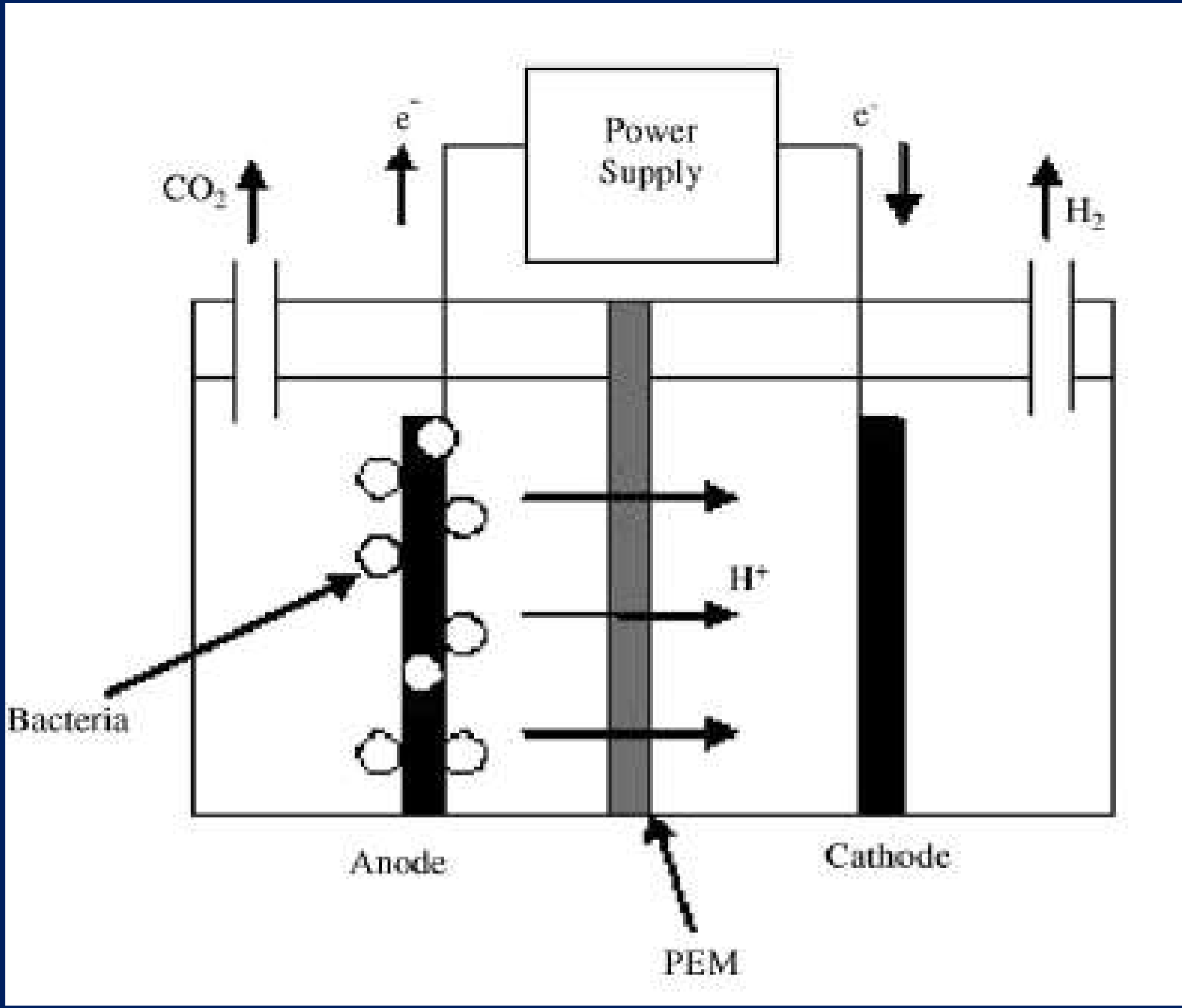
#3 Two- stage fermentation process



#4 Biocatalysed Electrolysis



#4 Biocatalysed Electrolysis



Input data used in the analysis

Input variable	Value	Unit	Ref.
Electricity use in sugarcane crushing	37.8	kJ/kg of sugarcane	[20]
Sucrose output	10.45	% of sugarcane	[21]
Dry bagasse output	17.34	% of sugarcane	[21]
Optimum sugar concentration in fermentation	2	%	-
Optimum C/N ratio	47	–	[22]
H_2 production in dark-fermentation	3.4	mol/mol C_6	[23]
CO_2 production in dark-fermentation	1.7	mol/mol C_6	-
H_2 production in photo-fermentation	9.6	mol/mol C_6	[11]
CO_2 production in photo-fermentation	4.8	mol/mol C_6	-
Methane/CO_2 molar ratio in biogas	60/40	–	-
Hydrogen recovery in PSA	90	%	-
Isothermal efficiency of compressor	65	%	-
Electricity requirement in biocatalyzed electrolysis	0.6	kWh/m^3 H_2	[16]
Platinum loading in biocatalyzed electrolysis	0.5	mg/cm^2	[16]

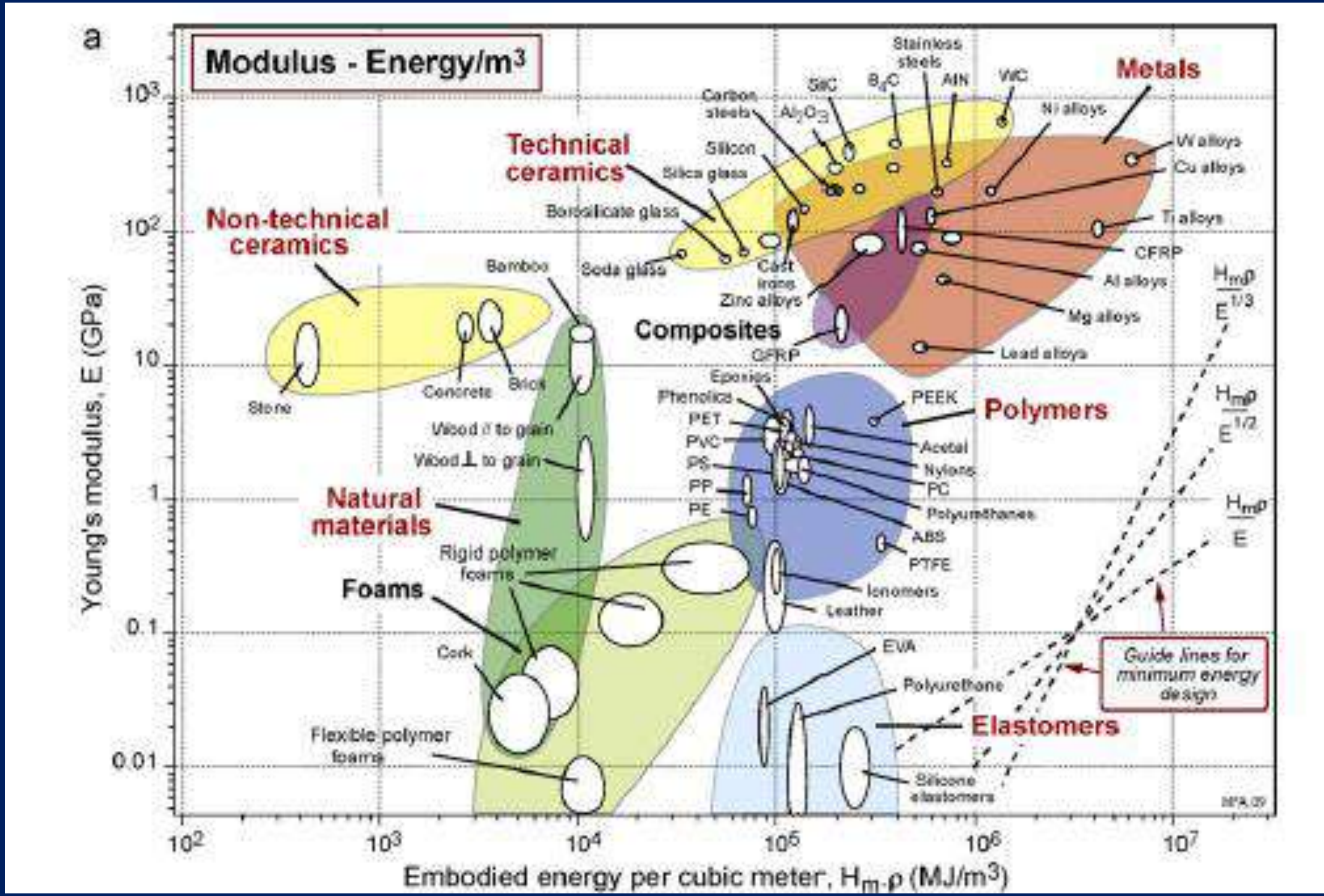
Results of mass and energy balance

Particular	Unit (/kg H2)	Dark-fermentation	Photo-fermentation	Two-stage process	Electrochemically assisted process
Input					
Sugarcane input	kg	281.45	99.68	93.09	90.56
Electricity input	kWh	5.8	3.89	3.82	6.42
Ammonia	kg	0.35	0.13	0.12	0.11
Platinum	mg	-	-	-	0.23
Output					
Bagasse (dry)	kg	46.06	16.31	15.23	14.82
Carbon dioxide	kg	24.59	13.44	13.04	12.39
Methane	kg	6.75	0.67	0.45	0.54

Results (without by product use)

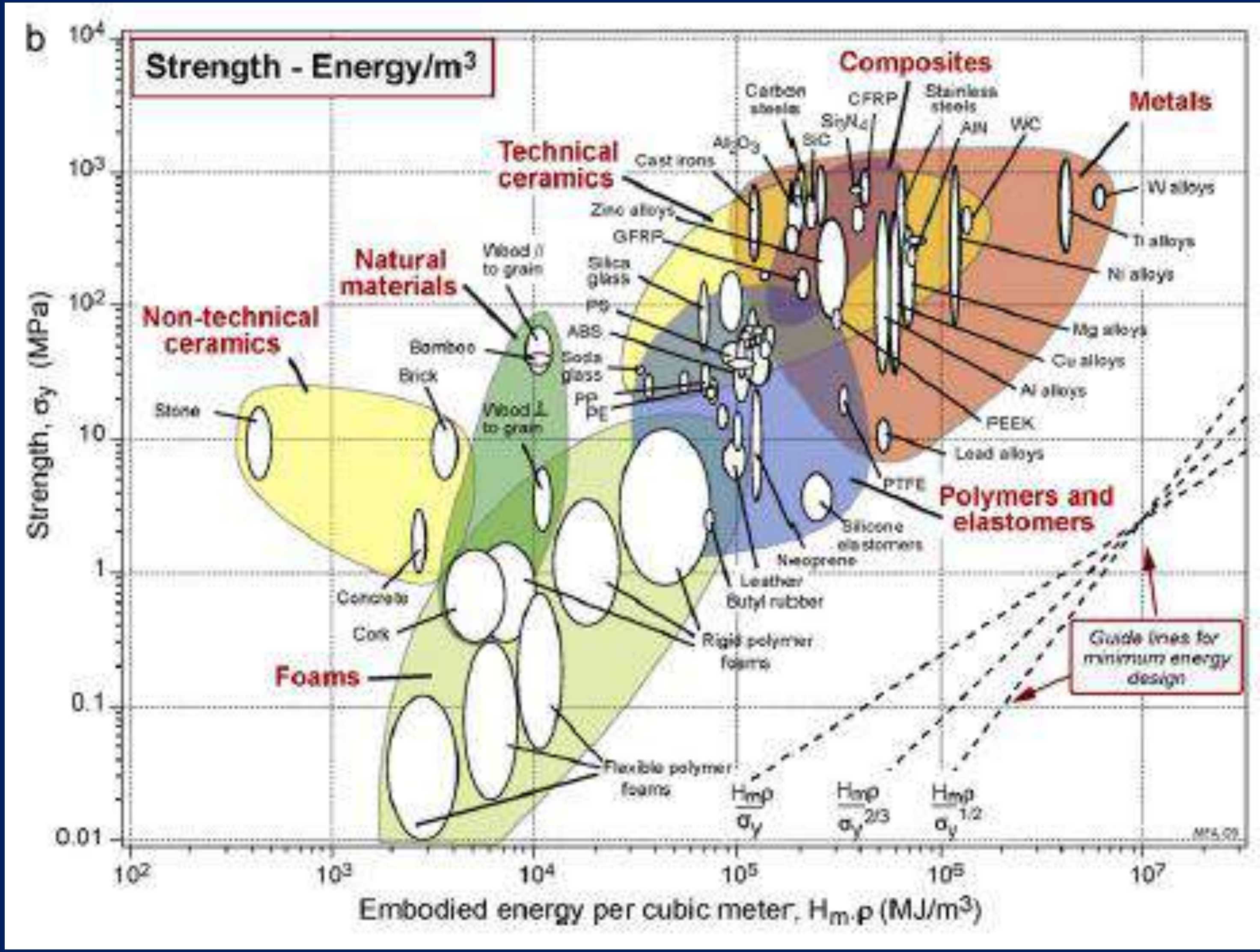
Process	Case 1: Without by-products		
	GHG ($kg\ CO_2$)	Non-renewable energy use (MJ)	Energy efficiency (%)
Steam methane reforming	12.8	188	64
Dark-fermentation	5.5	61.7	9.6
Photo-fermentation	3.5	40.1	25.6
Two-stage process	3.4	39.3	27.2
Biocatalyzed electrolysis	5.3	64.8	25.7

Material Choice



Allwood et al, 2011

Material Choice



Allwood et al, 2011

Sustainability Analysis

Why Sustainability Analysis?

- Sustainability – Life cycle analysis, Thermodynamic analysis, Techno-economic analysis.
- Screening of technologies – Setting technology development targets
- Comparative analysis – Prospects of technology, conditions for viability
- Decide on investments

Criteria for assessment

1. Life cycle assessment

a) Cumulative energy demand (CED)

b) Carbon emission footprint (CEF)

2. Thermodynamic analysis

a) Energy efficiency

b) Exergy efficiency

c) Primary energy consumption per kg product

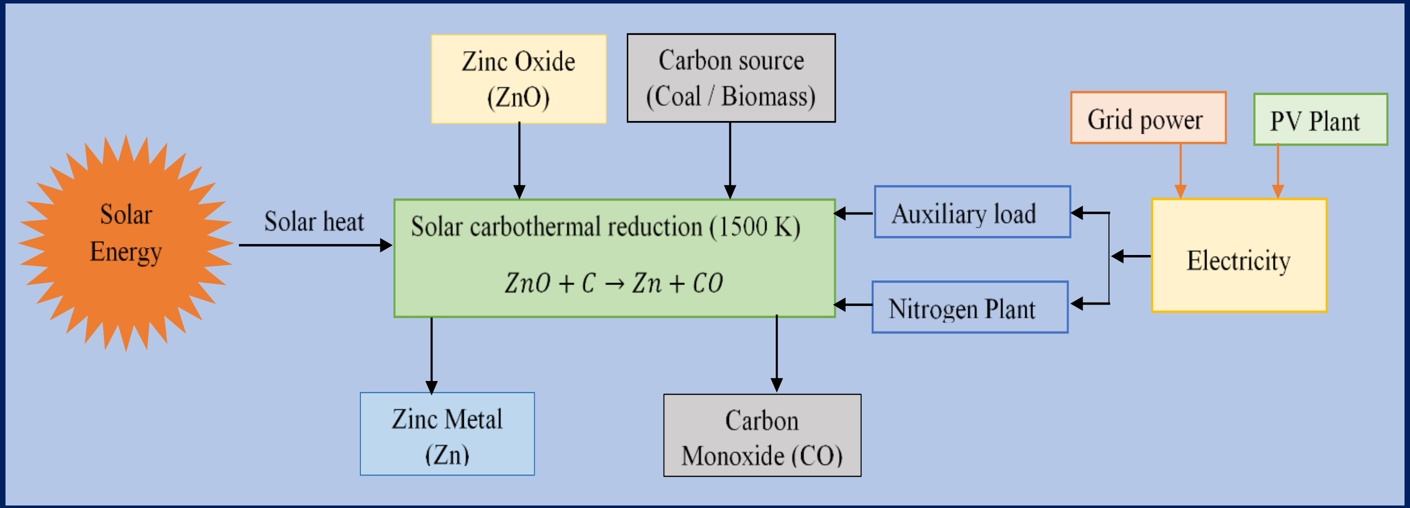
3. Economic analysis

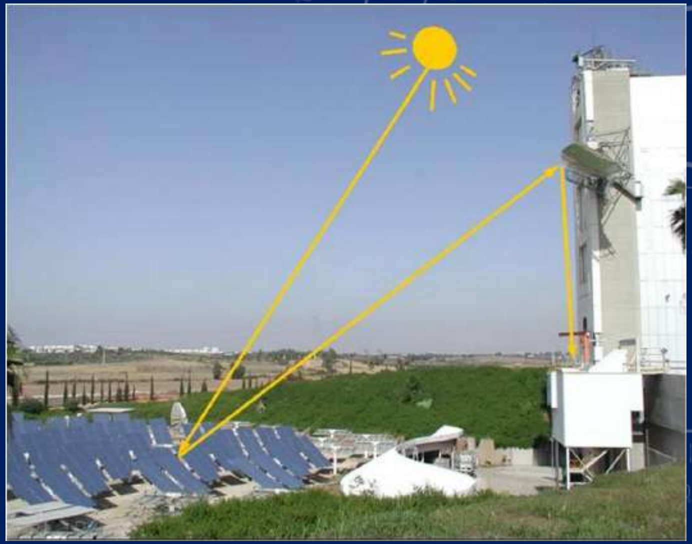
a) Current costs

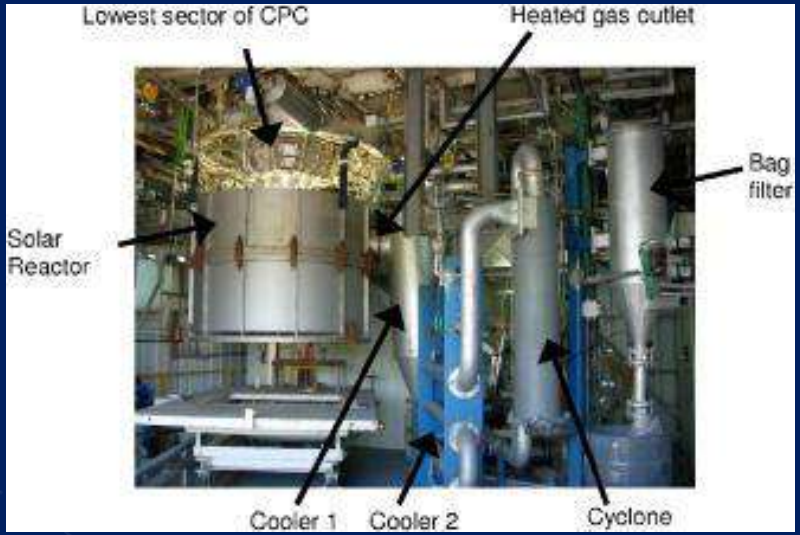
b) Future costs

c) Bottom-up costs

Concept for solar carbothermal reduction process

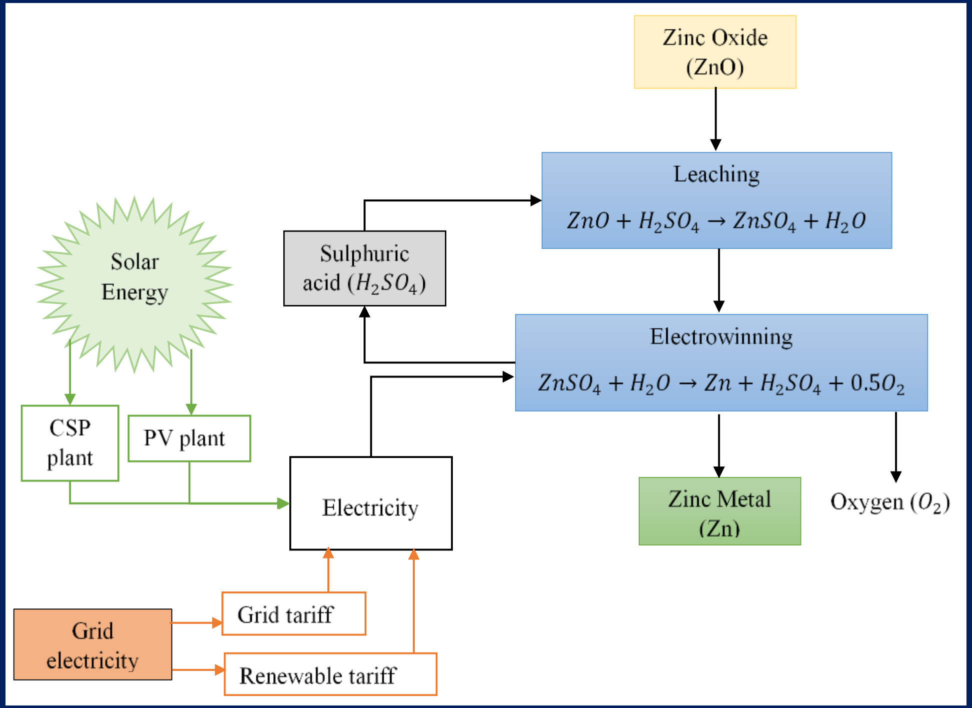


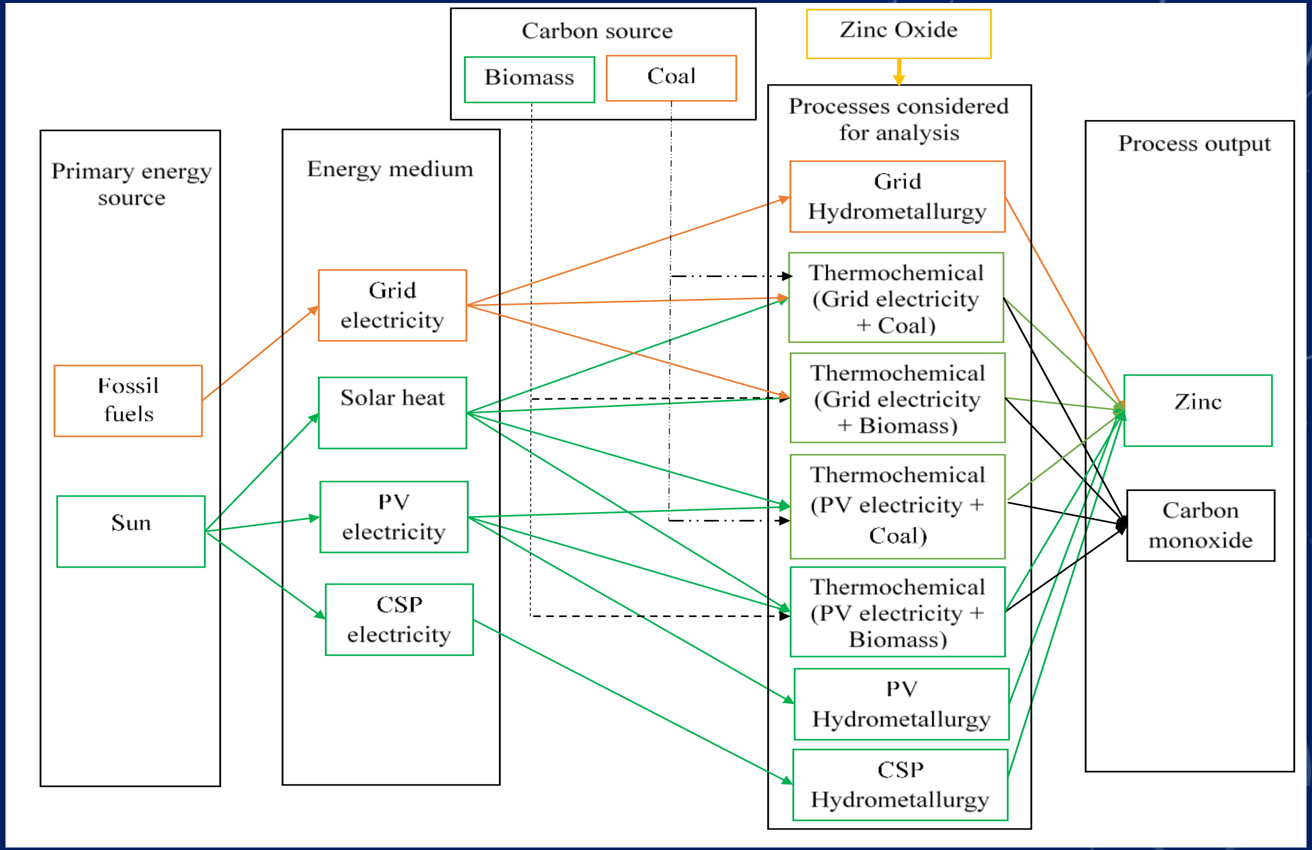




Wieckert C, Frommherz U, Kräupl S, Guillot E, Olalde G, Epstein M, et al. A 300 kW Solar Chemical Pilot Plant for the Carbothermic Production of Zinc. J Sol Energy Eng 2007;129:190. doi:10.1115/1.2711471.

Framework for assessment of solar thermochemical zinc production





Research question:

Keep current process (hydrometallurgy) intact by greening the electricity mix

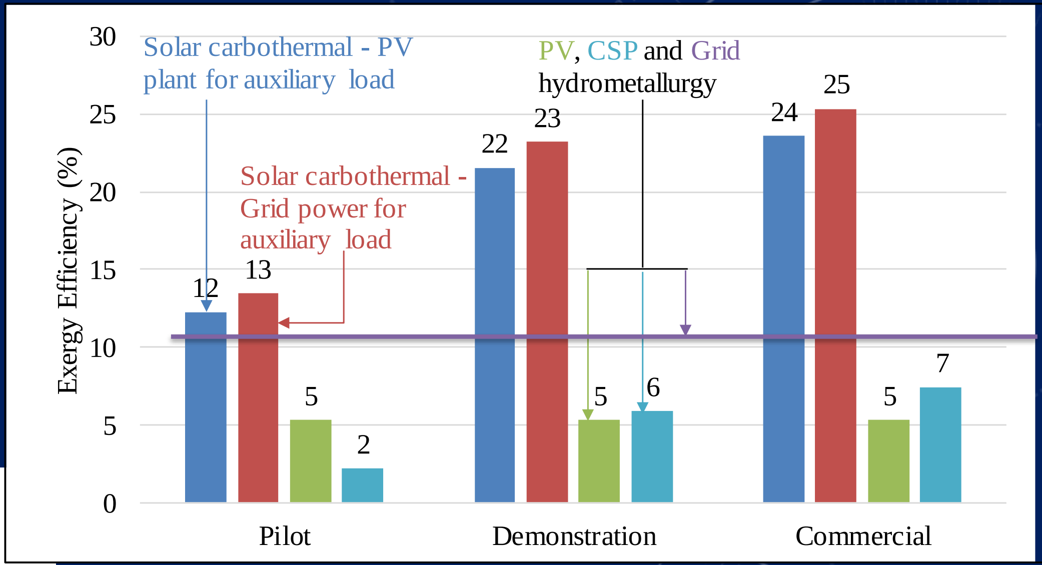
OR

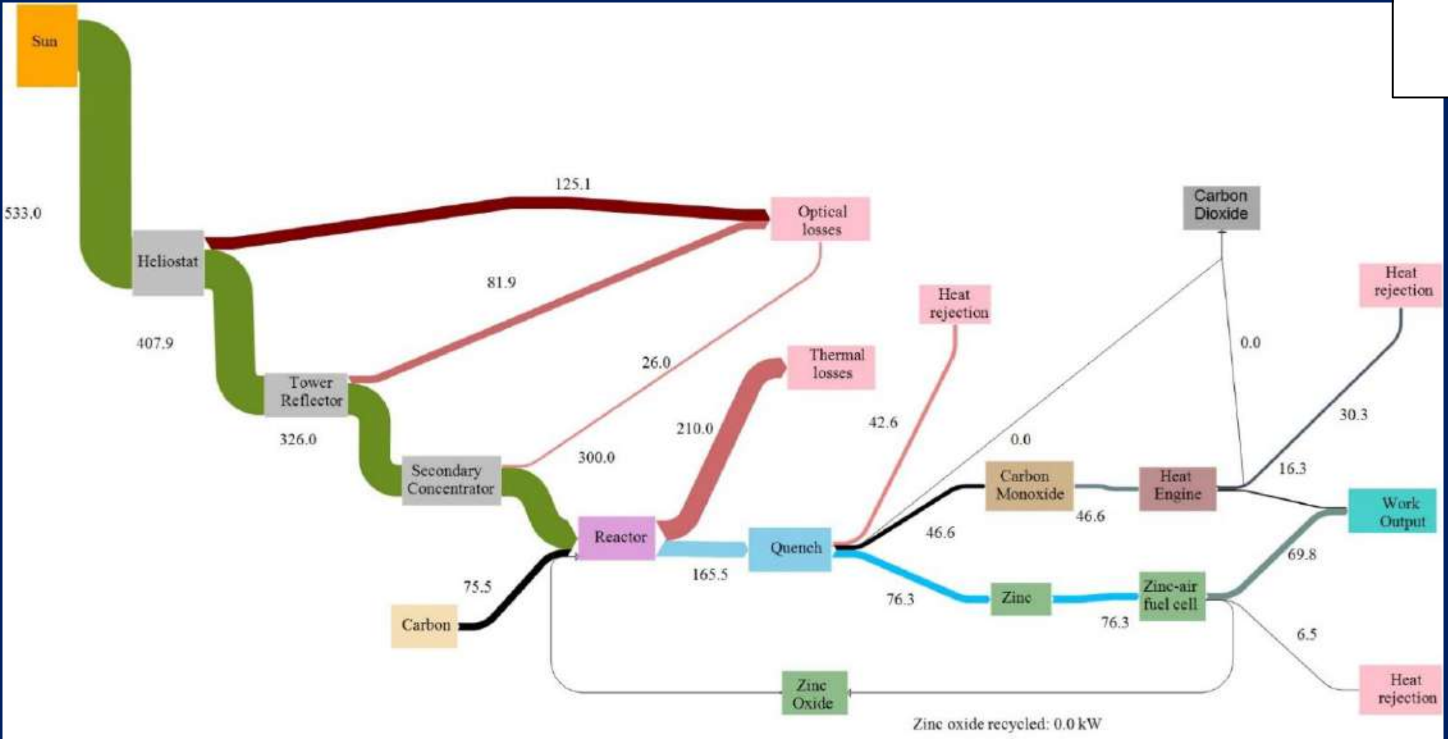
Develop novel alternative like solar carbothermal process

?

Yadav D, Banerjee R. A comparative life cycle energy and carbon emission analysis of the solar carbothermal and hydrometallurgy routes for zinc production. Appl Energy 2018;229:577–602. doi:10.1016/j.apenergy.2018.08.001.

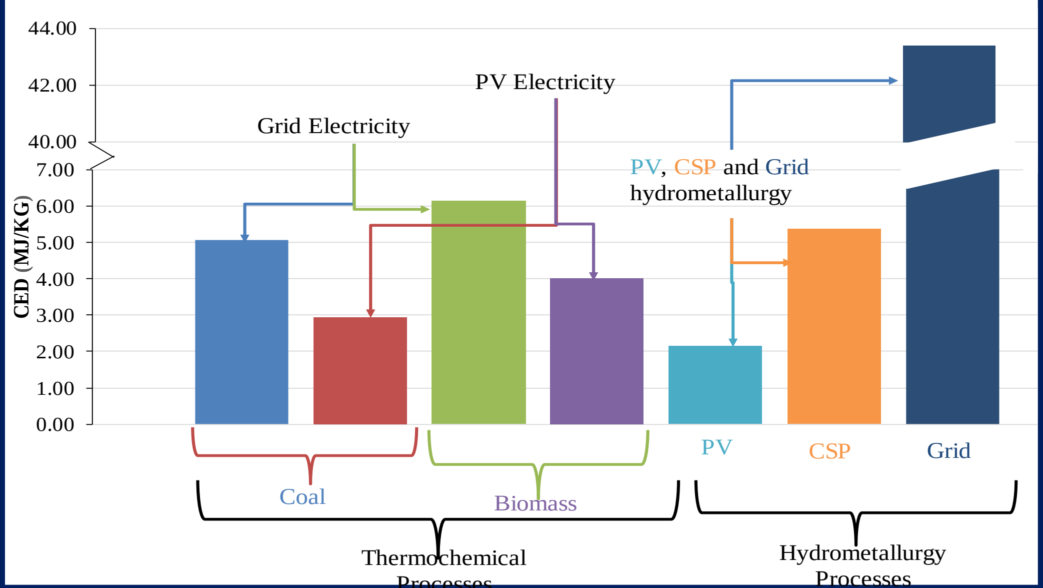
Thermodynamic efficiencies

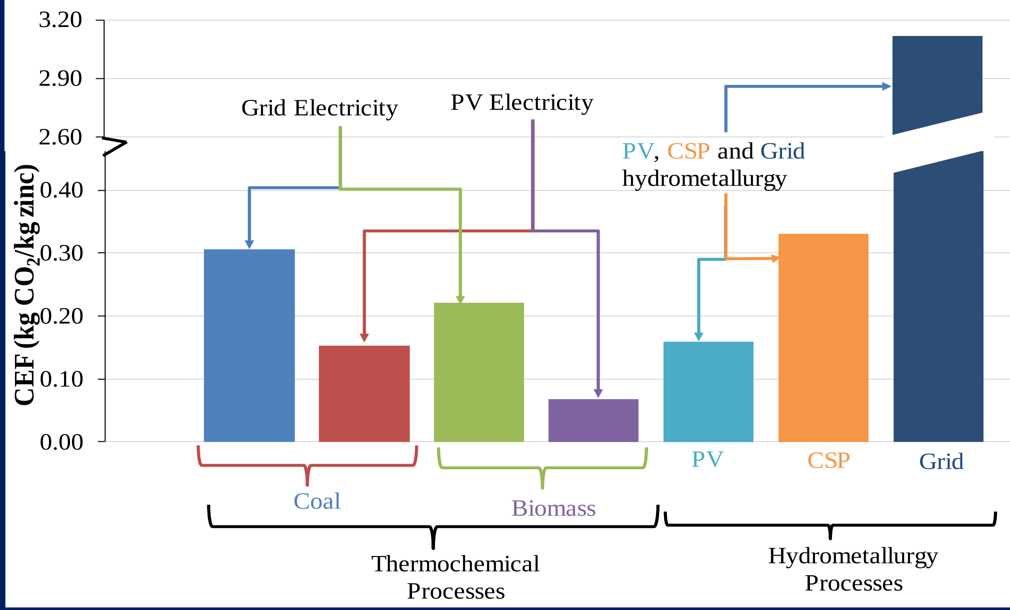


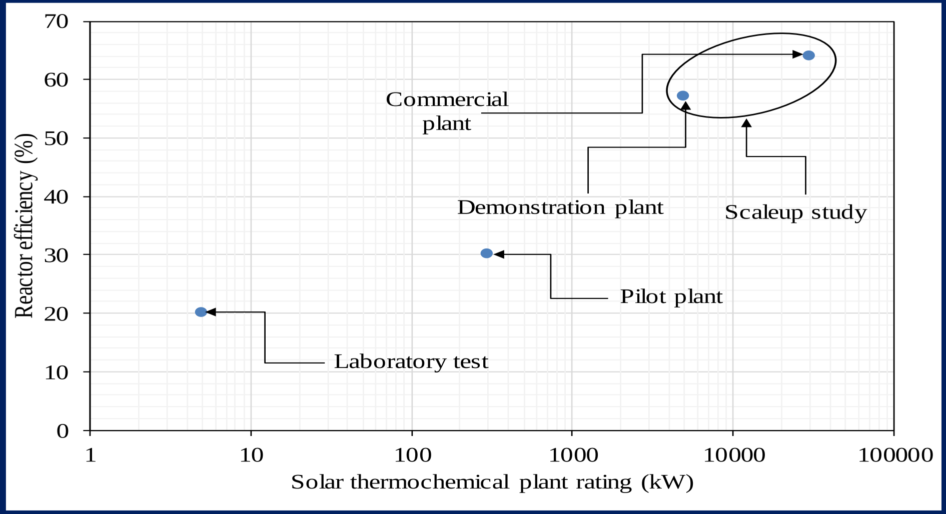


Yadav D, "Assessment of Solar Zinc and Hydrogen Production Processes", Ph.D. Thesis, Department of Energy Science and Engineering, IIT Bombay.

Life Cycle Assessment – Pilot Scale







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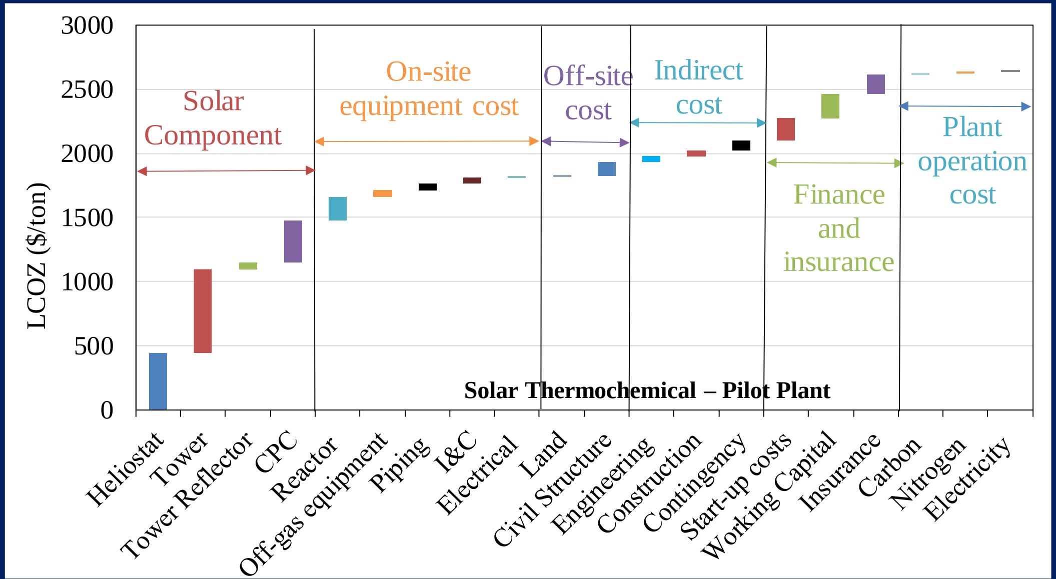
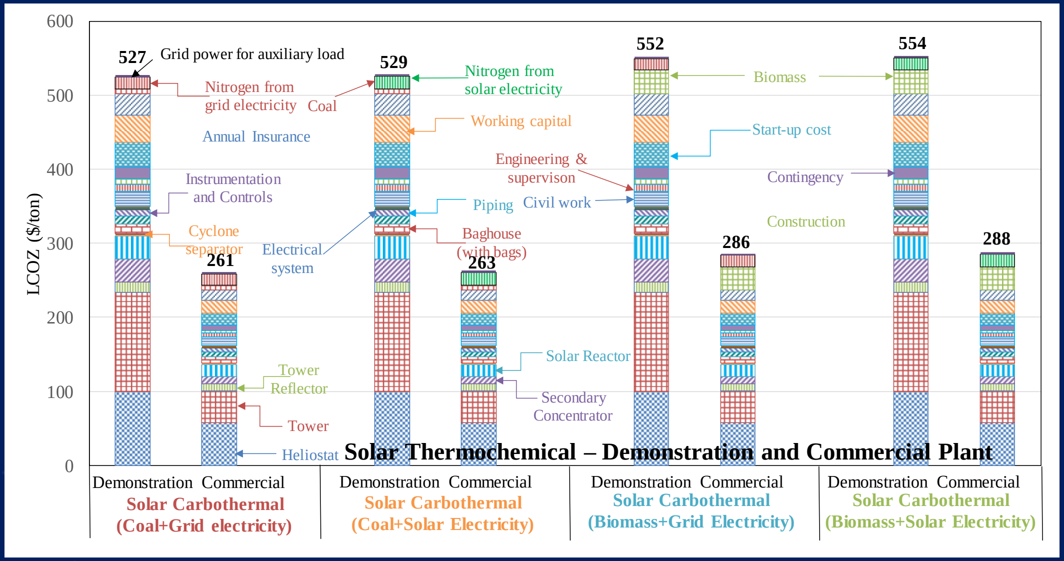
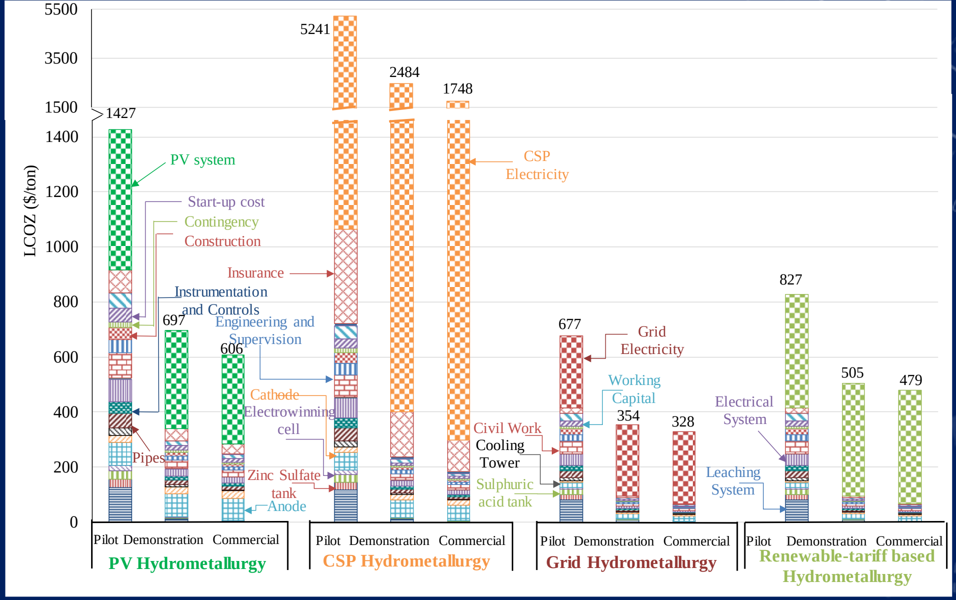
Economic Comparison







Hydrometallurgy systems – Pilot, Demonstration and Commercial scale

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Levelized cost of Zinc ($/ton)

Process / Year	Pilot			Demonstration			Commercial		
	2018	2030	Bottom-up	2018	2030	Bottom-up	2018	2030	Bottom-up
Solar carbothermal (Grid power + Coal)	2658	2145	950	527	420	285	261	217	184
Solar carbothermal (Solar power + Biomass)	2685	2172	977	553	447	312	288	243	210
Renewable tariff hydrometallurgy	827	786	-	505	464	-	479	437	-
Grid Hydrometallurgy	677	677	-	354	354	-	328	328	-

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