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Capacity Building Workshop for
Financial Institutions on Green Hydrogen

July 07, 2023

9:00 am - 5:30 pm IST

Session: Costing and economics of Green Hydrogen and Green Ammonia

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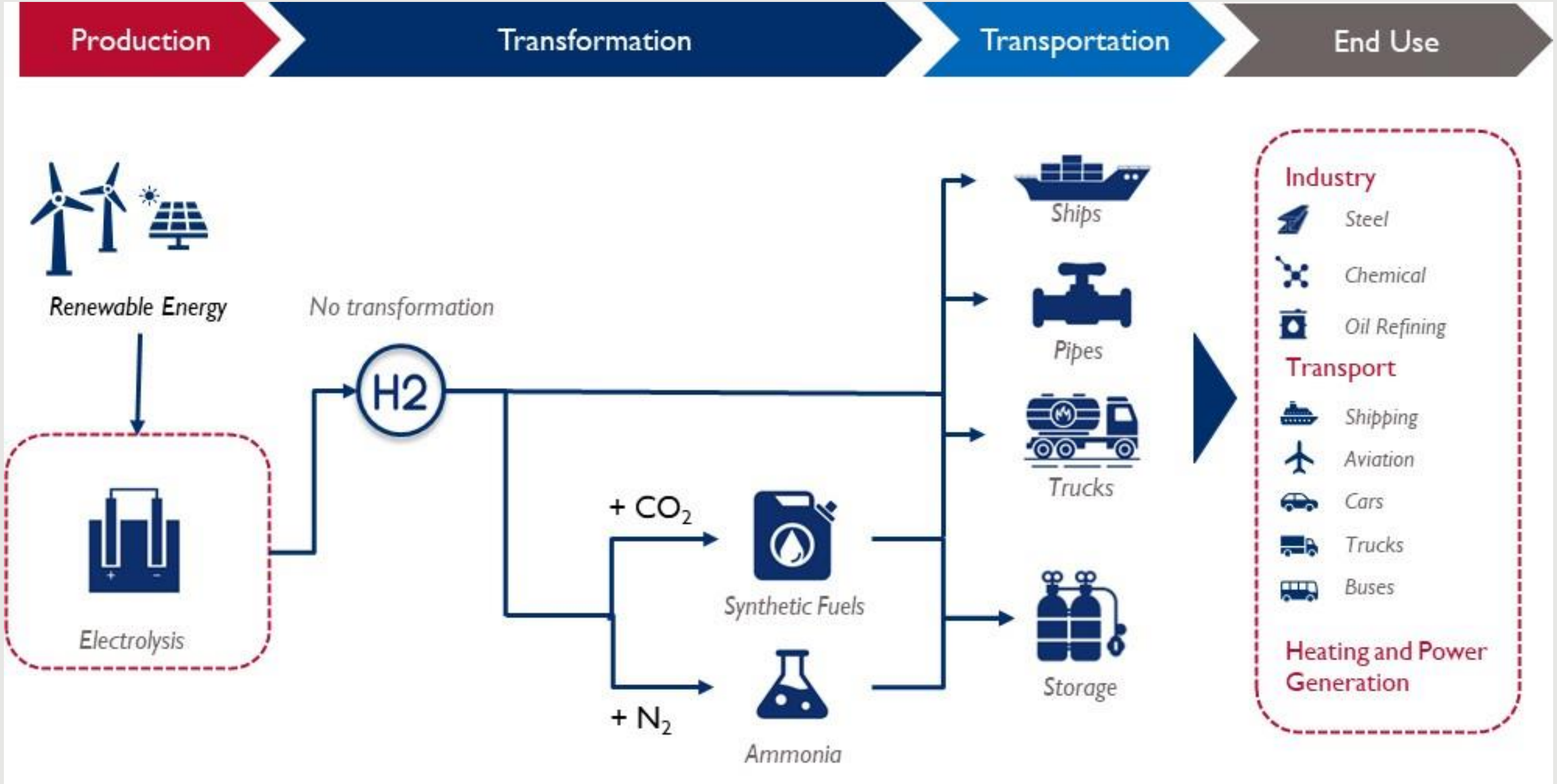
Agenda

- Components of Landed Cost of GH2
- RE Profiles & Impact on System Design
- Factors affecting Production Cost
  - Optimization & Trade-off
  - Electrolyser Technologies
- Chemical Conversion/Reconversion
- Storage : Physical & Chemical options
- Transportation & Distribution Cost
- Levelised Cost of Green Hydrogen

The Green Hydrogen Value Chain

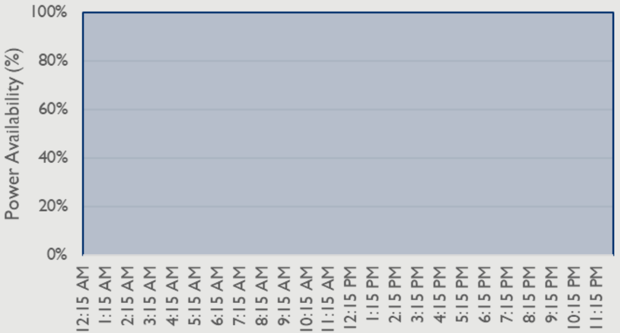


Landed Cost of Green Hydrogen

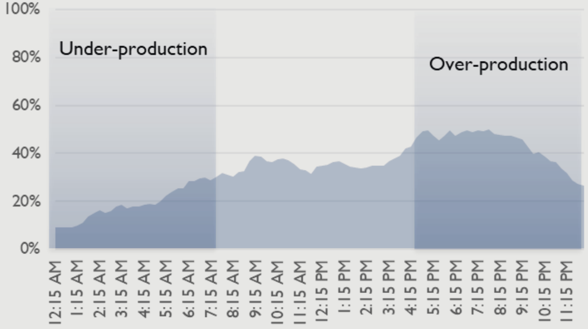
	Cost Component	Details/ Major Factors
01	**Renewable Energy Cost**	• Cost of Procurement/ Generation of Renewable Power Including Transmission Cost • Higher Cost for Higher Availability – Highest for Round-The-Clock (RTC) Availability
02	**Production Facility Cost**	• Optimization of Capital Cost vs Cost of Power Procurement – Equipment Sizing • Selection of Technology – Alkaline vs Proton Exchange Membrane
03	**Conversion / Reconversion Cost**	• Capital Cost for Conversion into Hydrogen Derivatives – Ammonia, Methanol & Hydrides • Energy Carrier – Loss of Energy when converted to derivative and reconverted back to H2
04	**Storage Cost**	• Small Storage to manage variability in H2 production due to variability in renewable energy • Large storage as buffer for lower production/demand at generation/consumption end resp.
05	**Transportation & Distribution**	• Mode of Transport/Distribution as per the distance and volumes involved • Major evaluation parameter for Export-oriented projects

RE Profiles & Impact on System Design

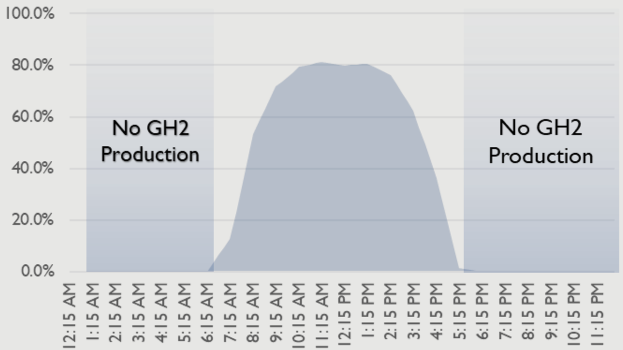
Constant Power: Hydro, Nuclear, Grid



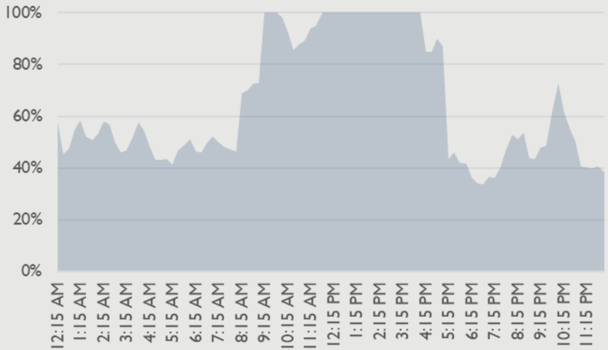
Wind Power - Medium



Solar Power



Wind + Solar Hybrid



Impact of RE Profile

Renewable Energy Variability

- RE power is highly variable, Reliance on co-located RE capacity a challenge
- Variability will lead to under-utilization of Electrolyser
- Discussion around RE Banking

Continuous Chemical Process

- Plants require continuous supply of feedstock
- Storage of Excess Production with electrolyzer overcapacity
- Employing Battery Storage but cost-prohibitive

Shutdown Costs

- Costs associated with shutdown and restart of electrolyzer

Regulatory/ Standards Issue

- Idle Plants require minimum base power – Grid Supply
- Risk of Hydrogen not certified as Green

Optimization Objective

Capital costs

$$C_{SYS} = C_{EZ} + C_{CP} + C_{H2STORAGE}$$

C_{EZ}:
- Minimization of size (MW)
- Maximization of utilization

INR/MW

C_{CP}:
- Minimization of size (MW)
- Maximization of utilization

INR/MW

$C_{H2STORAGE}$:
- Account for daily variations
- Account for seasonal variations
- Resiliency of system

INR/ton

Operating costs

Energy consumption per unit H2 produced

MWh / ton
kWh / kg

PEM, Alkaline, SOEC

50-55 (PEM)
55-60 (Alkaline)
37-40 (SOEC)

Electricity tariff

INR/kWh

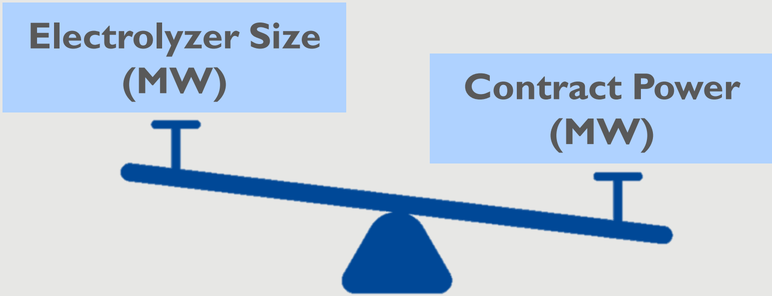
Fixed or Variable

Trade off between Electrolyzer size and Contract Power

- Contract Power size and electrolyzer size are inversely related

- Increasing the electrolyzer size (MW) leads to higher costs and lower utilization
  - Lower resiliency
  - Increased costs

- Increasing Availability & Size of contract power (MW)
  - Improved resiliency
  - Lower number of days of under-production
  - Increased cost, lower utilization



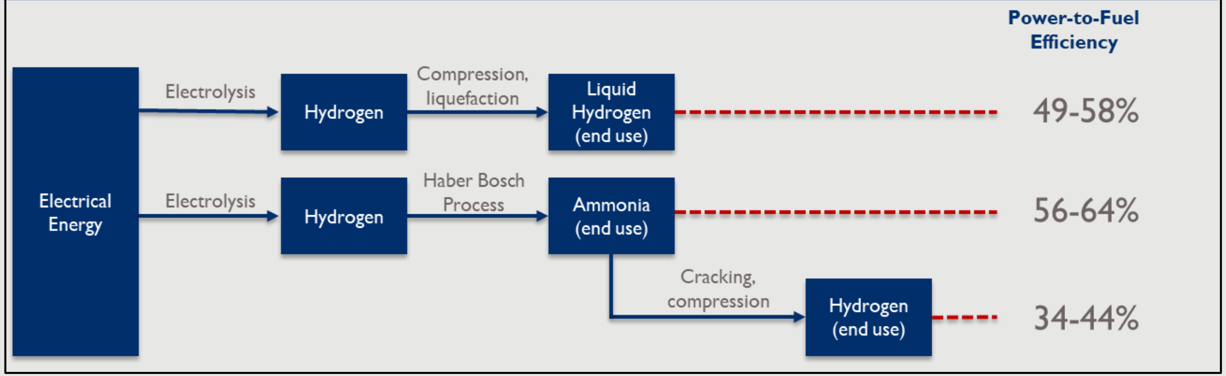
Comparison of Commercial Electrolyser Technologies

	Alkaline	PEM	Implications
Capital Costs	\$500 - \$1000/kW_{el}	\$700 - \$1400/kW_{el}	• Capex for PEM is higher due to usage of metals like platinum & titanium • PEM can have up to 20-30% lower opex requirements over the project life.
Response Time	Minutes	seconds	• Response Time to adjust output to adhere to changes in demand & conditions. • PEM has a better response time, suitable against variable RE supply
Efficiency	50– 78 (kWh / KgH_2)	50-83 (kWh / KgH_2)	• Efficiency indicates the ratio between the input energy and output energy. • Higher the efficiency, greater the conversion rate to H_2. • PEM electrolyzer generally have a slightly higher efficiency.
Lowest operating power (%)	10-15	5-10	PEM has a lower threshold for availability of power in comparison to its rated capacity, thus, more flexible to renewable variability
Stack Life (Hours)	60,000	80,000	PEM electrolyzers can run for a longer time period before requiring a stack replacement, which can cost upto 50-60% of electrolyzer's upfront capex.

Source: Oxford Institute for Energy Studies

Chemical Conversion and Reconversion

Energy Efficiency for end use cases: Direct H2 vs NH3 vs H2 from Intermediate NH3



Source: ACS Energy Letters

$$\text{Efficiency} = \frac{\text{Usable Chemical Energy in the end product}}{\text{Energy used in generating the product}}$$

To produce 1 kg of Ammonia, we need (14/17)= 0.824 kg of Nitrogen and (3/17)=0.176 kg of Hydrogen

Factors to be considered

Hydrogen properties

- Highly Flammable, safety issues
- Low volumetric energy density

End-use application

- Consumption as pure H2 or H2 derivative
- Chemical feedstock for Co-located Refineries/Steel Units
- Energy Carrier for Surface/ Maritime Transportation
- RE Transmission Costs vs GH2 Transport Costs

Storage/Transport of GH2

- For long distances & duration, NH3 is safe & economical
- Additional energy loss if NH3 to GH2 conversion required for end-use

Storage : Physical & Chemical options

Levelised Cost of Storage (LCOS) per kg	*Geological Storage*					*Chemical Storage*		
	Salt Caverns	Depleted gas fields	Rock Caverns	Pressurized containers	Liquid Hydrogen	Ammonia	LOHCs	Metal Hydrides
Volume	Large volumes	Large	Medium volumes	Small volumes	Small – medium volumes	Large volumes	Large volumes	Small volumes
Duration	Weeks - Months	Seasonal	Weeks - Months	Daily	Days - Weeks	Weeks - Months	Weeks - Months	Days - Weeks
LCOS (BM)	$0.23	$1.9	$0.71	$0.19	$4.57	$2.83	$4.5	Not evaluated
LCOS (Possible)	$0.11	$1.07	$0.231	$0.17	$0.95	$0.87	$1.86	Not evaluated
Technology readiness	TRL 9	TRL 2 - 3	TRL 2 - 3	TRL 9	TRL 7 - 9	TRL 9	TRL 7 - 9	TRL 7 - 9

● Gaseous Storage ● Gaseous Storage / Liquid Storage ● Liquid Storage ● Solid Storage

Source: UNECE, 2021

Capital Expenditure

- Specially constructed Vessels
- Require higher Strength than tanks for fossil Fuels

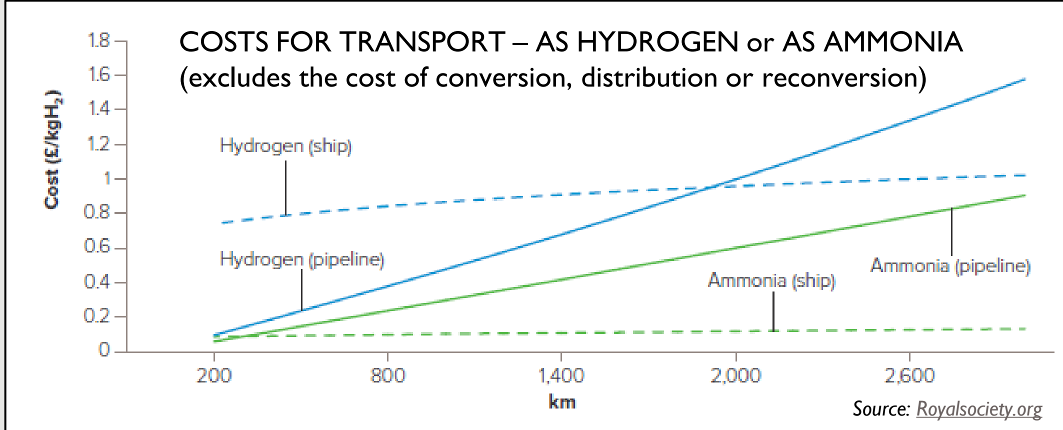
Operating Expenditure

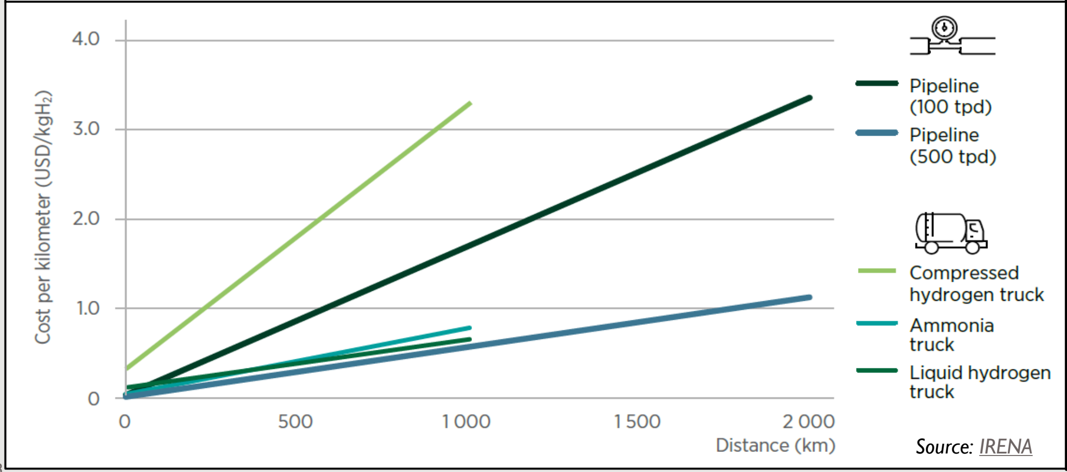
- Energy Penalty: Compression, Liquification, Refrigeration
- Maintain High Pressure & Low Temperature

Carrier Options

- Conversion and Reconversion Costs
- Both Capital Expenditure and Opex (Energy Losses)

Transportation & Distribution





Evaluating Transport Options

Transport Options

- Hydrogen vs Ammonia
- Maritime vs Pipeline
- Trucks vs Pipeline
- Pipeline capacity

Comparison

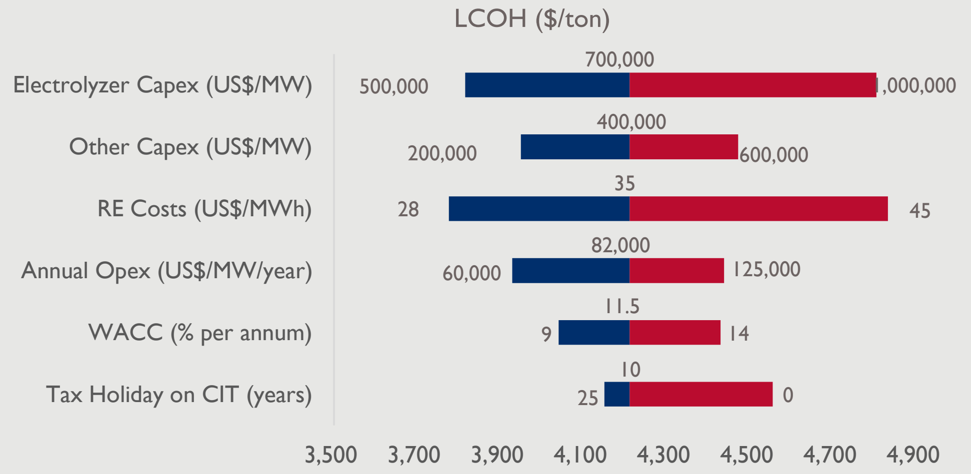
- Hydrogen transport in pipeline is cheaper than in ships up to a certain distance
- Through Pipeline: It is always cheaper to transport Hydrogen than Ammonia
- Through Ships: It is always cheaper to transport Ammonia than Hydrogen

Factors affecting the Storage Cost

- Throughput
- Capital Expenditure of various options
- Storage requirements & associated capex
- Opex – Compressor power, Ship/Truck Fuel
- Operation & Maintenance Expenses
- Presence of Existing Infra – Repurposed pipelines
- Conversion/Reconversion Efficiency (Not considered in the adjacent figures)

Investment Landscape Report for Green Hydrogen by SAREP

Green Hydrogen and Ammonia Production Costs in India



US$ 3.8-4.8 / kg

Estimated Levelized Cost of Green Hydrogen in India

Key Benchmarks and Assumptions

Electrolyzers (Stack and BOP)

CAPEX: USD 500-800k / MW (AEM);

USD 700-1200k / MW (PEM)

OPEX: 2-5% of EPC (ex stack replacement)

Ammonia Synloop

CAPEX: USD 120-200k / tpd

OPEX: 1-2.5% of EPC

Conversion Factors

- Energy to H2: 5.5 tons H2 / MWh energy
- Water to H2: 9-10 m3 / ton H2
- H2 to NH3: 5.5 tons NH3 / ton H2

Assumptions and Benchmarks based on internal analysis of data sourced from multiple primary and secondary sources and are indicative only.

Thank You

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