Integrated Life Cycle Assessment and Techno-Economic Analysis of Energy system

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IIT Roorkee: at a glance

IIT ROORKEE: AN OVERVIEW

- 1191 Staff
- 9210 Students
- 526 Faculty members
- 365 Acres at Roorkee
- 10 Acres at Gr. Noida
- 25 Acres at Saharanpur
- 23 Departments
- 7 Academic Center
- 1 Mehta Family School of Data Science and Artificial Intelligence

Ranked #1 in Architecture, #6 in Engineering and #7 Overall in National Institute Ranking Framework (NIRF) 2021 India

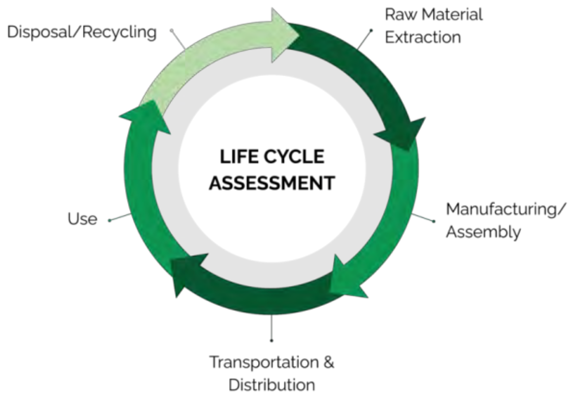
Ranked #5 in the excellent band in Atal Ranking of Institutions on Innovation Achievements (ARIIA) 2021

Ranked #400 in the QS World University Rankings 2022

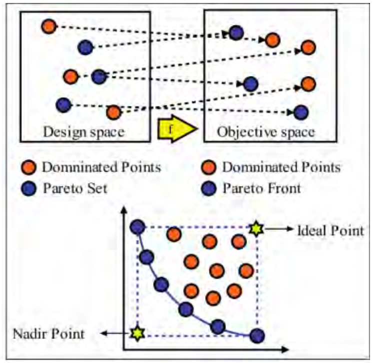
Ranked #1 in India Today Architecture and #5 in Engineering 2021

Energy Systems Modelling @IIT Roorkee

Lifecycle assessment



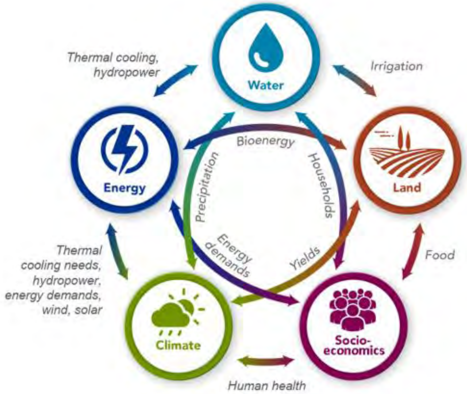
Multi-objective optimization



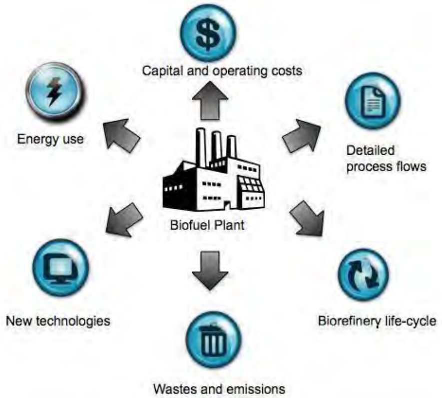
Multi-level modelling for Sustainable Energy Systems

Supply chain modelling

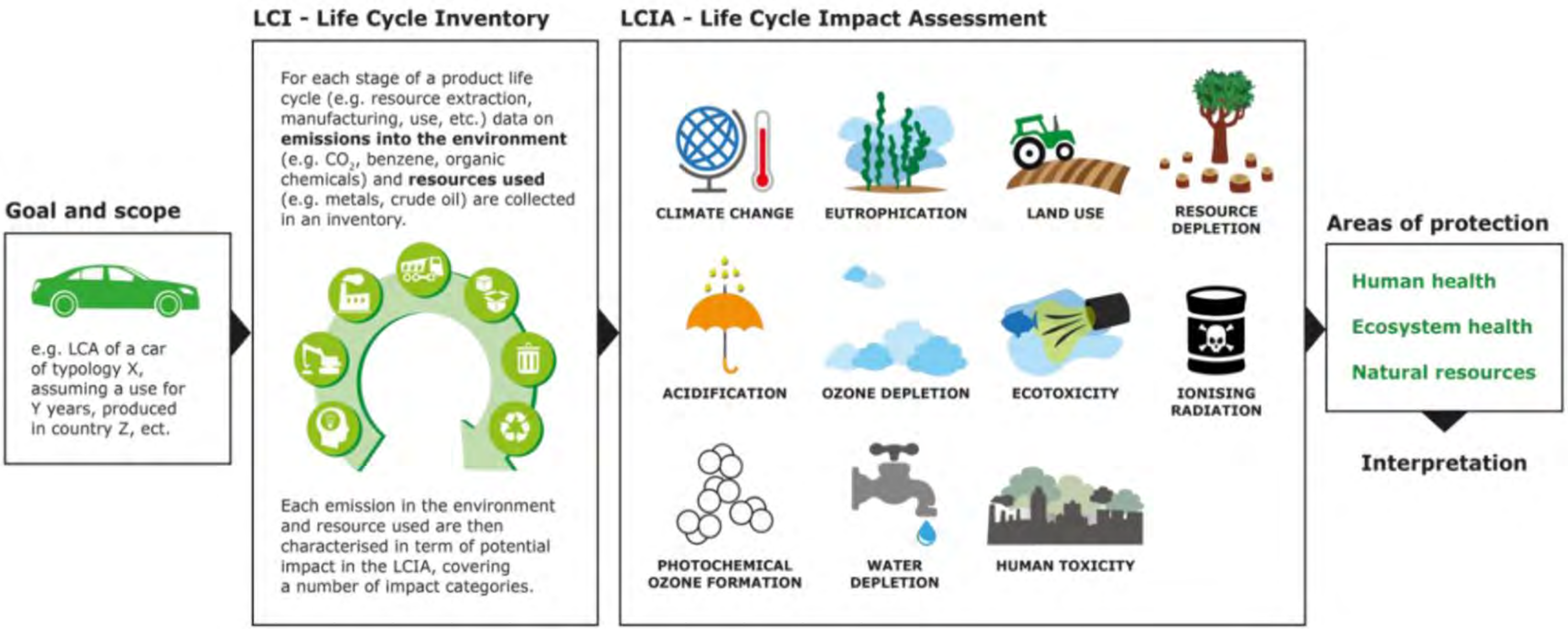
Integrated Assessment Models



Techno-economic modelling



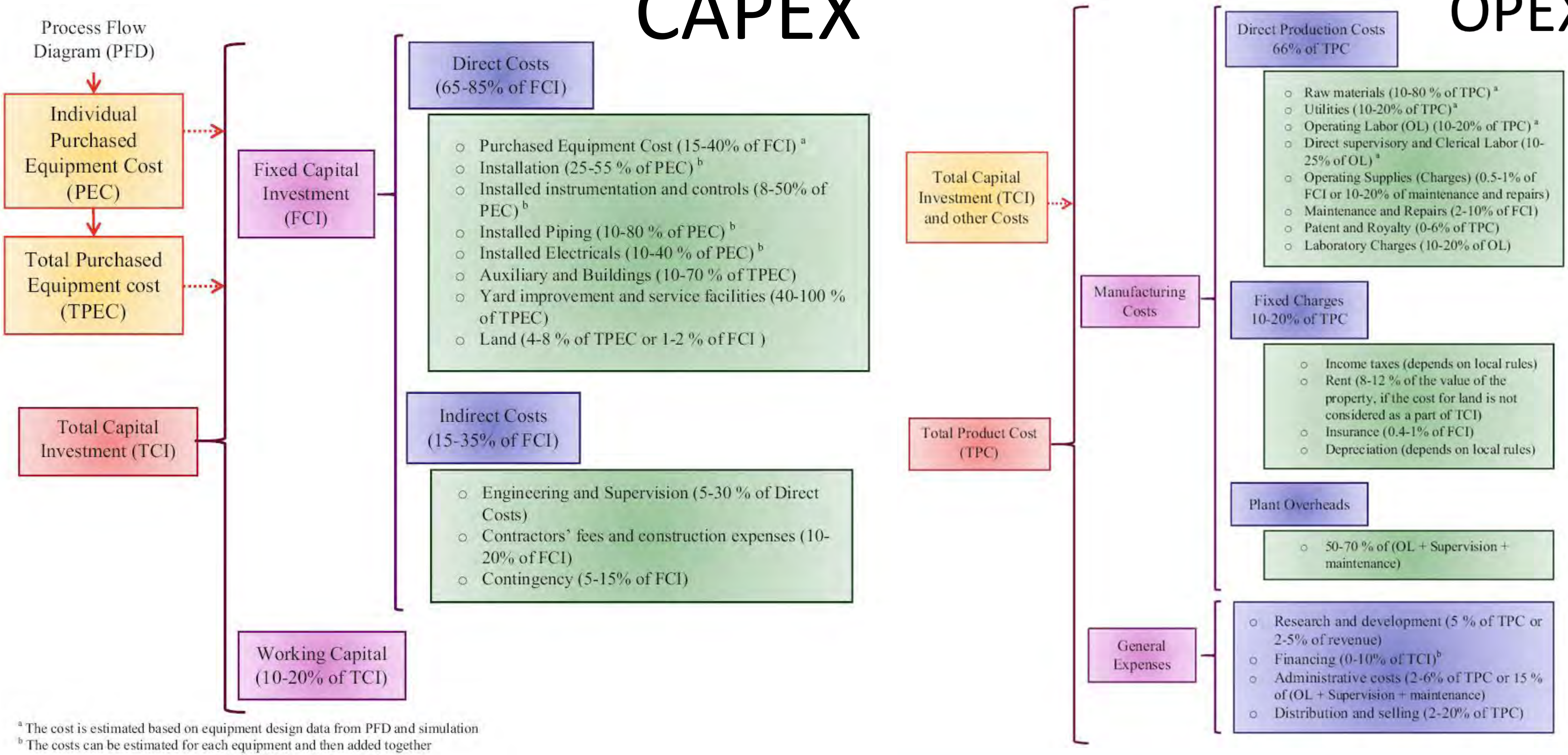
Life Cycle Assessment



Source: https://eplca.jrc.ec.europa.eu/lifecycleassessment.html

CAPEX

OPEX



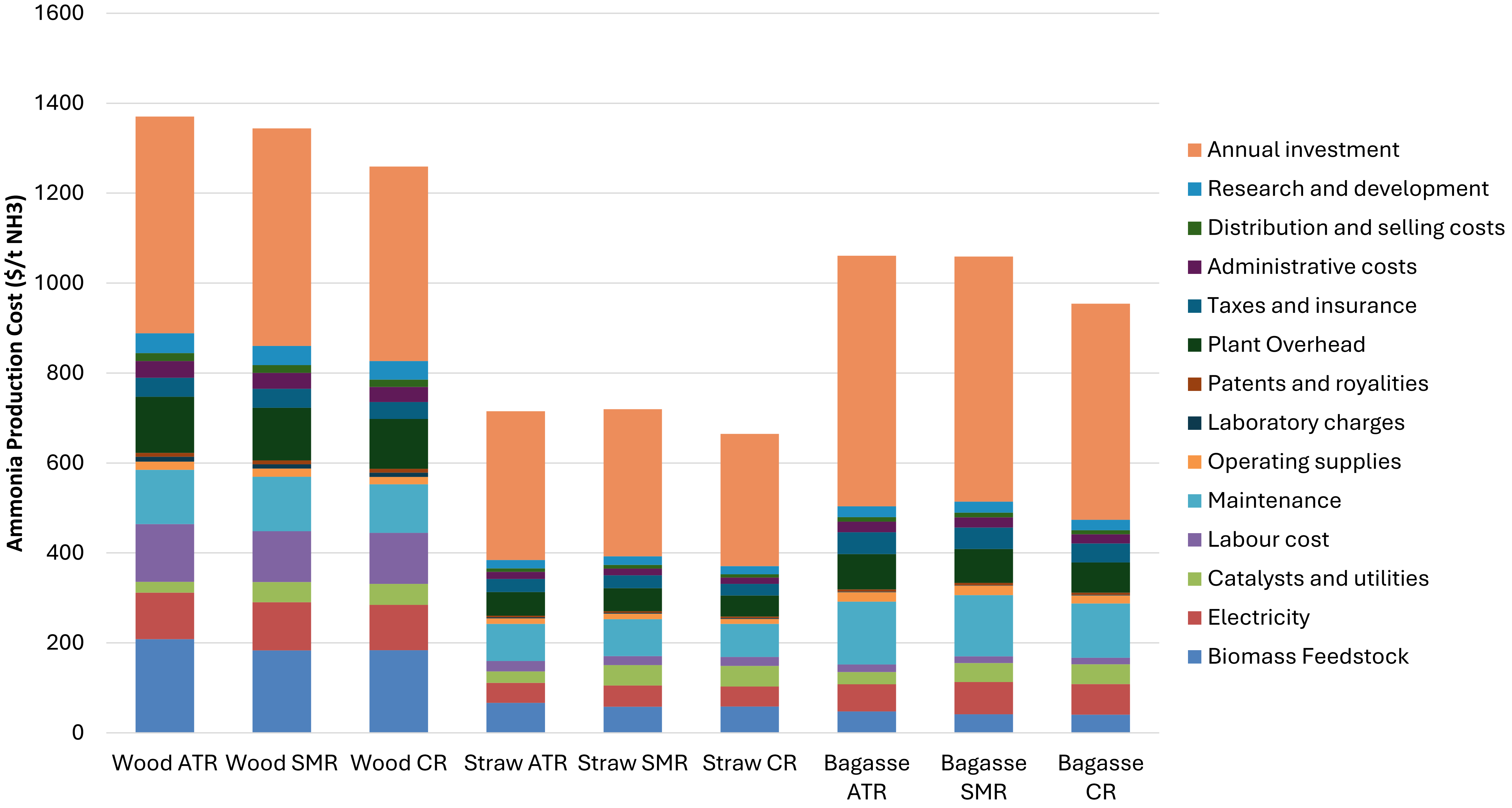
[a] The cost is estimated based on equipment design data from PFD and simulation
[b] The costs can be estimated for each equipment and then added together

Case Study I: Biomass-to-Hydrogen/Ammonia

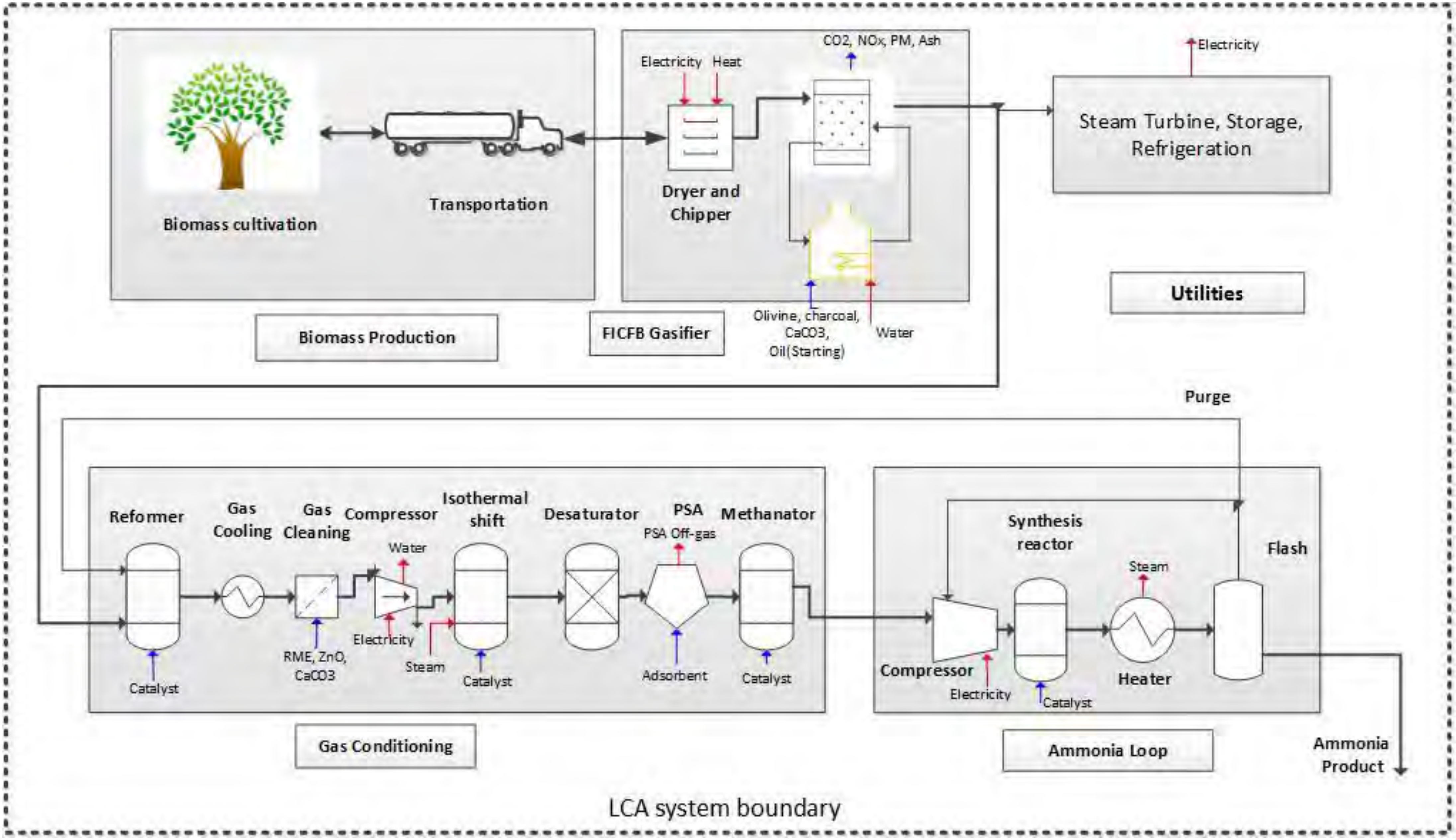
- Few facts regarding ammonia
  - **Annual production** : 240 Million tonne (3rd most produced chemical in the world.)
  - **Global primary energy consumption**: 2 %
  - **Global natural gas consumption**: 5 %
  - **70 %** of the ammonia produced is used in the **fertiliser industry**.
  - **Global Greenhouse Gas Emissions(GHG's)**: 2 % (Every Kilogram of Ammonia produced releases 1.8 Kilogram of Carbon-dioxide in the atmosphere)
  - Biomass with its wide availability and carbon neutrality is a strong candidate to replace fossil fuels.


Straw
Courtesy of www.sechilienne-sidec.com
Bagasse
Eucalyptus

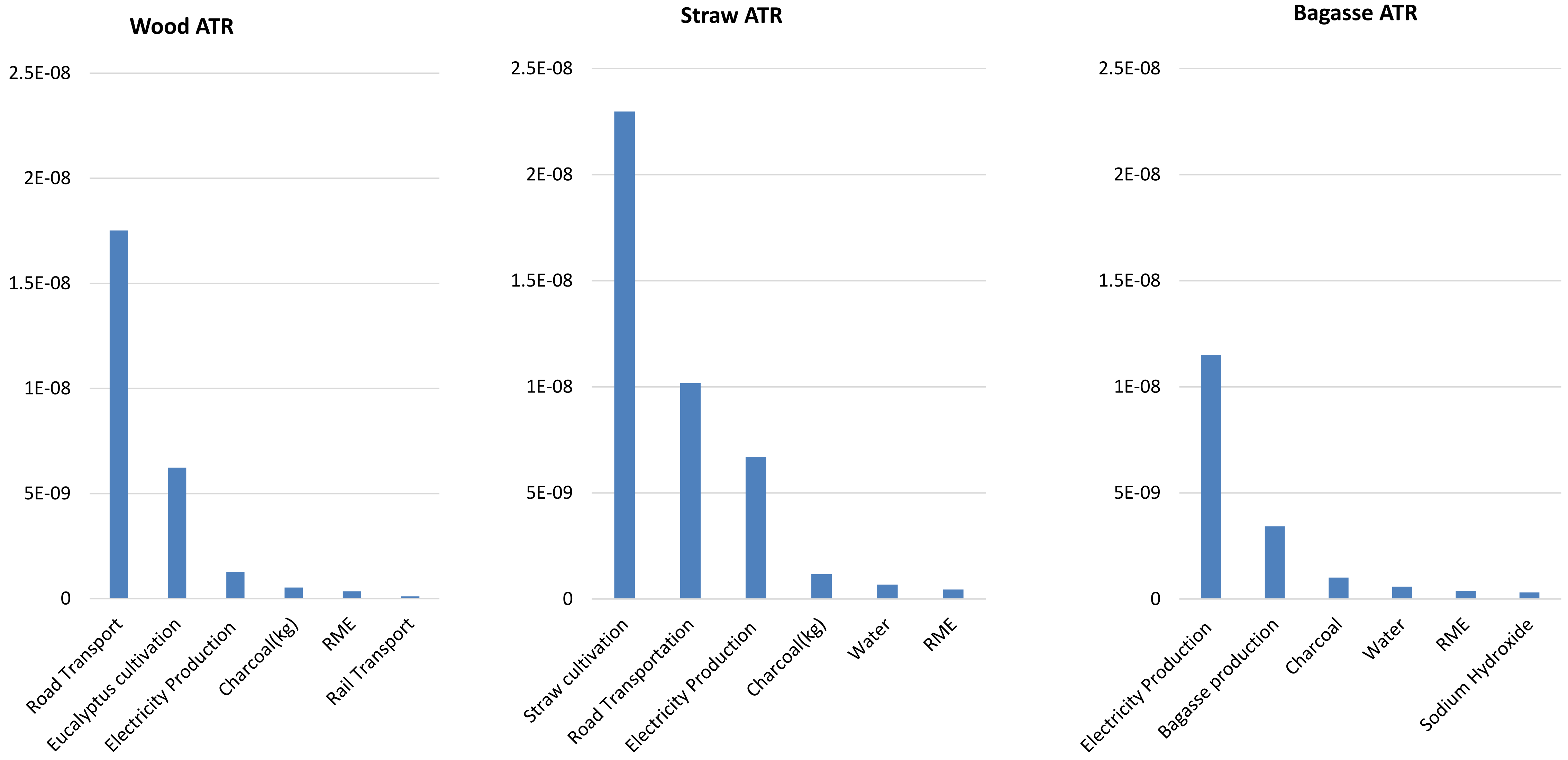
Process economics



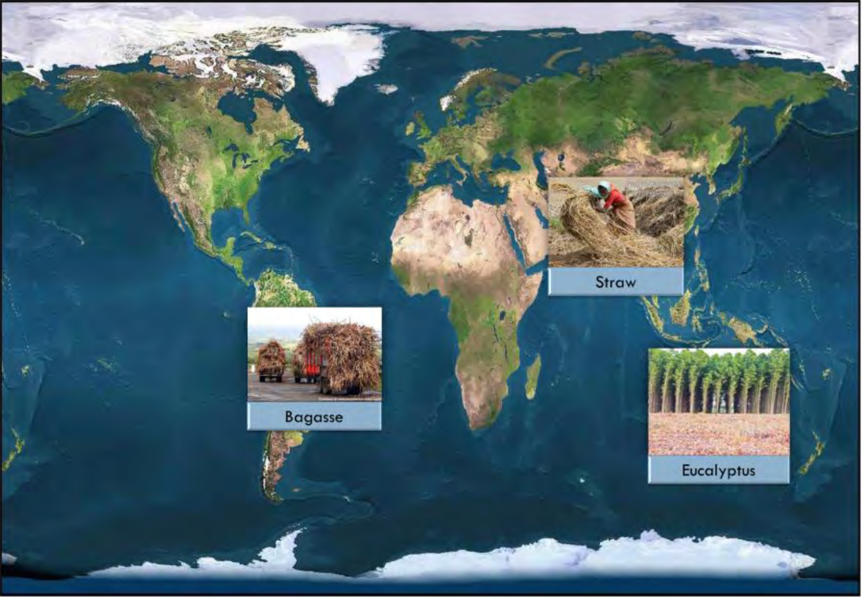
Life cycle assessment

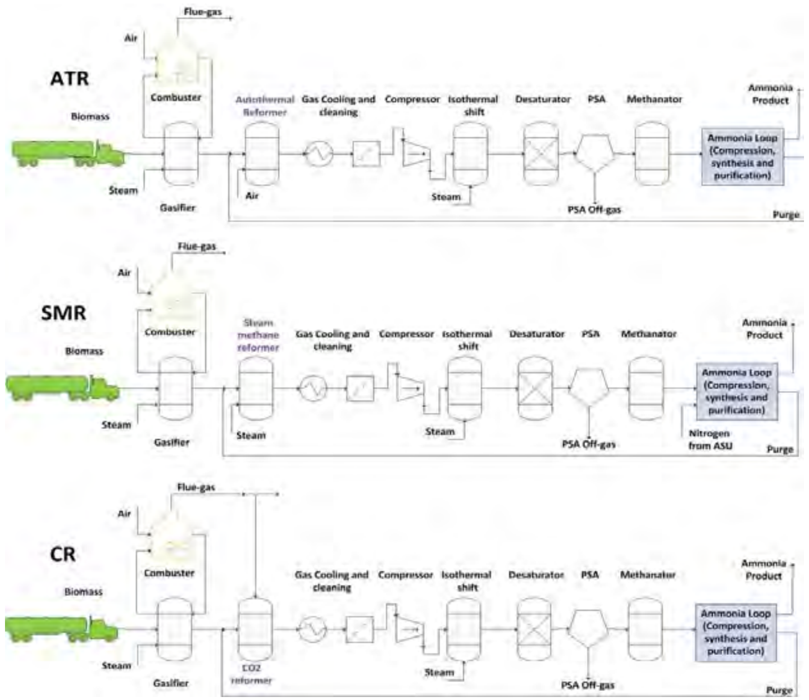


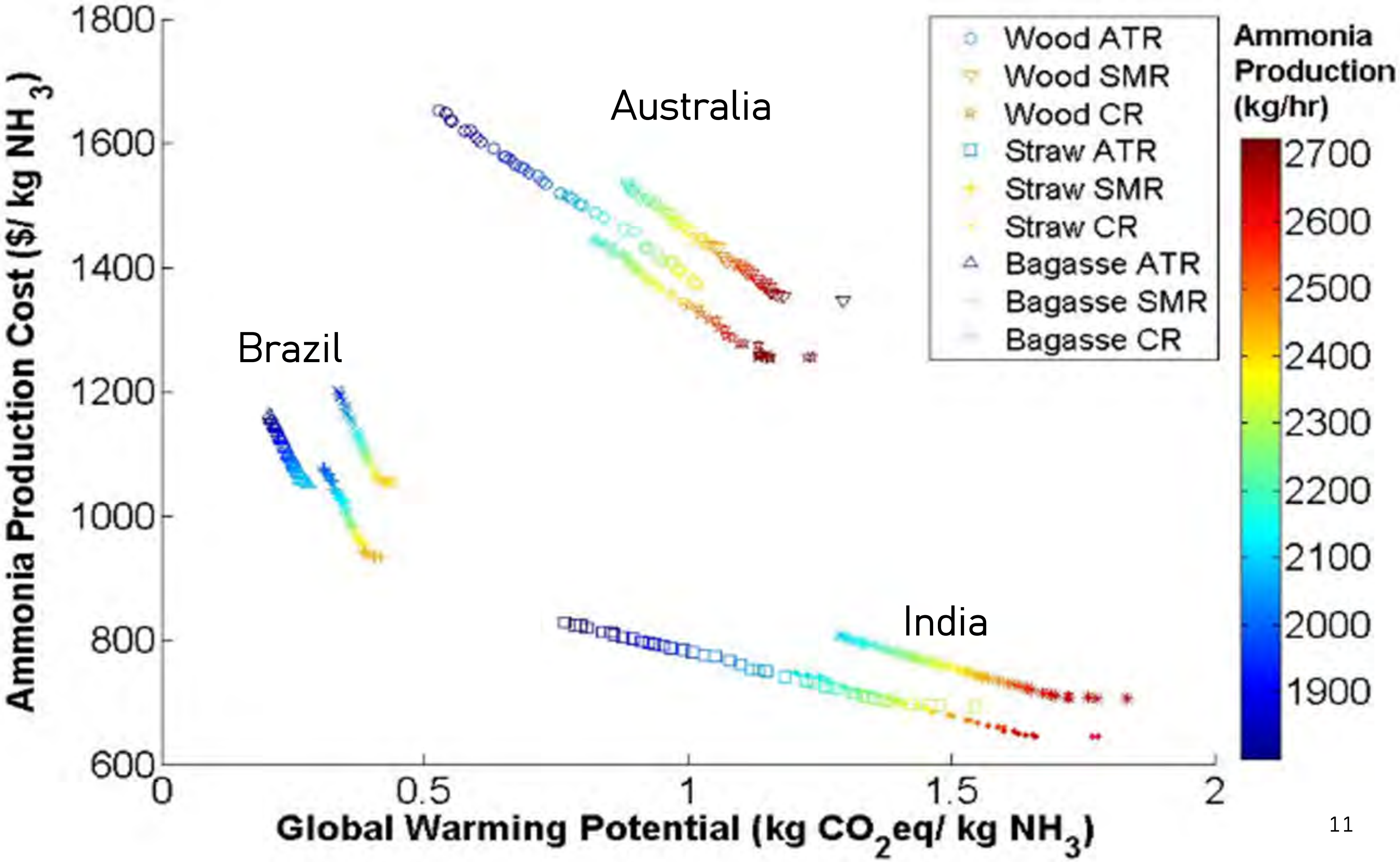
Ozone depletion potential



BIOMASS BASED AMMONIA







I&EC research
Industrial & Engineering Chemistry Research
Article
pubs.acs.org/IECR

Small-Scale Ammonia Production from Biomass: A Techno-Enviro-Economic Perspective

Pratham Arora,[†,‡,§] Andrew F.A. Hoadley,[*,‡] Sanjay M. Mahajani,[∥] and Anuradda Ganesh[§]

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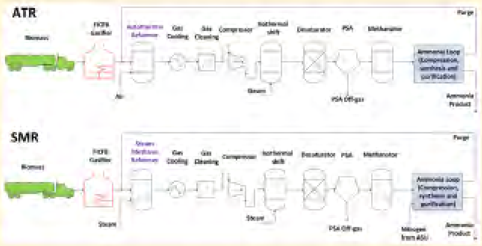
Supporting Information



ABSTRACT: Ammonia production has traditionally been based on large-scale plants. The thrust toward large-scale production to gain economic advantages has overshadowed the benefits that could be derived from small-scale production plants. Additionally, the ammonia industry consumes a major chunk of global fossil fuels, which also burdens the planet with greenhouse gases. To effectively counter these issues, this study investigates the production of ammonia from biomass. Processes based on biomass plants are usually small-scale and are limited by biomass supply. To ensure sustainable ammonia production, this study tries to highlight the techno-economic advantages that result from small-scale ammonia plants based on biomass feedstock. This paper proposes a new process that takes inputs from a relatively old, natural gas based process (leading concept ammonia) specifically designed for small-scale ammonia manufacture and couples it with a recently developed dual fluidized bed technology for biomass feedstock. Two different flowsheet configurations are simulated rigorously and compared to gain a better understanding of the process. The flowsheets are optimized, and energy integration is performed to provide a wider insight. The life cycle assessment calculations that are carried out using ASPEN Plus simulation results and ecoinvent databases predict a CO_2 emissions reduction of 54−68% when compared to conventi

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Cleaner Production

Multi-objective optimization of biomass based ammonia production - Potential and perspective in different countries

CrossMark

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Multi-objective optimization
Biomass gasification
Ammonia
Economic analysis
Life cycle assessment
Different feedstocks

ABSTRACT

More environmentally-benign processes are required for the production of important chemicals such as ammonia. Techno-enviro-economic studies that utilize process modeling and optimization play a decisive role in predicting the viability of these processes, but they tend to focus on a single geographical location. This limits the usefulness of the results from such studies, because it is hard to compare results for different feedstock and location factors. Thus, the present study compares the economics and environmental potential of several variations of a novel biomass-based ammonia production process in different locations. The process is simulated for three biomass feedstocks grown in Australia, Brazil, and India. A comprehensive economic analysis and life cycle assessment is performed for the different process variants. A Multi-Objective Optimization (MOO) approach is used to minimize the manufacturing costs and the environmental impacts of the biomass-to-ammonia process specific to each feedstock and country. The Indian scenario was found to be the most favorable economically, whereas the Brazilian scenario had the lowest greenhouse gas potential. The results demonstrate that each type of biomass is specific to its location and both the economic and environmental profiles are strongly related to the location. The results of the individual studies are superimposed to provide a Global Pareto Front for the cost and environmental impact of the production of ammonia from biomass. This provides a very useful resource for future researchers who can compare results for alternative biomass, locations and processes.

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Remote, small-scale, 'greener' routes of ammonia production

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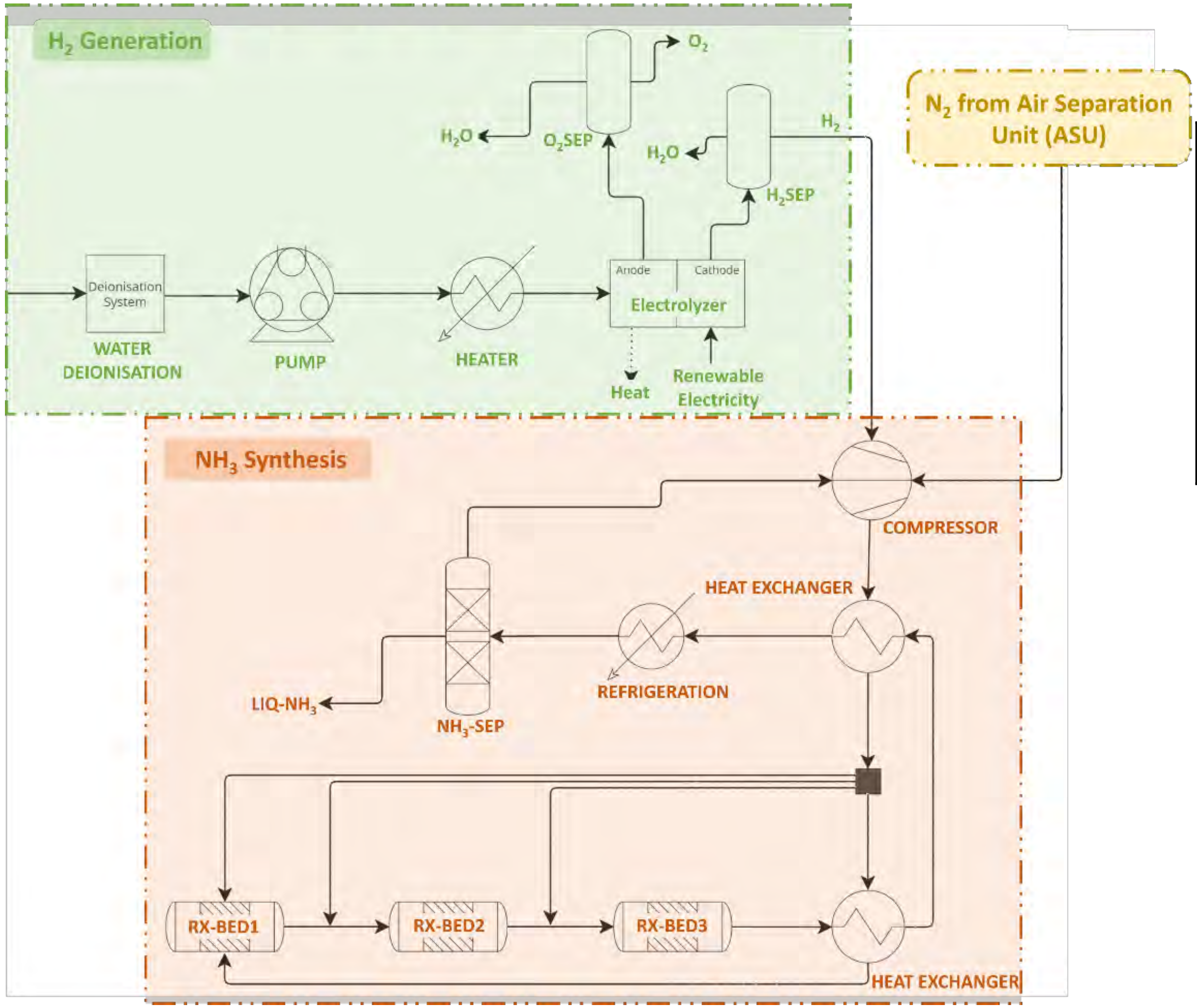
ARTICLE INFO

ABSTRACT

Case Study II: Economic and Emission Analysis of Decentralized Green Ammonia Production Plant

Flow Process Diagram

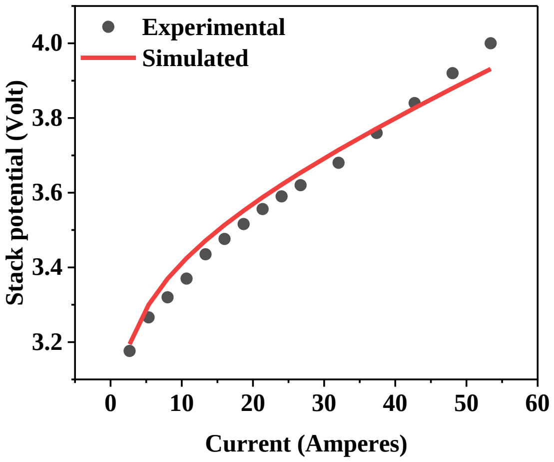


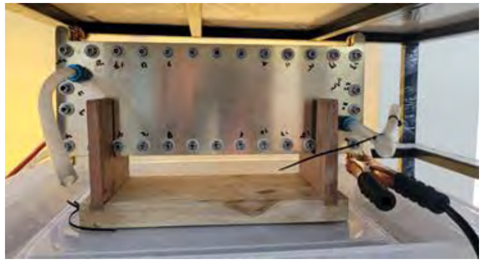
Major Equipment

N_2 Production
1. ASU

NH_3 Synthesis	
6.	Reactor (Bed 1, 2, & 3)
7.	Compressor
8	Ref - Compressor
9.	Heat Exchangers 1
10.	NH_3 Separator

H_2 Production	
2.	Deionisation system
3.	Pump
4.	Heater
5.	PEMe

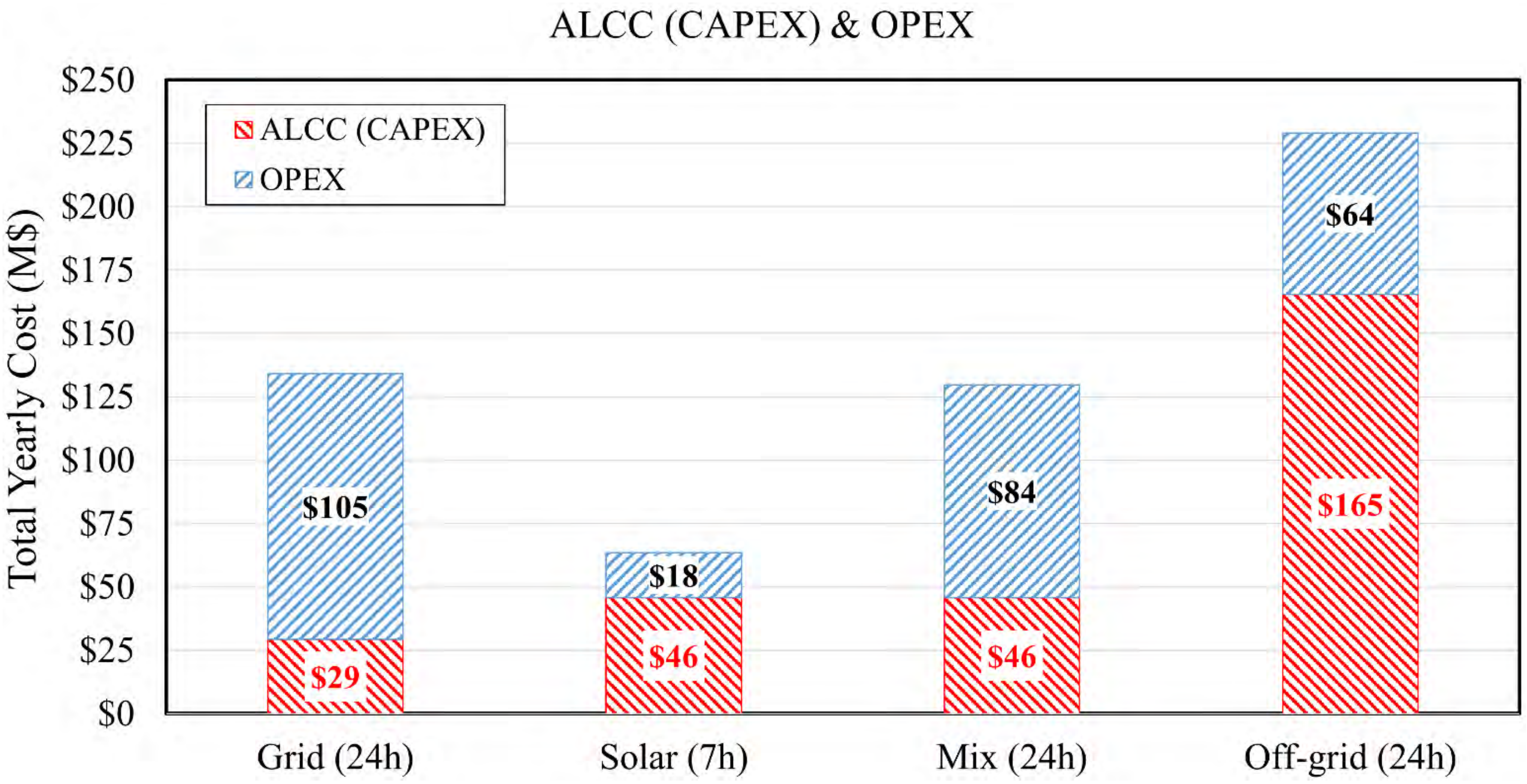




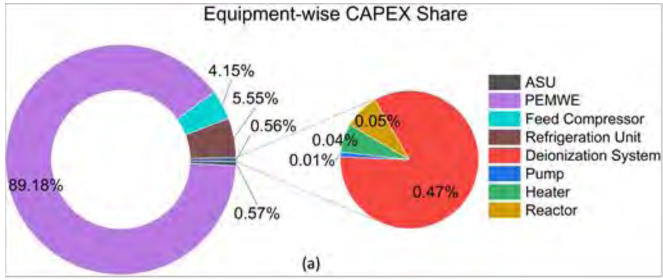
Scenarios

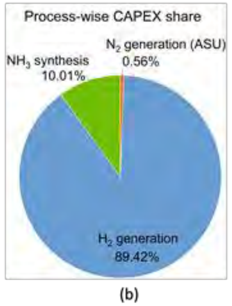
Energy Supply from	Operating hours per day	Energy supply distribution
GRID	24 hours	
Dedicated Solar Plant	7 hours	
MIXED-GRID	24 hours	7h from Solar & 17h from Grid
OFF-GRID Solar Plant	24 hours	7h from direct Solar; 17h from BES system charged by dedicated solar plant

Capital Expenditure (CAPEX) and Operating Expenditure (OPEX)

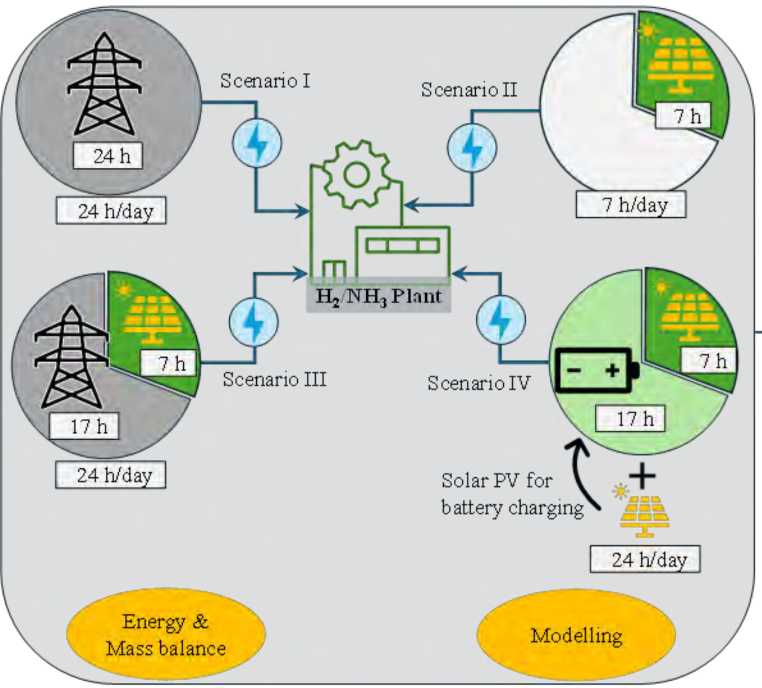


ALCC: Annualized Life Cycle Cost





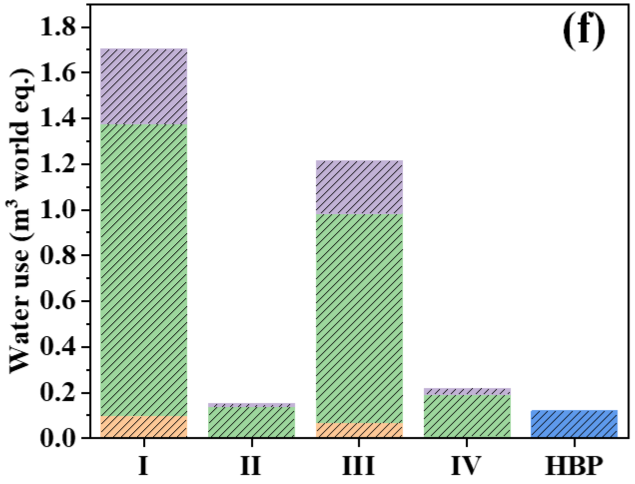
ELECTROLYTIC AMMONIA IN INDIA

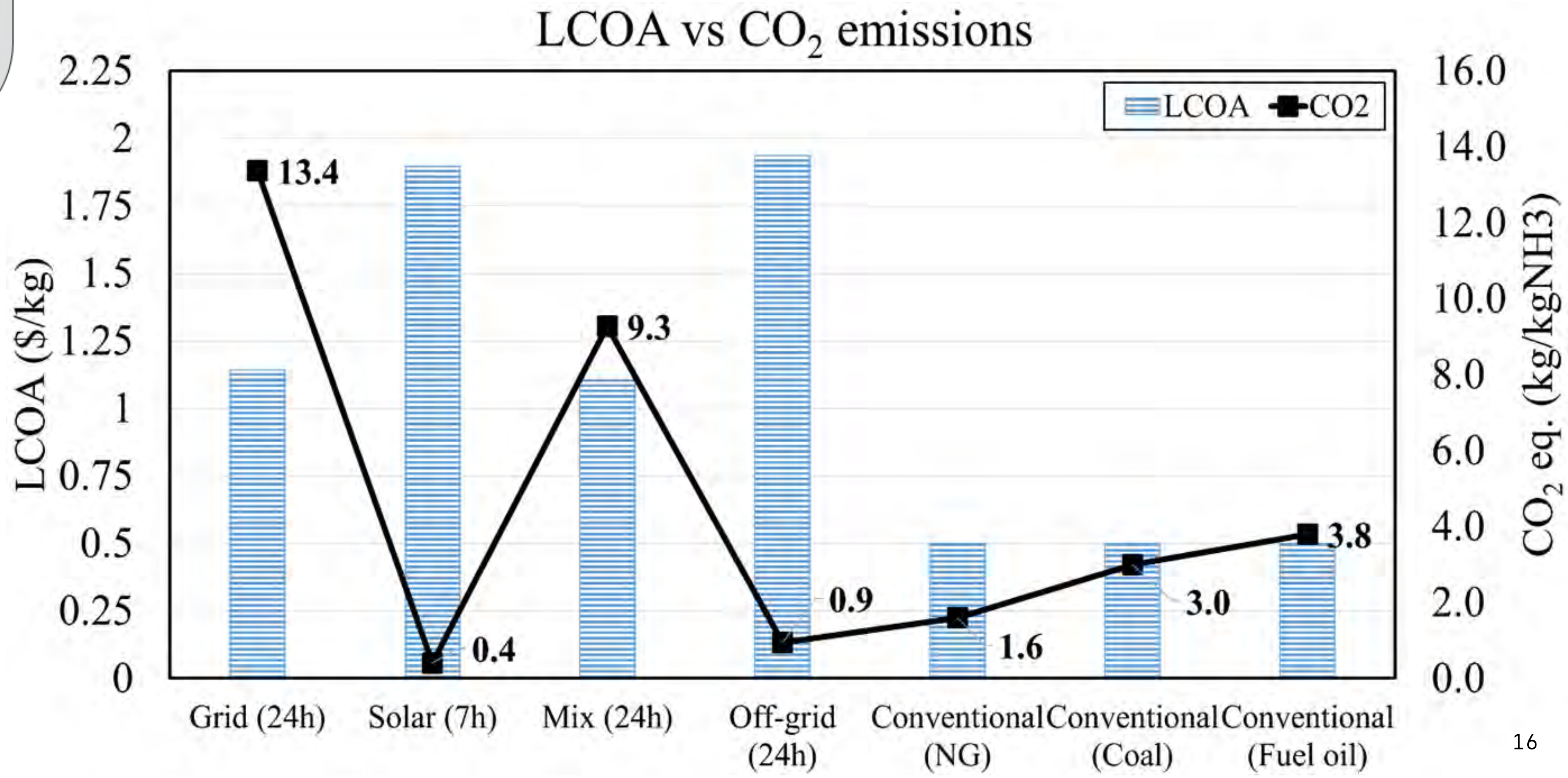


Sizing

Economic analysis

Life cycle assessment





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2	E-12/4390/2024/DEL	202411050667	2500	45500	FORM 9	—
3	E-106/9102/2024/DEL	202411052393	0	—	FORM28	—
4	R20241039429	202411050667	4000	45500	FORM 18	—

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ELSEVIER

Prospects of solar-powered nitrogenous fertilizers

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ARTICLE INFO

Keywords:
Renewable energy
Solar hydrogen production
Solar ammonia production
Solar fertilizer
Life cycle assessment

ABSTRACT

Nitrogenous fertilizer is integral to the food system for better yield of crops, and urea is the most common one. It requires ammonia as the primary reactant, while ammonia requires hydrogen for its production. Synthesis of these products is based on fossil fuels and is very carbon intensive, and pose many environmental threats. To reduce these, this review aims at understanding major solar energy-based pathways for three scenarios of producing solar fertilizers; producing urea using ammonia synthesized via solar hydrogen through water using thermolysis, photocatalytic, thermochemical, or electrolysis processes; using solar-powered ammonia using nitrogen and air/water by thermochemical, electrochemical, or photoelectrochemical methods; or directly producing urea using solar energy via photocatalytic and electrochemical processes. The potential of solar fertilizers, along with their advantages and disadvantages in agriculture, have also been highlighted. Besides this, an estimate of the land required (percent) to produce urea for all the scenarios using solar energy has been carried out for India with typical values of 0.119–0.130% for hydrogen production, 0.003–0.010% for ammonia and least for urea production. The review of techno-economic analysis and life cycle assessment for different hydrogen and ammonia production methods has been presented, and a comparative life cycle assessment study for certain hydrogen, ammonia, and nitrogenous fertilizer production methods using GaBi software was undertaken. Global warming potential, acidification potential, and eutrophication potential for 1 kg solar urea production were found as 0.092 kg CO_2 equivalent, 0.014 mol of H+, and 1.869×10^{-6} kg phosphate equivalent.

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ELSEVIER

Exploring synergy between solar pumping and nitrogenous fertilizer requirement in India

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Department of Hydro and Renewable Energy, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

ARTICLE INFO

Keywords:
Agro-climatic zones
Irrigation requirements
Solar energy
Solar nitrogenous fertilizer
Solar pumping
Sustainable agriculture

ABSTRACT

The sustenance of increasing population and climate change obligation have drifted the research towards integrating renewable energy with farming practices. The present study aims to understand the synergy between energy requirements of solar pumping and N-fertilizer in Indian conditions and presenting a techno-enviro-economic benchmark for producing sustainable nitrogenous fertilizer using unused energy from solar pumping at the farm level. Five major crops and their land shares have been identified for each agro-climatic zone, followed by the estimation of irrigation and N-fertilizer requirements, and sizing of solar pumping. The analysis using the surplus energy from solar pumping and N-fertilizer requirement suggests a required yield and rate of 0.126 kg N/kWh and 0.086 kg N/h for meeting 75 percent of the total requirement. A correlation between potential reduction in CO_2 emissions, carbon tax, and cost, in terms of ammonia, the crucial reagent of N-fertilizers, estimates a benchmark cost of 0.768 USD/kg NH_3 at a target emission of 0.5 kg CO_2 eq./kg N. Integrating solar pumping with decentralized N-fertilizer production technology at the farm level can be effectively realized to cater to the irrigation and N-fertilizer requirements using solar energy and contribute to the fields of solar energy, agriculture, and sustainable development.

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ELSEVIER

Techno-enviro-economic evaluation of decentralized solar ammonia production plant in India under various energy supply scenarios

Saket Sahu [a,1], Nitish Srivastava [a,1], Pratham Arora [a,*], Indraneel Natu [b], Amit C. Bhosale [a], Rhythm Singh [a], Dhirendra Tiwari [c], Vineet Saini [d]

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ARTICLE INFO

Keywords:
Decentralized Haber-Bosch process
Green ammonia
Green hydrogen
PEM electrolyzer
Solar energy
Sustainability

ABSTRACT

The growing potential for ammonia as an energy carrier and the need to minimize environmental emissions have created a demand for green and decentralized ammonia production (power-to-ammonia) as an alternative to conventional processes. One of many alternatives is to use a Haber-Bosch process where hydrogen is synthesized using electrolysis, and nitrogen is obtained via an air separation unit utilizing electricity from various sources, having their own economic and environmental implications. This study presents a detailed economic and life cycle assessment comparing four different energy supply scenarios in India for decentralized ammonia production based on low pressure (80 bar). A 150 MW polymer electrolyte membrane water electrolyzer (PEMWE) modeled using the Aspen custom modeler is utilized for hydrogen generation, and subsequent ammonia production has been modeled using Aspen Plus®. Energy consumption analysis indicates the power consumption of PEMWE to be 83.59 percent. The minimum levelized cost of ammonia, $1106/ton of ammonia, is obtained by combining a local solar plant and the grid. Moreover, ammonia production using a solar photovoltaic (SPV) plant has the minimum environmental impact, with a global warming potential of 0.305, compared to 13.98 kg of carbon dioxide equivalent produced per kg of ammonia using grid electricity. However, such plants are not economically viable in locations with very low solar availability. Combining an SPV system with battery energy storage has been found to be environmentally viable; however, it is the most expensive alternative of all the scenarios considered. The sale of oxygen can have an added benefit on the cost and may result in a levelized cost of $672/ton of ammonia in 2030 with a projected electrolyzer cost of $264/kW.

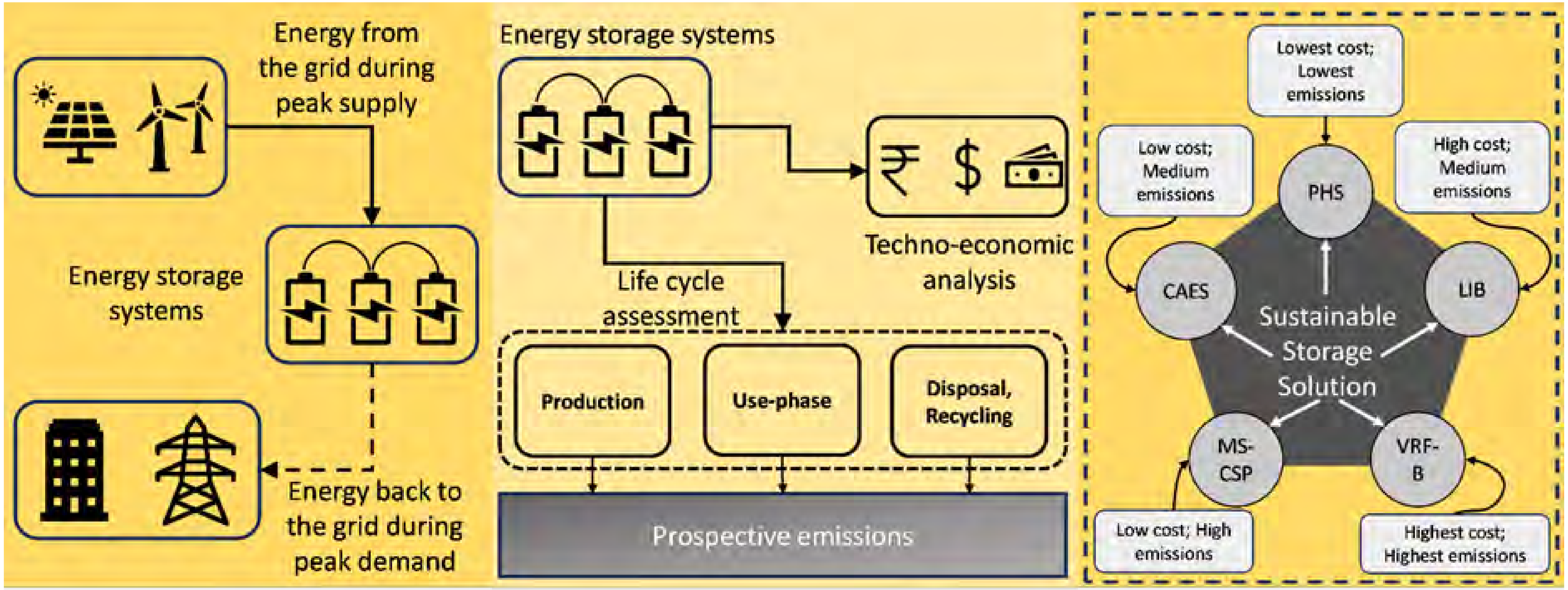
1. Introduction

Ammonia (NH_3) is one of the most widely produced chemicals in the world (~176 MT in 2018), with 85% of globally produced ammonia converted into fertilizers [1]. Currently, most ammonia production plants use fossil fuels, which emit a considerable amount of CO_2 (1.6–3.8 kg CO_2 eq./kg NH_3) [2–4] underlying the very need for environmentally friendly methods of generating chemicals, like ammonia, to meet the Paris Climate Agreement by the year 2050. Furthermore, the increasing recognition of ammonia as a sustainable, carbon-free fuel for future transport is likely to increase its demand.

Conventional plants worldwide have capacities greater than 2000 tons per day (TPD) and are typically situated in locations with easy access to natural gas, affecting the surrounding area and resulting in additional shipping expenses for landlocked nations far from the ports, thereby restricting consumption [5]. Small-scale green ammonia plants where the energy requirement is met by renewable sources have the potential to overcome the drawbacks of conventional plants; however, they are restricted by the economy of scale [5,6]. Some common routes to produce green ammonia include hydrogen generation via electrolyzer technologies or electrochemical water-splitting and subsequent ammonia synthesis [1,7]. Non-thermal plasma-assisted ammonia production has also been investigated by various authors [8,9], while others have focused on electrochemical, photochemical, and photo-electrochemical ammonia synthesis [10,11]. However, hydrogen

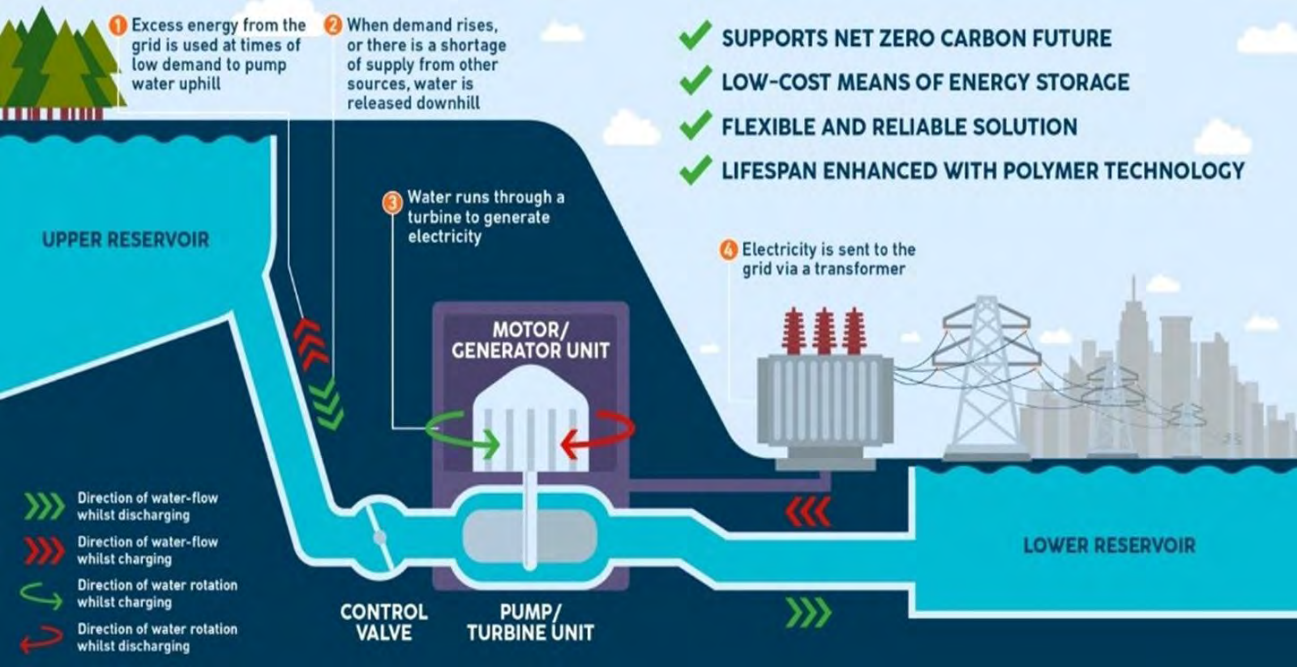
Case Study III: Energy storage?

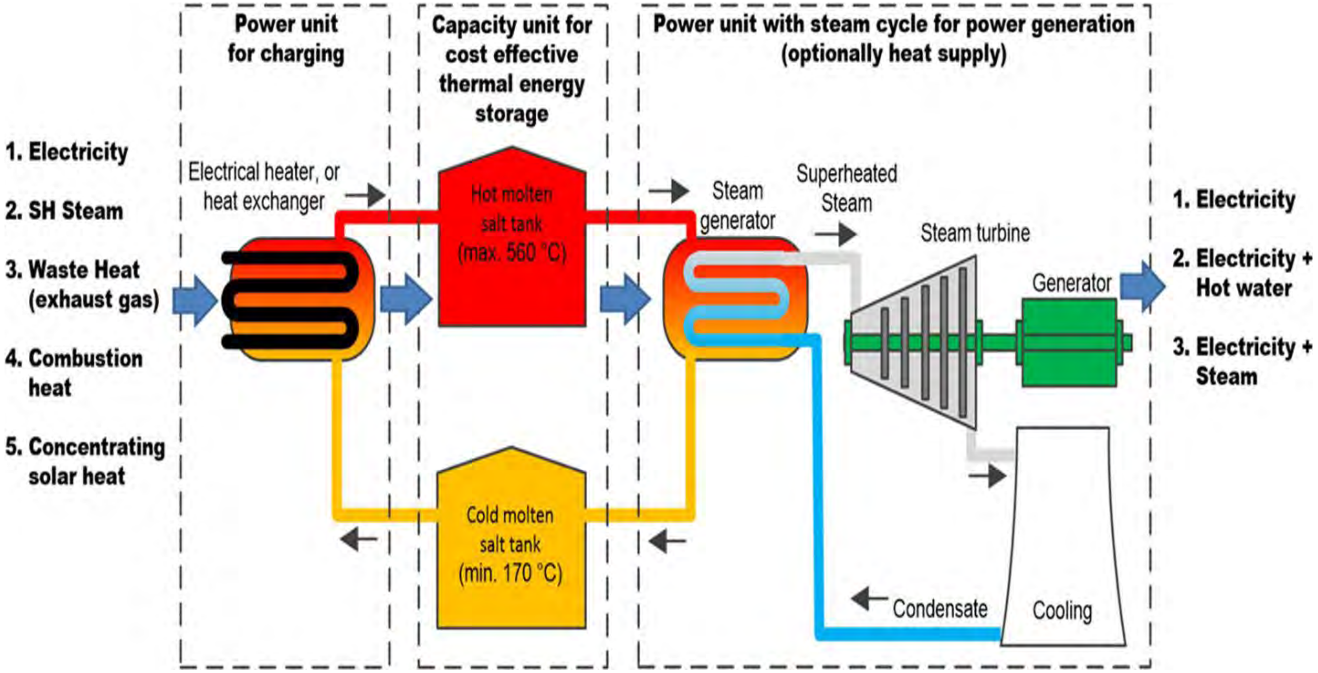
- Intermittent renewable energy
- Grid stabilization
- Peak demand management
- Energy resilience
- Decarbonization of the grid

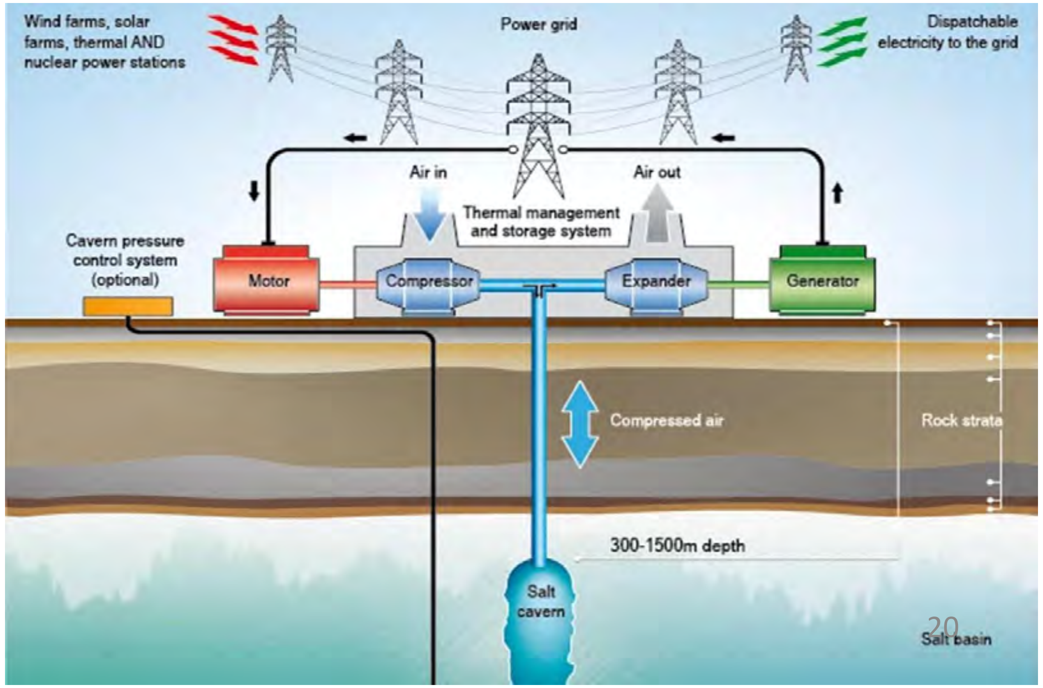


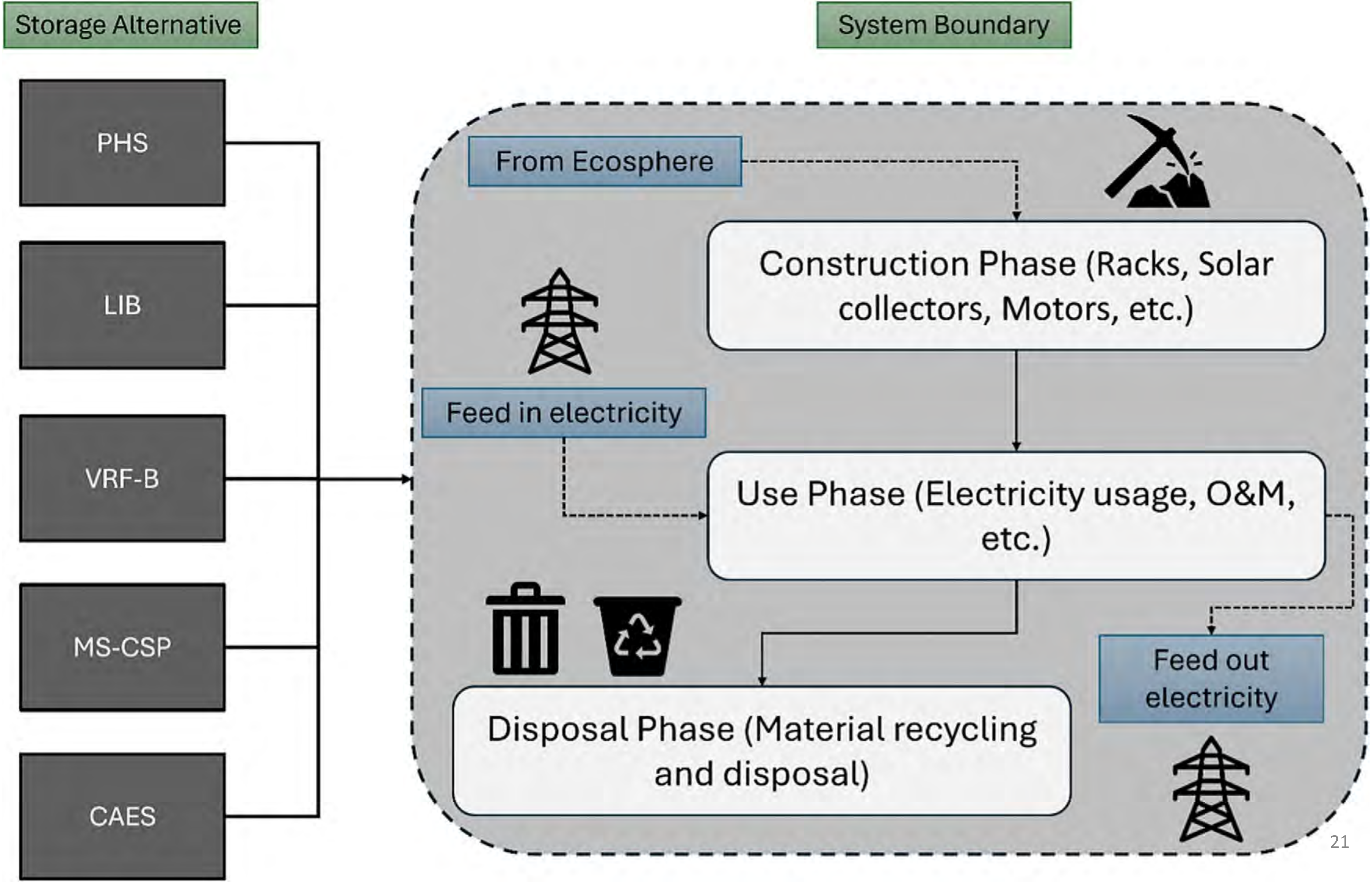
Storage alternatives considered

- Lithium-ion Battery (LIB)
- Molten Salt Storage (MS-CSP)
- Pumped Hydro Storage
- Vanadium Redox Flow Battery (VRF-B)
- Compressed Air Energy Storage

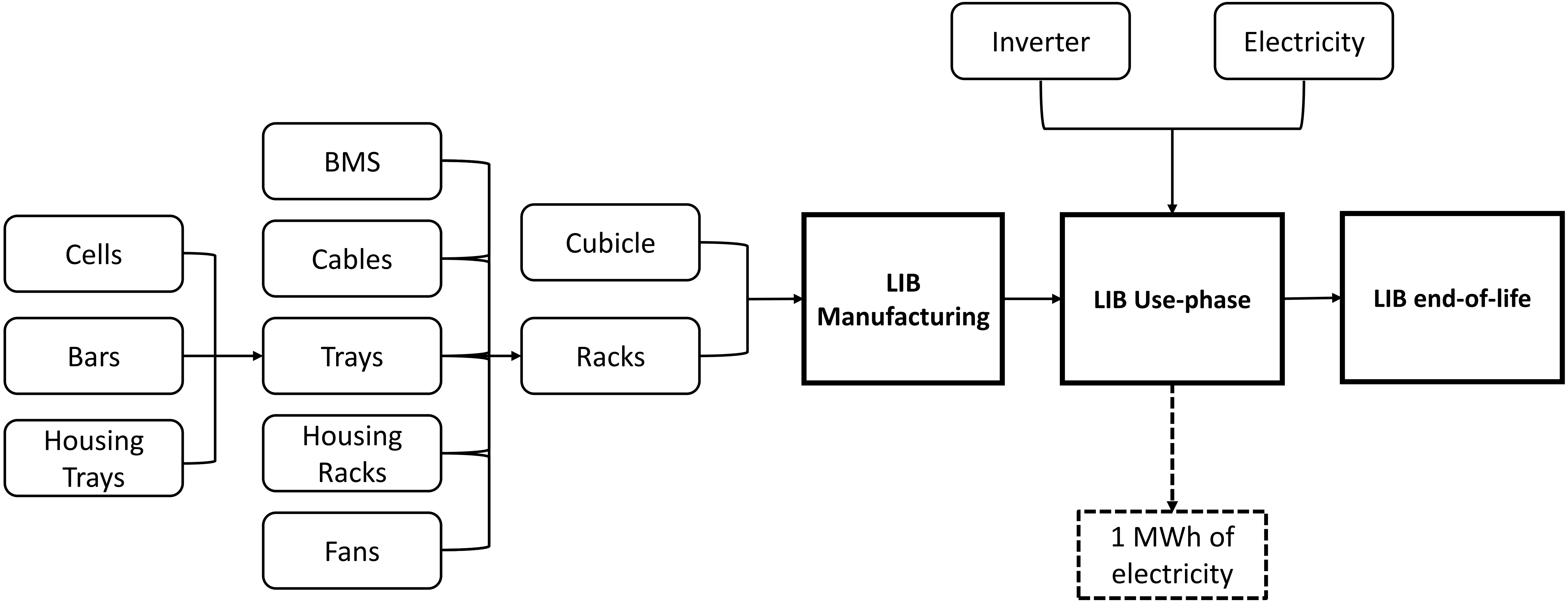

1 Excess energy from the grid is used at times of low demand to pump water uphill
2 When demand rises, or there is a shortage of supply from other sources, water is released downhill
SUPPORTS NET ZERO CARBON FUTURE
LOW-COST MEANS OF ENERGY STORAGE
FLEXIBLE AND RELIABLE SOLUTION
LIFESPAN ENHANCED WITH POLYMER TECHNOLOGY
UPPER RESERVOIR
3 Water runs through a turbine to generate electricity
4 Electricity is sent to the grid via a transformer
MOTOR/ GENERATOR UNIT
LOWER RESERVOIR
Direction of water-flow whilst discharging
Direction of water-flow whilst charging
Direction of water rotation whilst charging
Direction of water rotation whilst discharging
CONTROL VALVE
PUMP/ TURBINE UNIT


Power unit for charging
Capacity unit for cost effective thermal energy storage
Power unit with steam cycle for power generation (optionally heat supply)
1. Electricity
2. SH Steam
3. Waste Heat (exhaust gas)
4. Combustion heat
5. Concentrating solar heat
Electrical heater, or heat exchanger
Hot molten salt tank (max. 560 °C)
Cold molten salt tank (min. 170 °C)
Steam generator
Superheated Steam
Steam turbine
Generator
Condensate
Cooling
1. Electricity
2. Electricity + Hot water
3. Electricity + Steam


Wind farms, solar farms, thermal AND nuclear power stations
Power grid
Dispatchable electricity to the grid
Air in
Air out
Thermal management and storage system
Cavern pressure control system (optional)
Motor
Compressor
Expander
Generator
Compressed air
Rock strata
300-1500m depth
Salt cavern
Salt basin


Storage Alternative
System Boundary
PHS
LIB
VRF-B
MS-CSP
CAES
From Ecosphere
Construction Phase (Racks, Solar collectors, Motors, etc.)
Feed in electricity
Use Phase (Electricity usage, O&M, etc.)
Feed out electricity
Disposal Phase (Material recycling and disposal)

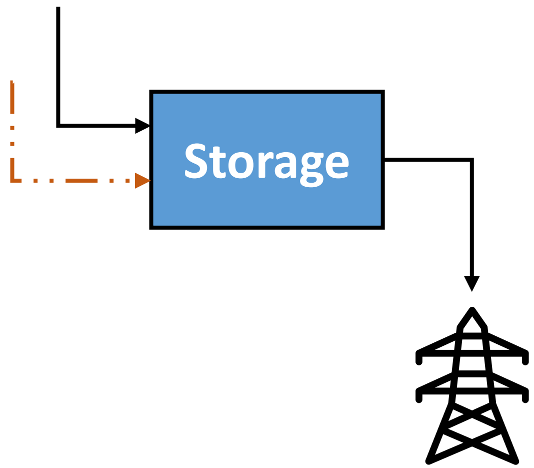
LIB system layout



Scenarios Considered

S1

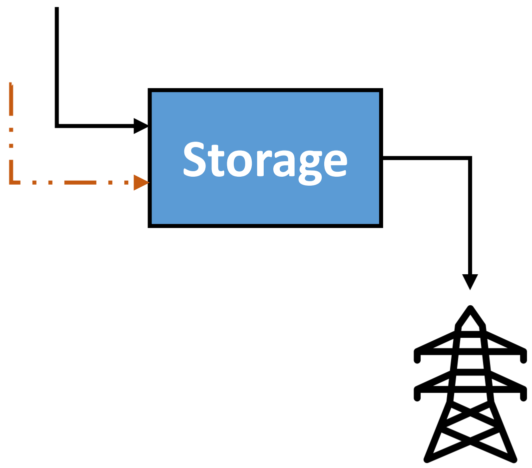
Input electricity from solar grid (based on **a future** solar grid)



- LCA impacts of total electricity input have been considered

S2

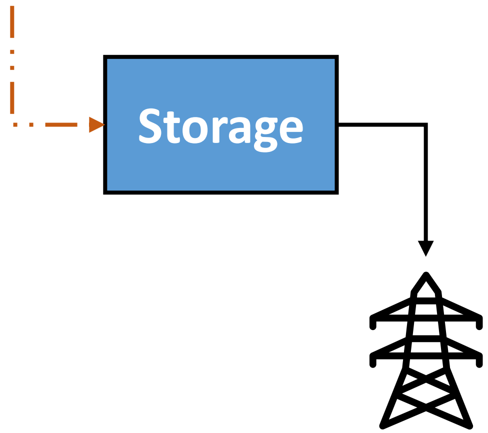
Input electricity from **Indian** conventional grid



- LCA impacts of total electricity input have been considered

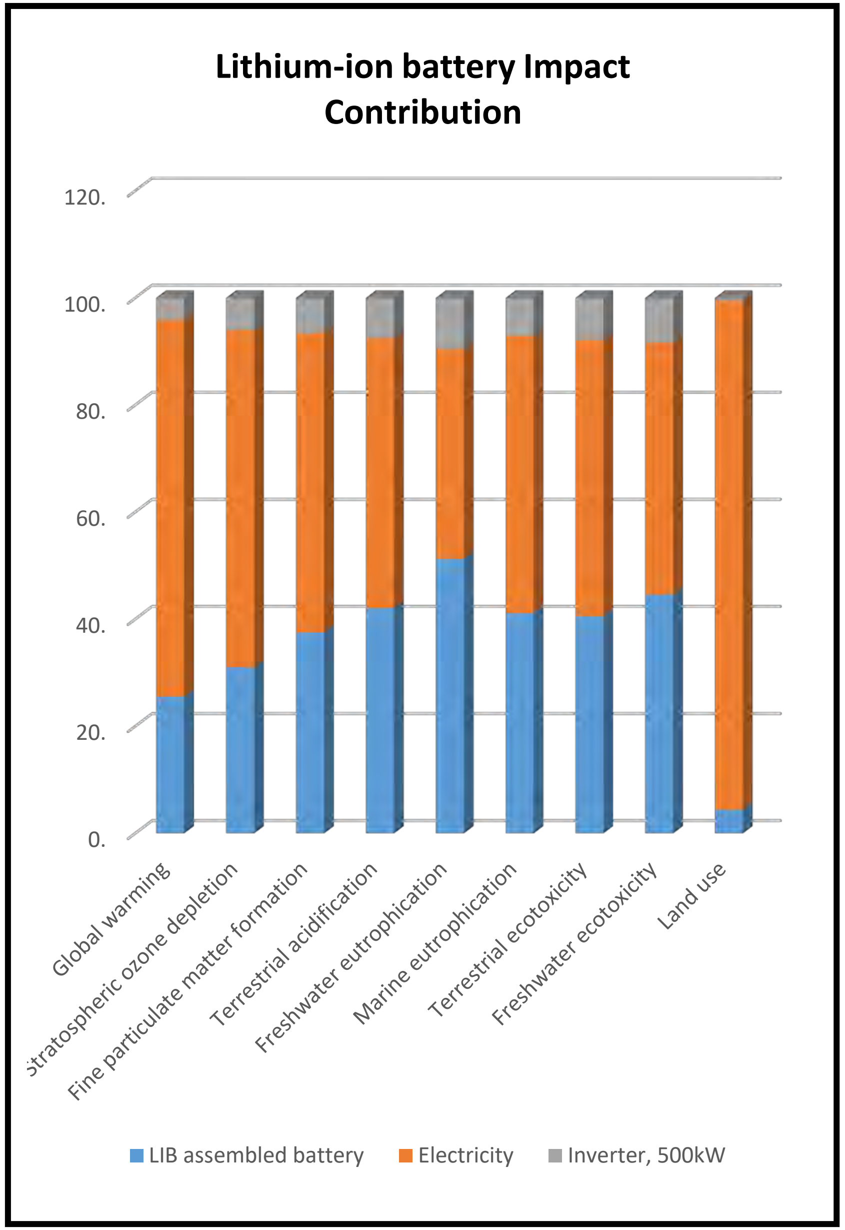
S3

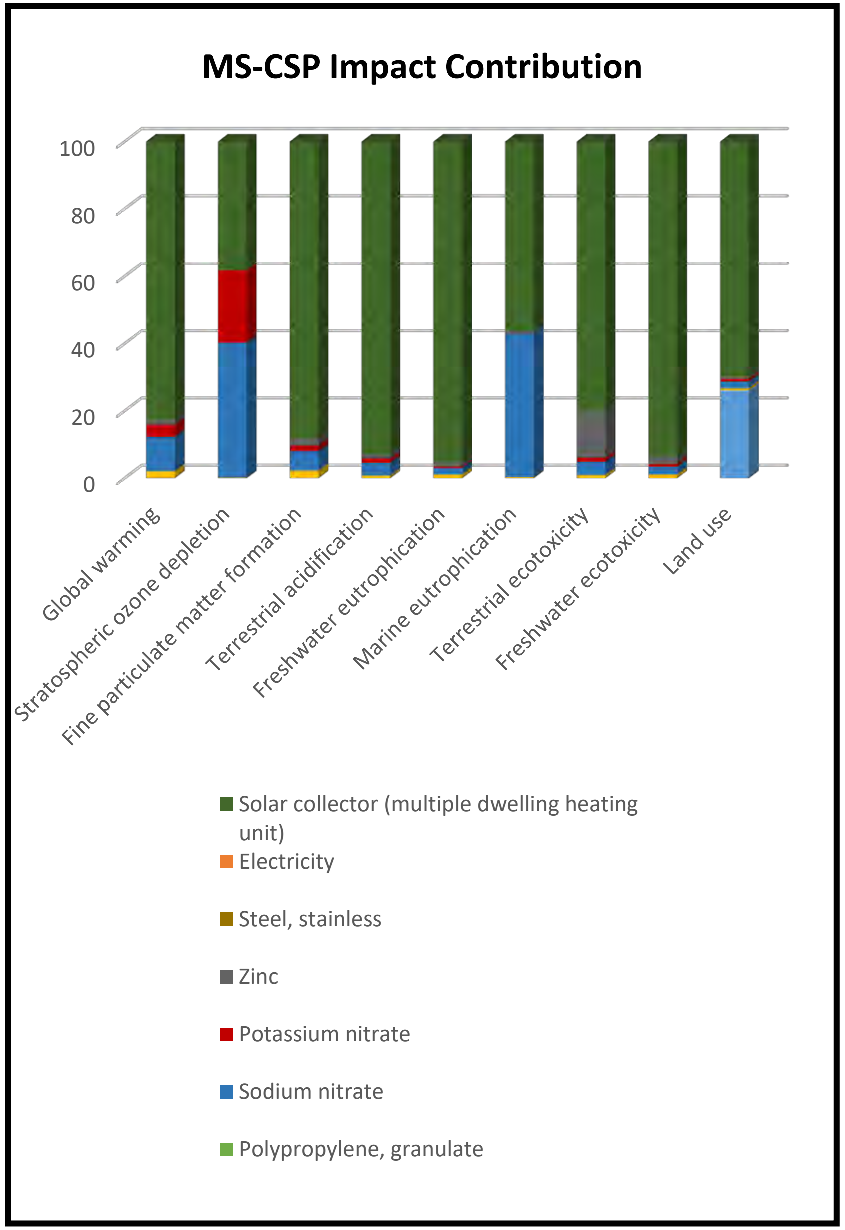
Input electricity from solar grid (based on **a future** solar grid)

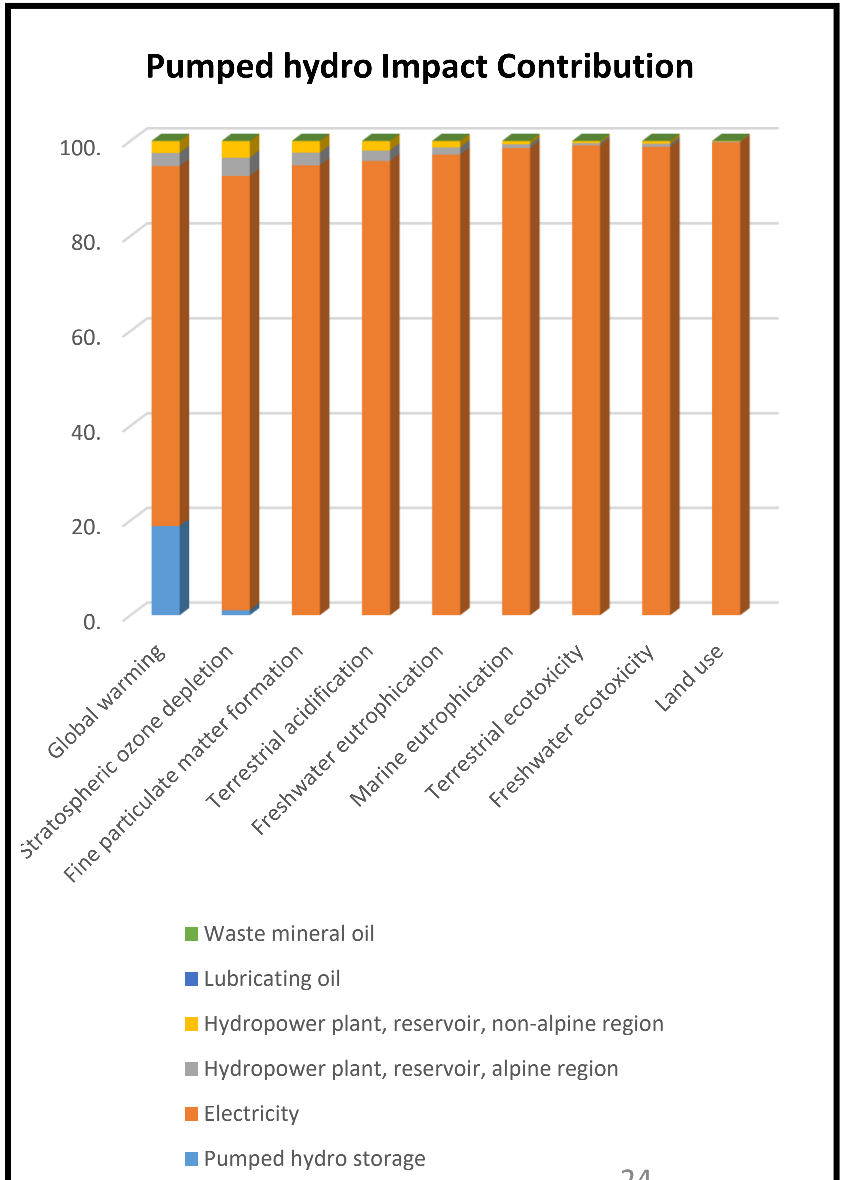


- LCA impacts of electricity (only storage operation and maintenance) input have been considered

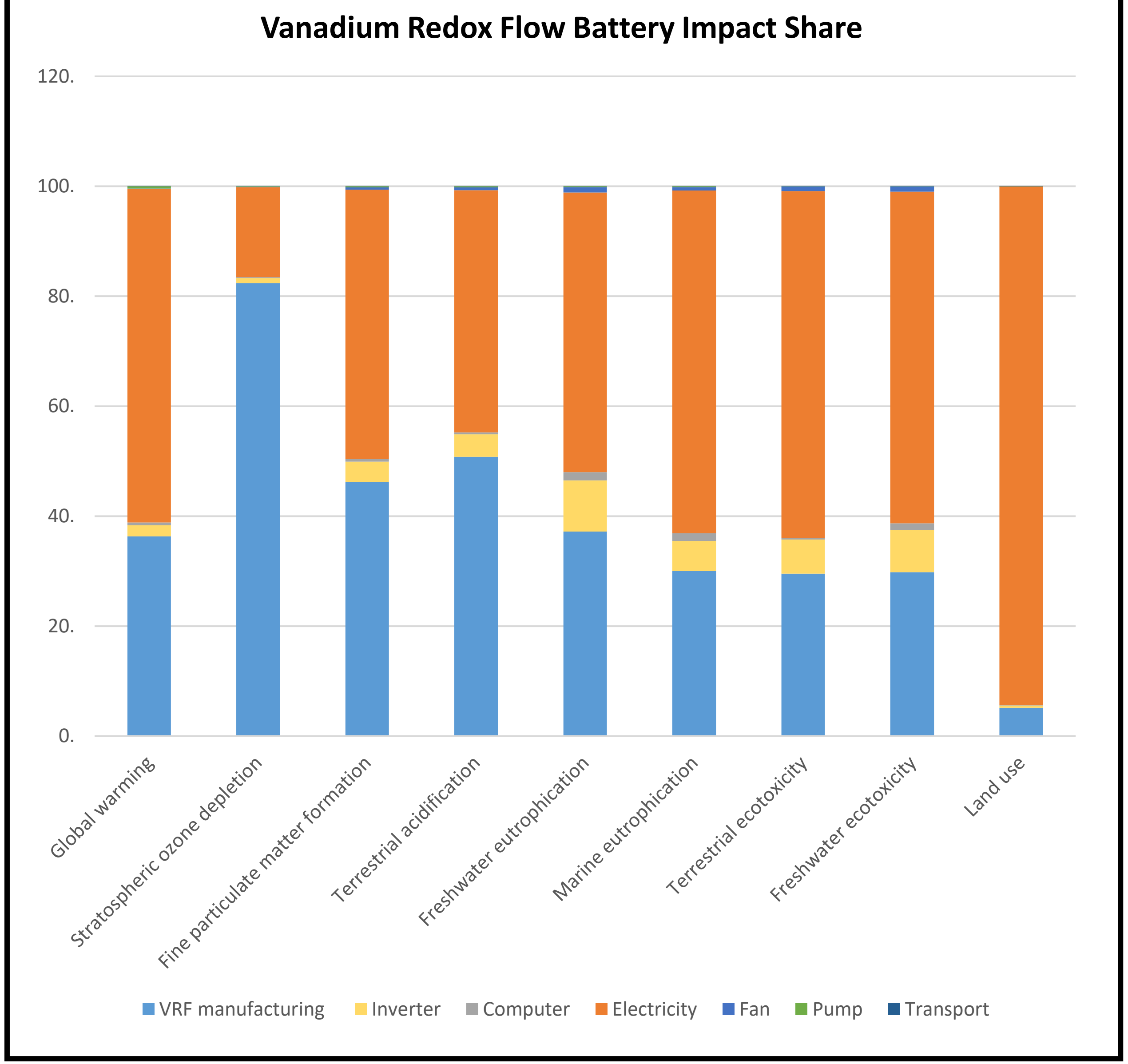
S1: LCIA of LIB, MS-CSP, and Pumped Hydro (Impact Share)

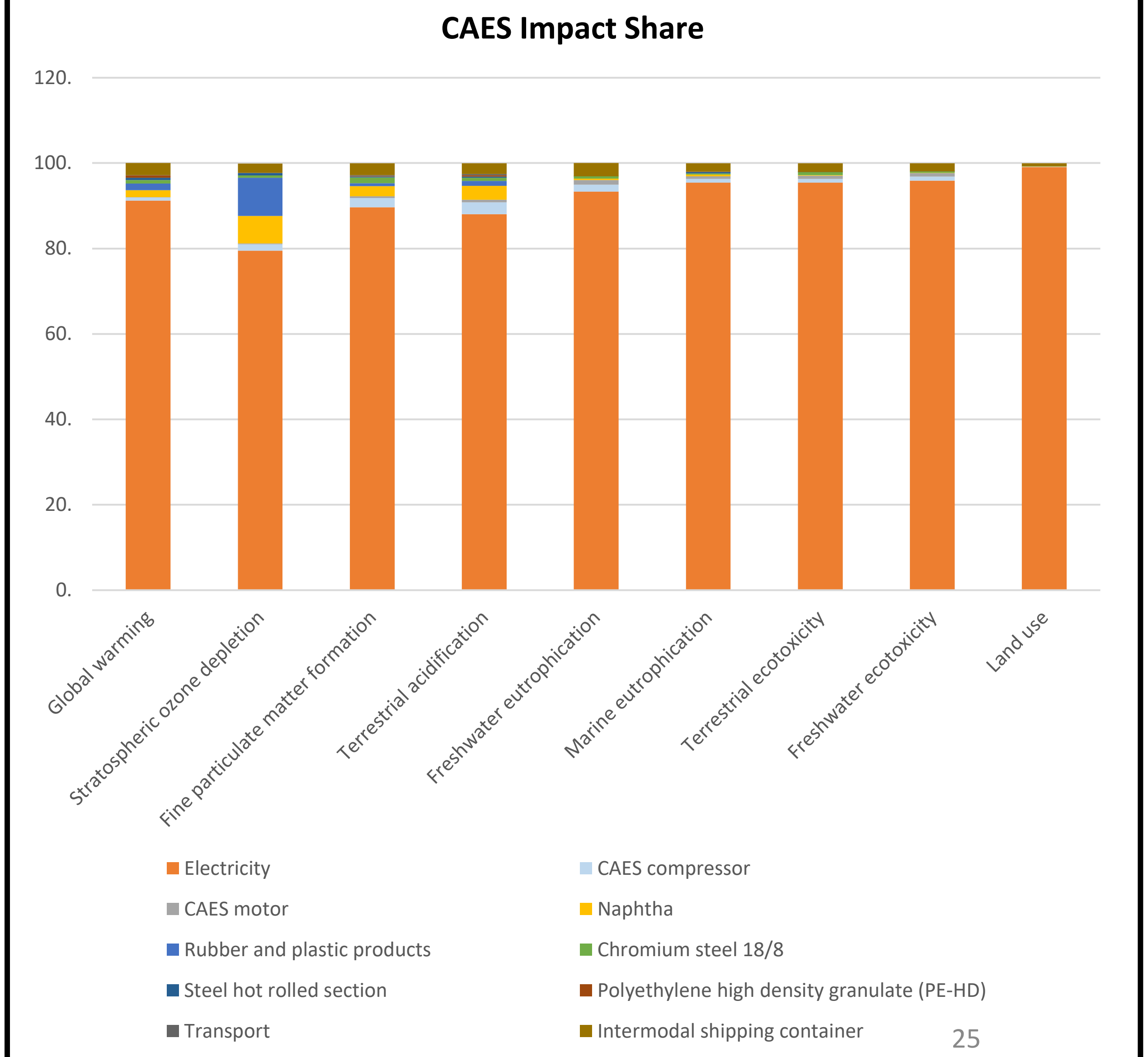






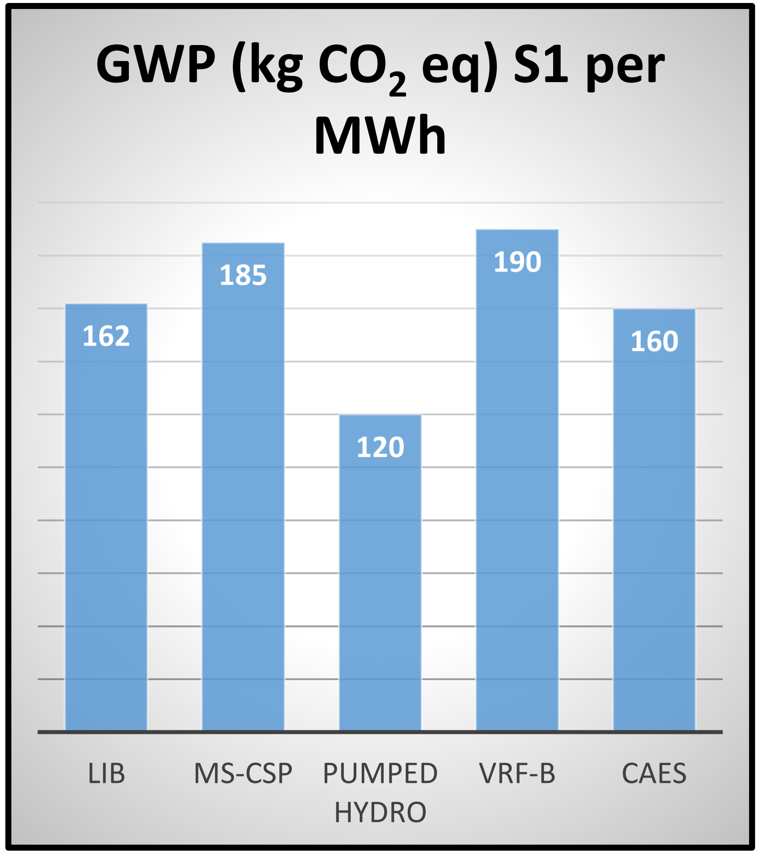
S1: LCIA of VRF-B, CAES (Impact Share)

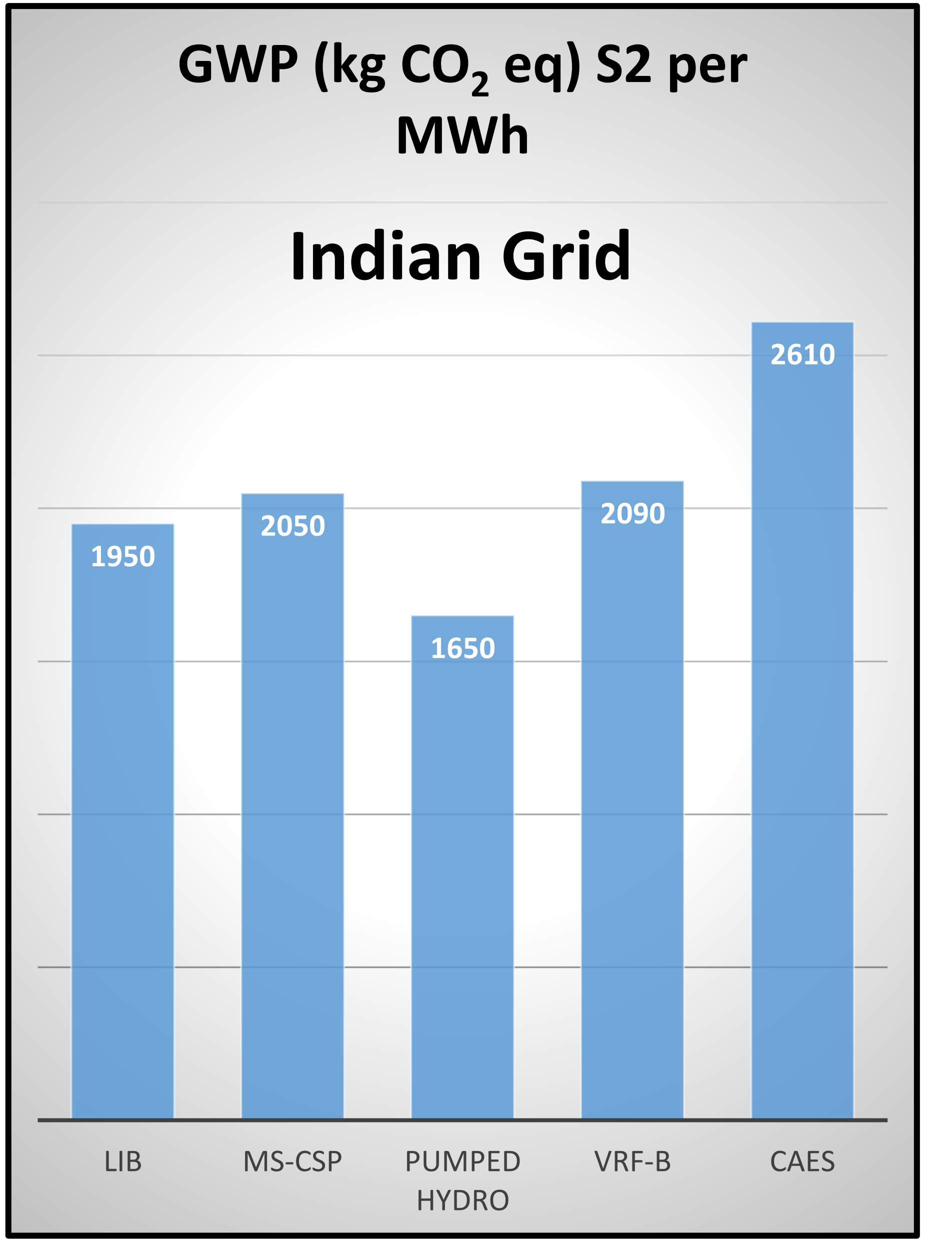




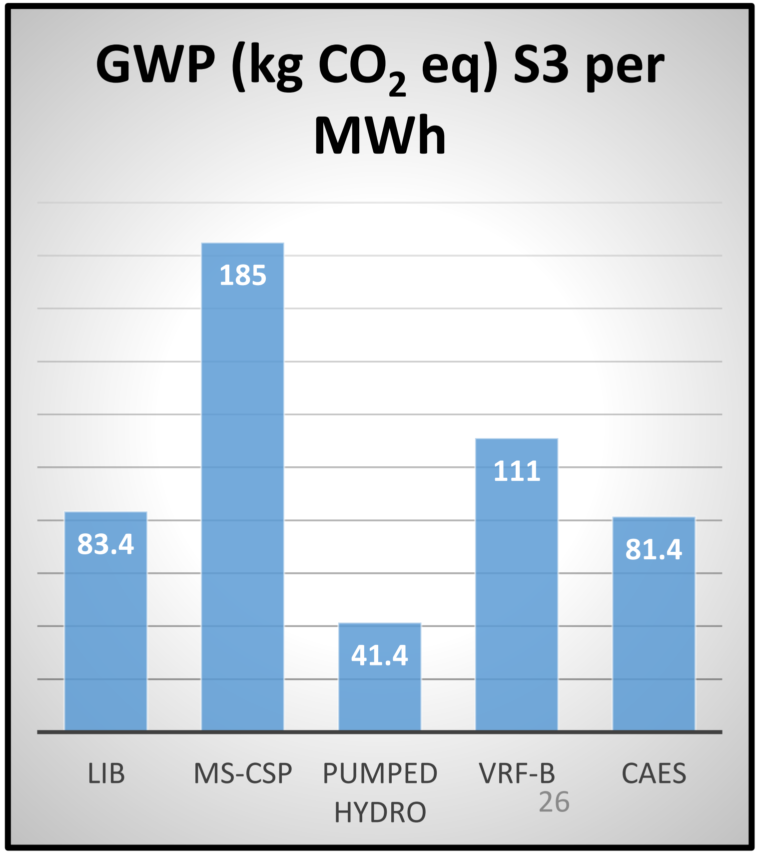
GWP Comparison (S1 vs S2 vs S3)

Solar Grid





Solar Grid (only O&M)



Techno-economic analysis of PSP

Table: Technical assumption in the analysis of a BESS

Parameter	Unit	Value
Base year for LCOS calculation	Year	2023
Technology		PHS
Projeect construction time	Years	5
Project lifetime excluding the construction time	Years	40
Power capacity	MW	250
Charging/discharging cycle per day	Number	1
Discharging time	Hrs	6
Operation cycles per year	Cycles	365
Normative availability	%	95%
Storage round trip efficiency	%	80.5%
Annual gross energy generation capacity	GWh	547.5
Annual energy generation @95% availability	GWh	520.1 25
Transformation losses	%	0.5%
Auxillary consumption	%	0.7%
Net annual saleable energy	GWh	513.8
Annual energy required for pumping	GWh	680.1

Table: Financial assumption

Parameter	Unit	Value
Equity	%	30.0%
Return on Equity	%	16.5%
Interest on loan	%	9%
Discount rate (WACC)	%	11.25%
Loan Tenure	Years	20
Moratorium	Years	1
Annual O&M expense	%	3.5%
Annual O&M cost escalation	%	4.77%
Working Capital - O&M	Months	1
Working Capital - Receivables	Months	1.5
Working capital - Maintenance spares	%	15%
Salvage value at end of life	%	10%
Number of years for accelerated depriciation	Years	14
Annual depriciation rate for first 14 years	%	5.28%
Interest on Working Capital	%	11%
Corporate Tax	%	25%
Tax holiday	Years	10
Assumed CAPEX	Crore ₹/MW	4
I. Direct costs	Lakh ₹/MW	196
II. Indirect costs	Lakh ₹/MW	4
III. Electro Mechanical work cost	Lakh ₹/MW	200
Total Capex	Lakh ₹/MW	400
Electricity tariff for charging battery	₹/kWh	3
Cost escalation for input/saleable electricity	%	0%
Sale tariff	₹/kWh	15

Table: Parametric results

		1 cycle per day	1.5 cycle per day
IRR	%	28.54%	37.6%
NPV	Lakh ₹	1,85,525	3,34,085
LCOS	₹/kWh	7.88	6.58

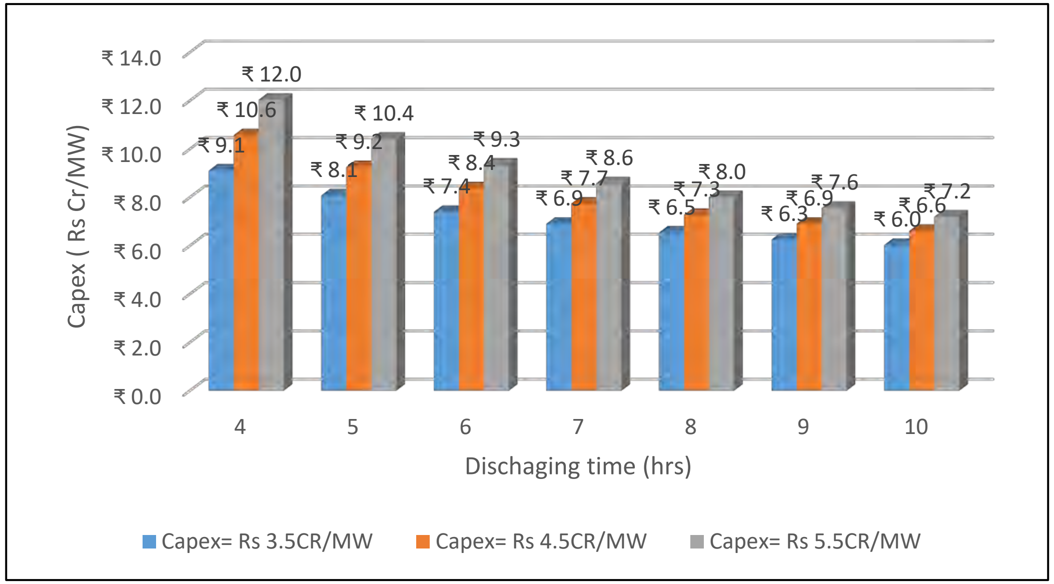


Fig: LCOS sensitivity analysis

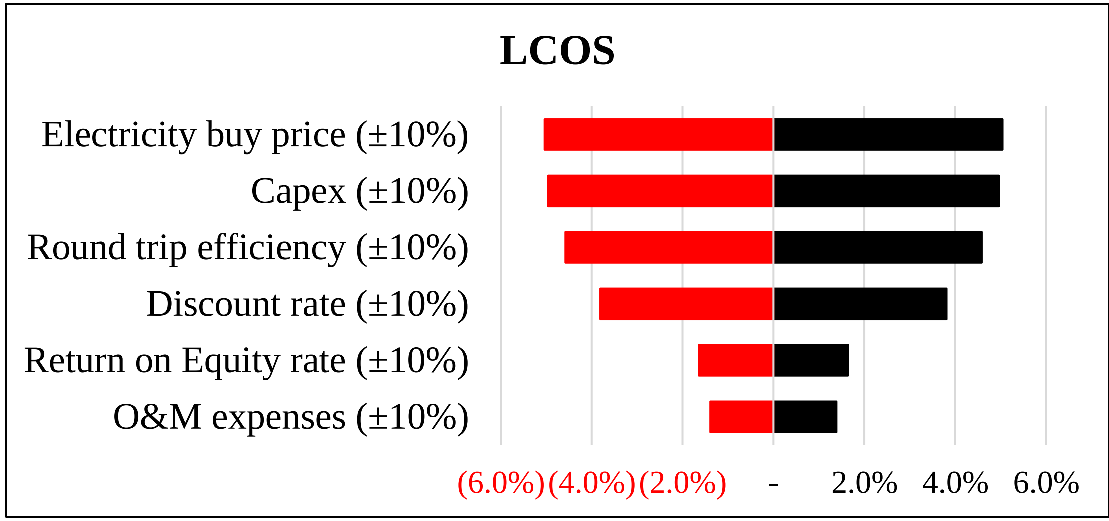


Fig: LCOS sensitivity analysis

Note: LCOS also includes the cost of electricity for charging.

Comparative analysis

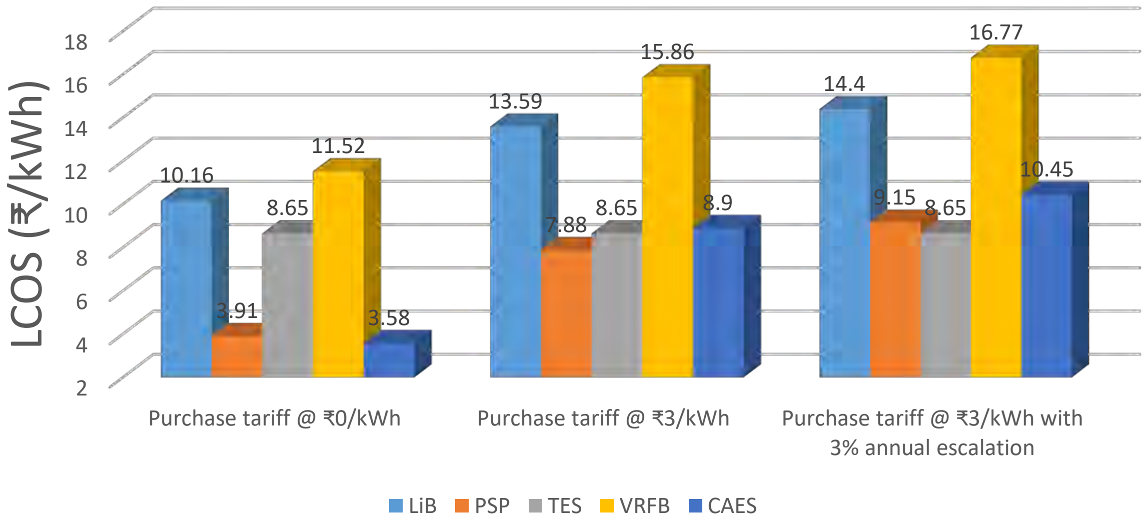


Fig: LCOS comparison

Power capacity 150MW with 4 hours discharge
Power sale tariff is ₹15 per kWh

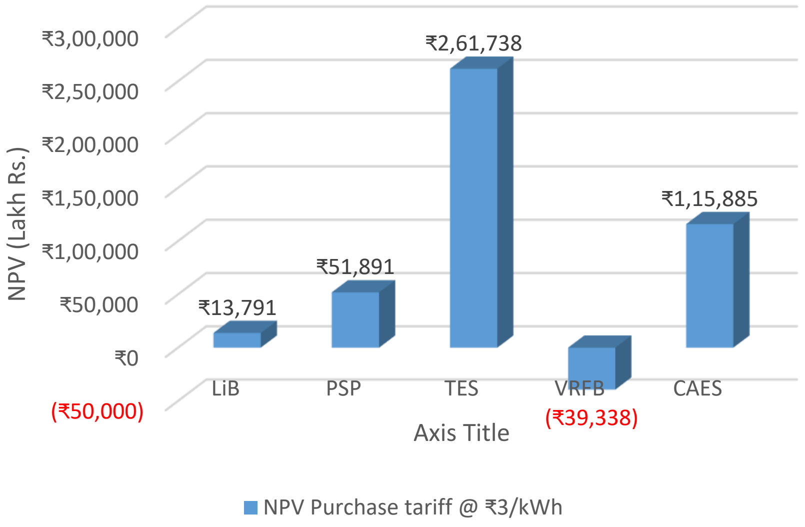


Fig: NPV comparison

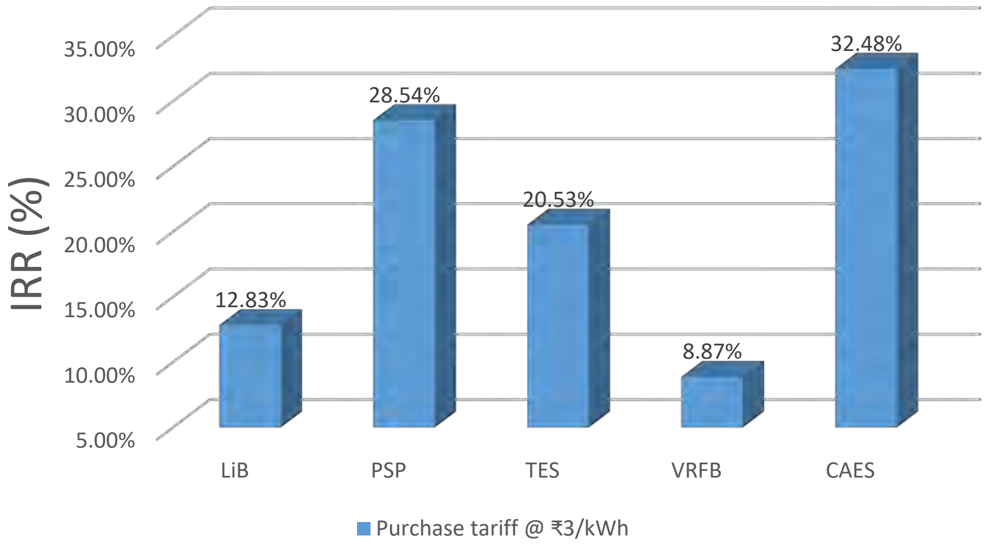
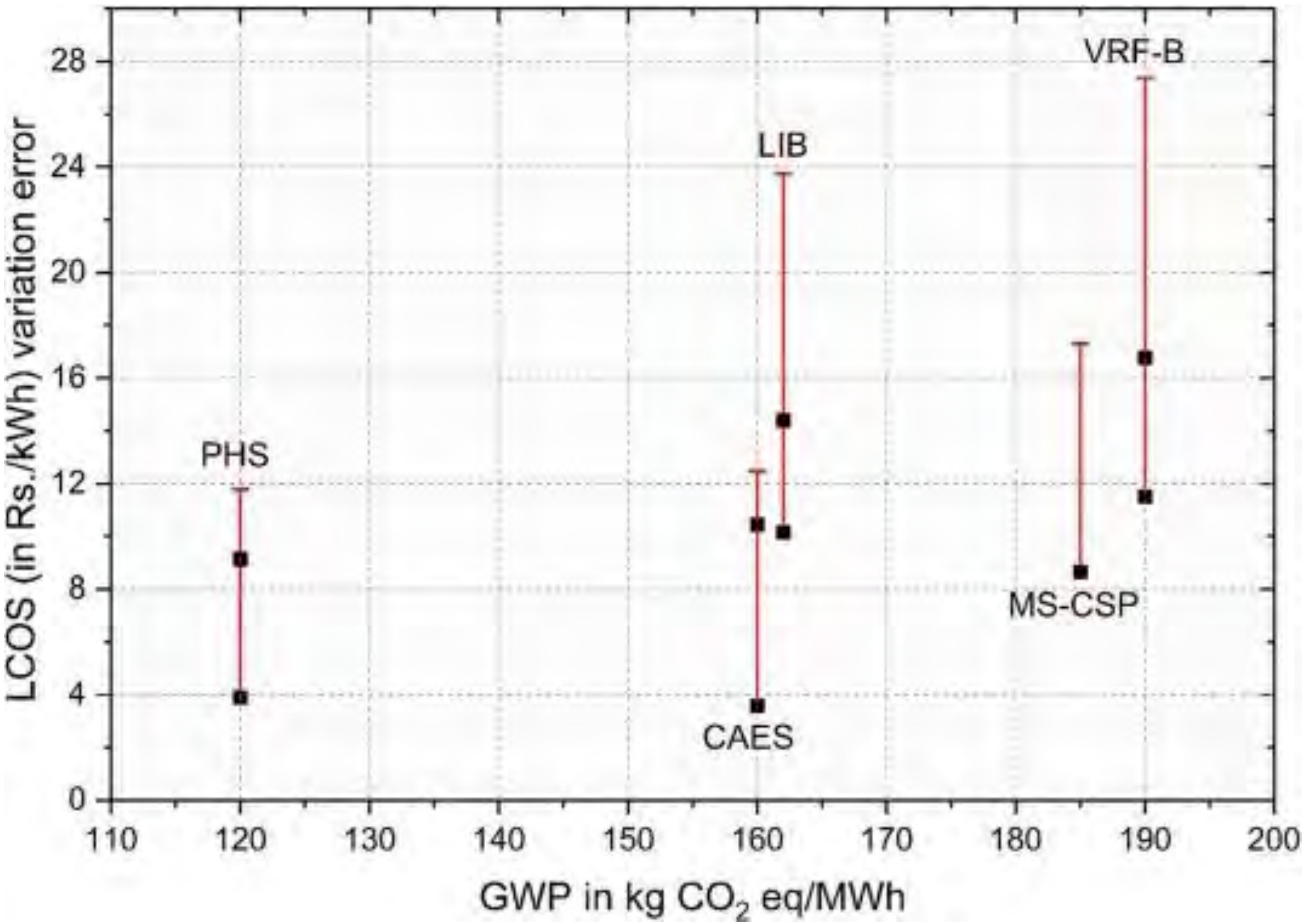
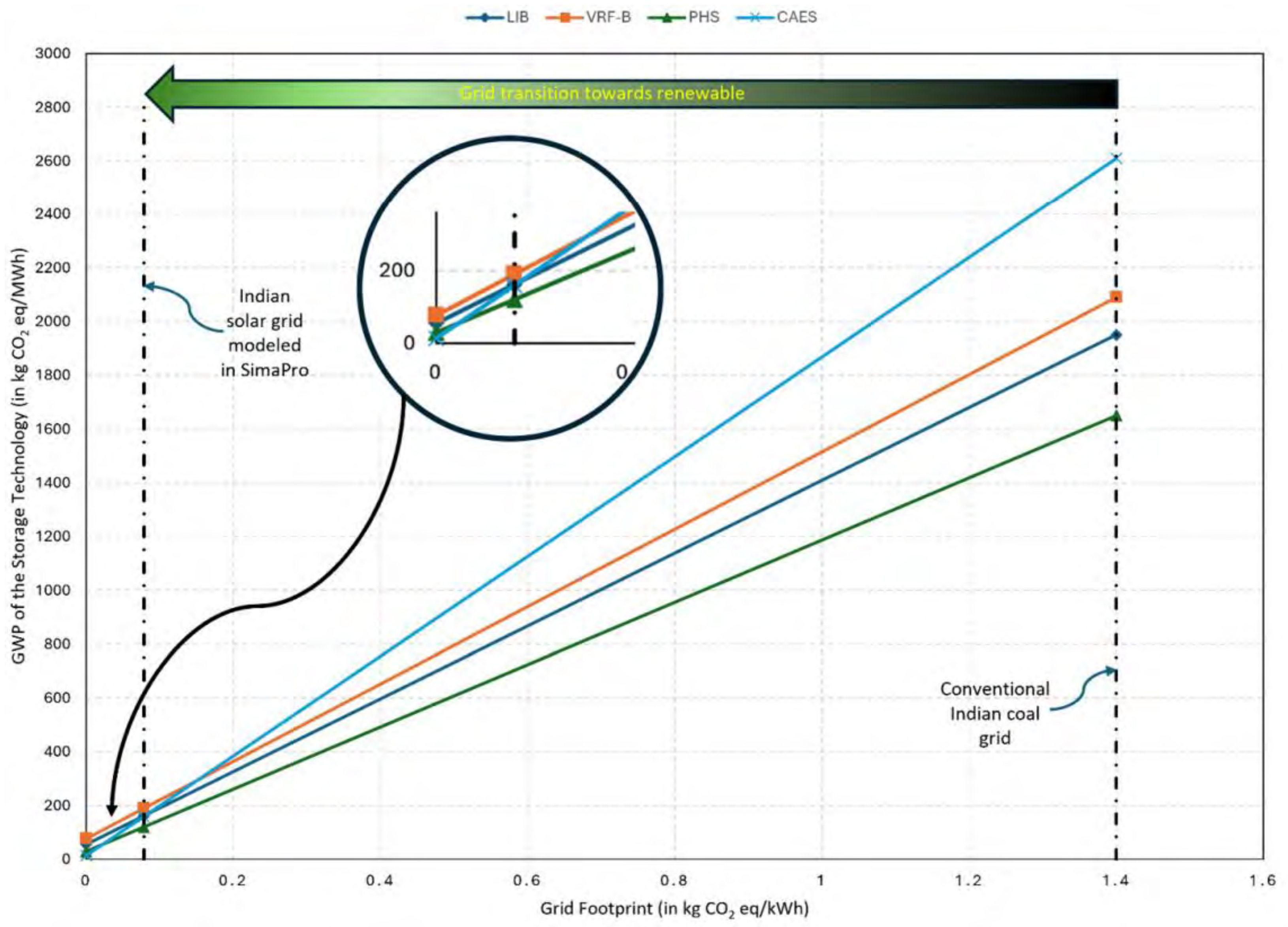


Fig: IRR comparison

GWP vs LCOS



VRF-B
LIB
PHS
CAES
MS-CSP
LCOS (in Rs./kWh) variation error
GWP in kg CO_2 eq/MWh
0
4
8
12
16
20
24
28
110
120
130
140
150
160
170
180
190
200



LIB
VRF-B
PHS
CAES
Grid transition towards renewable
Indian solar grid modeled in SimaPro
Conventional Indian coal grid
GWP of the Storage Technology (in kg CO_2 eq/MWh)
Grid Footprint (in kg CO_2 eq/kWh)
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

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Integrated life cycle assessment and techno-economic analysis of grid-scale energy storage alternatives for India

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A R T I C L E I N F O

Editor: Prof. Shabbir Gheewala

Keywords:
Renewable grid
Energy transition
Emissions analysis
Economic indicators
Storage sustainability & viability

A B S T R A C T

Renewable energy will dominate India's grid in the future. The intermittent nature of renewable energy requires energy storage. This research examines grid-scale deployment options for India, including pumped hydro, lithium-ion batteries, vanadium redox-flow batteries, molten salt storage, and compressed air energy storage. A cradle-to-grave life cycle assessment for midpoint categories was conducted in SimaPro. Pumped hydro storage exhibits the lowest impact in all the categories. Vanadium redox flow batteries exhibit the highest degradation scores in almost all categories except non-carcinogenic human toxicity, where the anode graphite causes the most impact in lithium-ion batteries. The impacts are found to be most sensitive towards electricity usage, except for molten salt storage (solar collectors) and usage of tetrafluoroethylene in vanadium redox flow batteries and salts (sodium and potassium nitrate) in molten salt storage for stratospheric ozone depletion, using anode graphite in lithium-ion batteries for terrestrial ecotoxicity. The techno-economic study shows that the lowest levelized cost of storage is ₹7.88/kWh (0.1 US$/kWh) for pumped hydro and the highest at ₹15.86/kWh (0.2 US$/kWh) for vanadium redox flow. Sensitivity analysis showed that pumped hydro storage is most sensitive to changes in power purchase prices. The cost of lithium-ion, molten salt, compressed air energy storage, and vanadium redox-flow battery is most susceptible to capital expenditure and roundtrip efficiency. Further, the Global Change Analysis Model (GCAM) projections revealed the vanadium redox flow battery to be the most expensive. Pumped hydro storage was the most affordable due to its higher energy efficiency and longer lifespan.

Study on Advanced Grid-scale Energy Storage Technologies

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Energy Systems Modelling Lab

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