PEM & Alkaline Electrolyzers Bottom-up Manufacturing Cost Analysis

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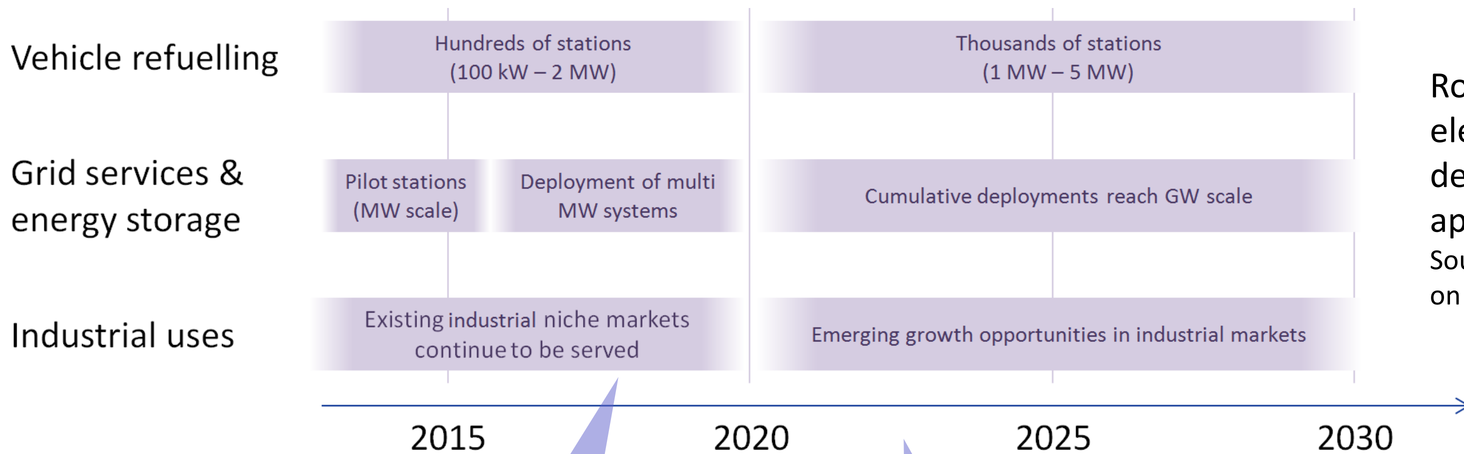
Water electrolysis could play a significant role in the future energy system …

Consolidated views on rollout potential



Roadmap for electrolyser deployment by application.
Source: 2014 FCH-JU study on water electrolysis

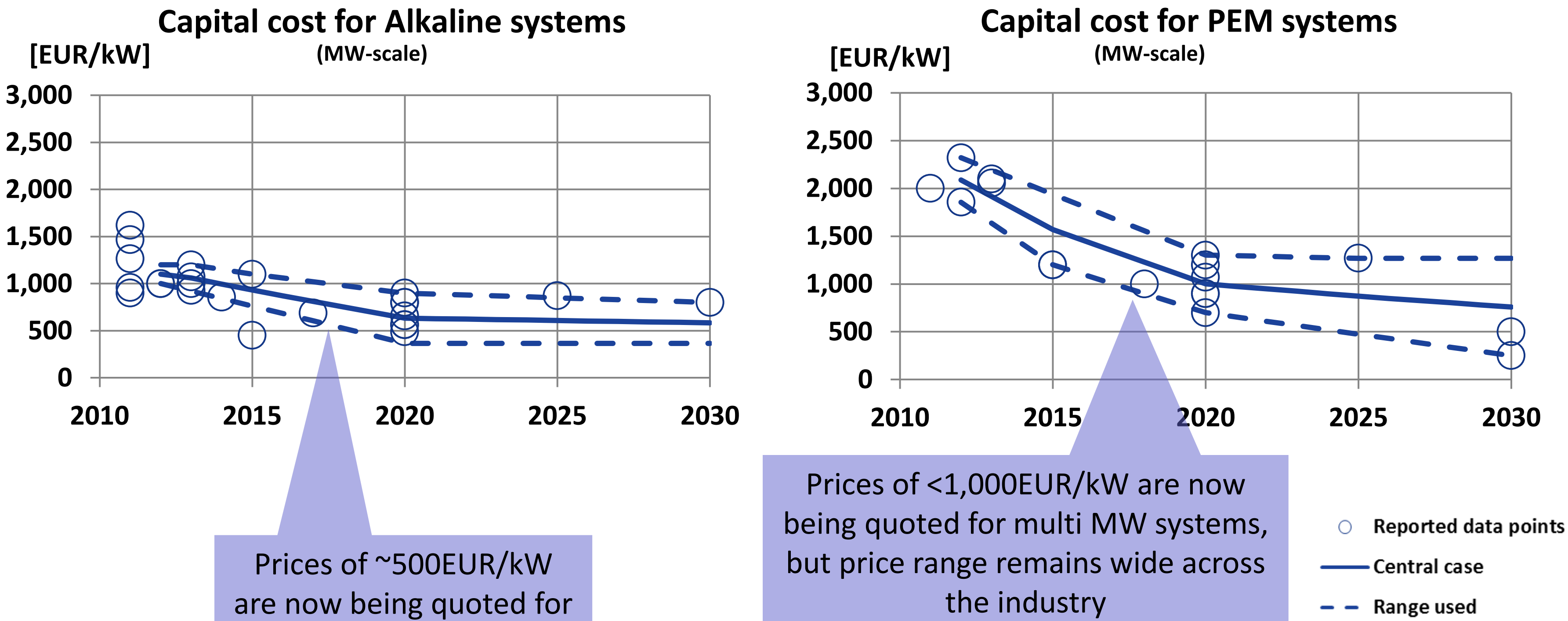
Multi MW demo projects in industry

Germany is considering to support roll-out of ~1GW of electrolysers in the 2020ies timeframe

A 2017 study commissioned by the FCHJU found that by 2025, an estimated cumulative electrolyser capacity of 2.8 GW could be installed in Europe

… if predicted cost reductions can be realised.

Expert 'predicted' cost reductions



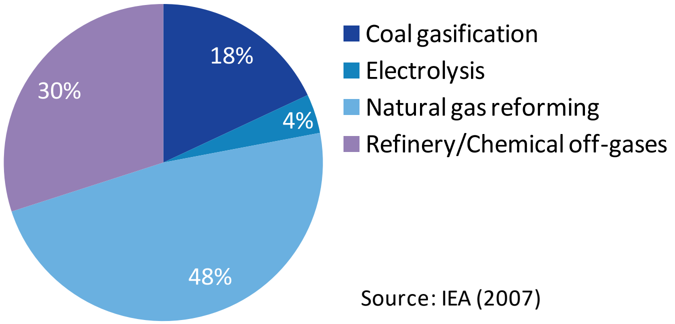
Prices of ~500EUR/kW are now being quoted for 50MW+ systems

Prices of <1,000EUR/kW are now being quoted for multi MW systems, but price range remains wide across the industry

Data source cost reduction expectations: 2014 FCH-JU study on water electrolysis

Today's electrolyser market is comparatively small, the industry landscape is highly fragmented and no single design dominates

- Perhaps 4% of global hydrogen supply is produced via electrolysis (incl. Chlor-Alkali)
- Larger (> 50 kW) water electrolysis systems are typically deployed for continuous operation. Examples are fertilisers and methanol production, fats & oils, float glass, …
- The industry is highly fragmented, with a few established players and many start-ups / new entrants – and cost reduction potential

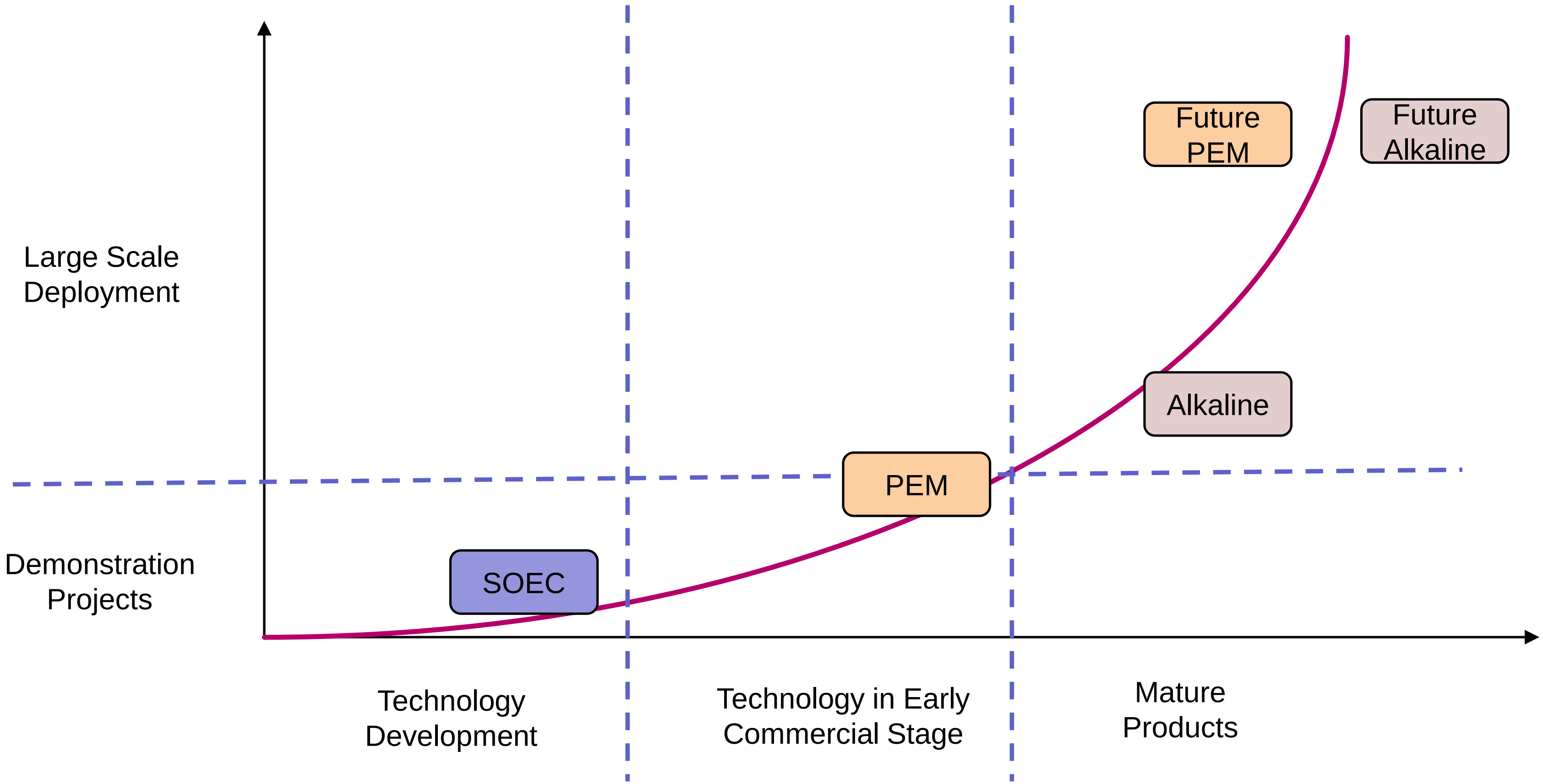


Source: IEA (2007)

Chemistry	Manufacturing Capacity (MW/year)	Revenue (million USD/year)
Alkaline	~300 MW	~100
PEM	~ 50 MW	~50
Total	~350 MW	~150

Rough estimates – revenue varies year-on-year dependent on individual projects. Current manufacturing capacities are underutilised, but could be scaled up quickly if demand rises.

We work with clients with various electrolysis technologies from the technology development stage to the large scale (GW) deployment.



This approach has been used successfully for estimating the cost of various technologies for commercial clients and the DOE.

Technology Assessment

- Literature research
- Definition of system and component diagrams
- Size components
- Develop bill-of-materials (BOM)

Manufacturing Cost Model

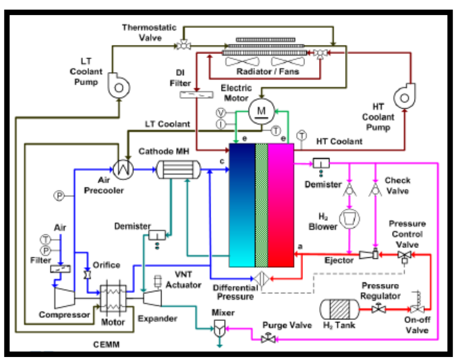
- Define system value chain
- Quote off-shelve parts and materials
- Select materials
- Develop processes
- Assembly bottom-up cost model
- Develop baseline costs

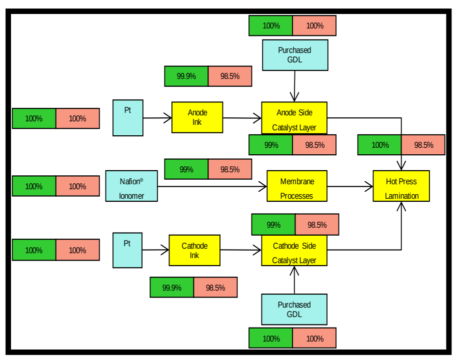
Scenario Analyses

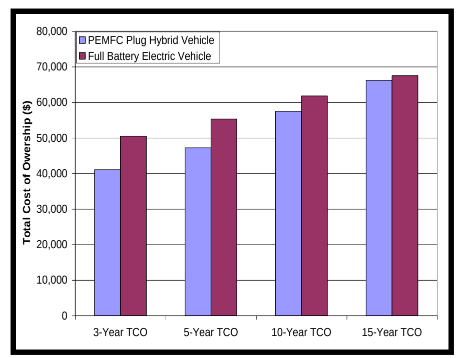
- Technology scenarios
- Sensitivity analysis
- Economies of Scale
- Supply chain & manufacturing system optimization
- Life cycle cost analysis

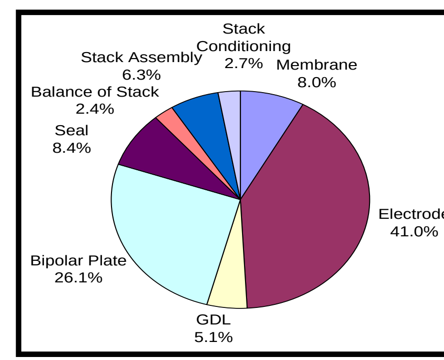
Verification & Validation

- Cost model internal verification reviews
- Discussion with technical developers
- Presentations to project and industrial partners
- Audition by independent reviewers



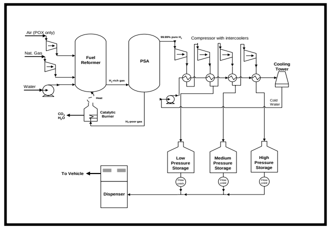






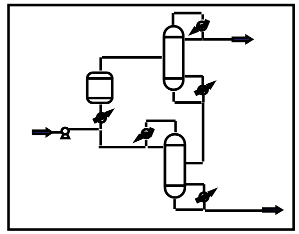
Combining performance and cost model will easily generate cost results, even when varying the design inputs.

Conceptual Design



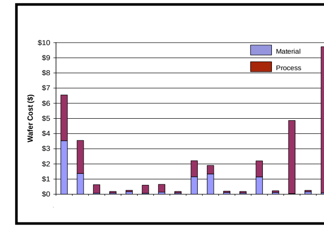
- System layout and equipment requirements

Process Simulation



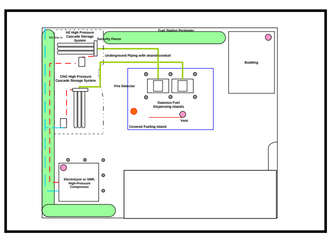
- Energy requirements
- Equipment size/ specs

Process Cost Calcs



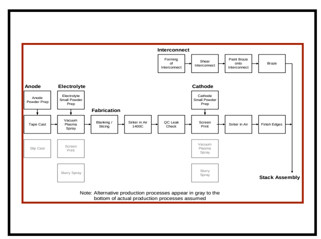
- Process cost
- Material cost

Site Plans



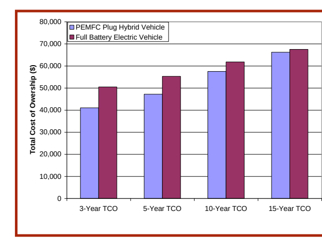
- Safety equipment, site prep, land costs

Capital Cost Estimates



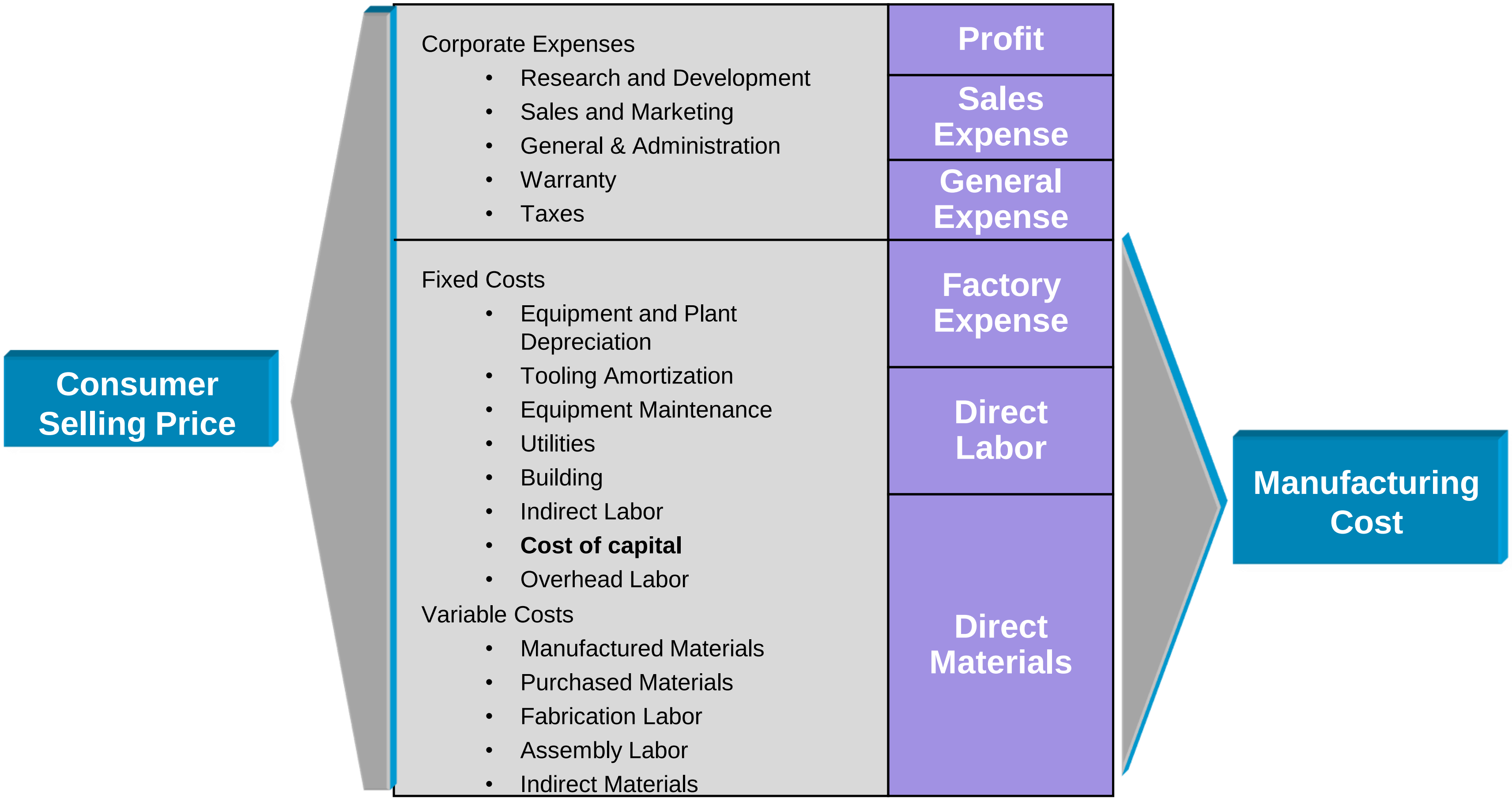
- High and low volume equipment costs

Product Costs



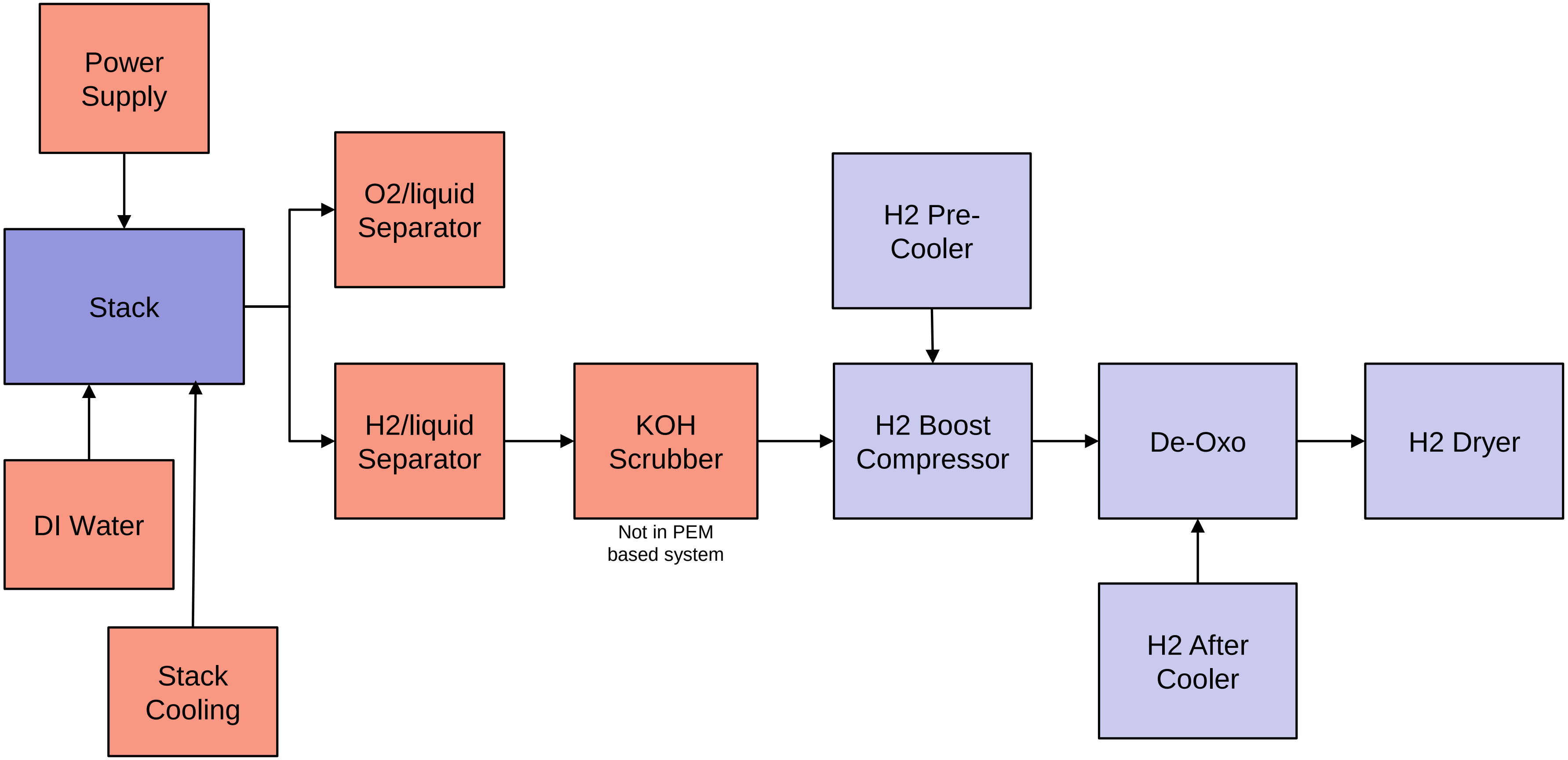
- Product cost (capital, O&M, etc.)

Austin Power Engineering’s manufacturing cost models can be used to determine a fully loaded selling price to consumers at high or low volumes.



We assume 100% financing with an annual discount rate of 10%, a 10-year equipment life, a 25-year building life, and three months working capital.

The hydrogen electrolysis system design is primarily driven by the output hydrogen flow rate, purity, and pressure requirements.



Generic Hydrogen Electrolysis Plant Major Components

Different Alkaline system and stack designs can be tested in in different scenarios

Alkaline	Unit	Current	Future
System size	MW	<120 MW	GW
Stack size	Nm3/h	0.5 ~1,500	10,000
Stack power	MW	~6	~50
System pressure	Barg	0.02 ~ 30	0.02 ~ 30
System H2 purity	%	99.999%	99.999%
Active cell area	m^2	~ 3	~ 3
Cell voltage	V	1.8	1.8
Current density	A/cm^2	0.2	0.6 ~ 0.8
Membrane material		Zirfon type	Zirfon type
Anode / cathode material		Ni, NiAl,	Ni, NiAl, NiMoAl, etc
Cell frame material		Carbon steel with coating	Carbon steel with coating / Ni
Bipolar plate material		Ni coated carbon steel	Ni coated carbon steel / Ni

In Alkaline stacks, higher current densities are key to reducing costs, but all options are subject to fundamental limits.

Cost contributors	Pathways to cost reduction	Identified limits
Membrane and electrodes	Increase current density and reduce materials use through innovative component design and advanced electrode materials	Industry reports 0.6 to 0.8 A/cm^2 as a long term target. Limitation is acceptable efficiency at high currents. (Current density today typically: 0.2 A/cm^2)
Cell frame	Reduce material use through large cell concepts with a better ratio between active area and frame area	Mechanical stability of cell components, depending on stack pressure level
Cell frame material	Replace by (cheaper) injection moulded thermal plastic, though mechanical stability at pressure may be limited	Mechanical stability of thermal plastic

Different PEM system and stack characteristics for current and future designs can be tested in in different scenarios

PEM	Unit	Current	Future
System size	MW	<5 MW	GW
Stack size	kW	<5MW	>10MW
System Pressure	Barg	10~30	10 ~30
H2 Purity	%	99.999%	99.999%
Active cell area	cm^2	~ 0.2	> 1
Current density	A/cm^2	1 ~2	> 2
Membrane material		Nafion 200µm	Nafion 200µm
Catalyst		Ir, Pt	Ir, Pt
Catalyst loading	mg/cm^2	~ 5	< 1
Conductive porous layer		Ti foam	Ti foam
Screen pack plates		Ti mesh	Function replaced by flow field plates
Bipolar plate		Ti foil	Ti foil; or SS316 with Ti coating
Cell frame material		Ti or polymer based	Polymer based with metal inlay

PEM cost reduction opportunities are strongly related to the reduced use of high price materials, though other components contribute.

Cost contributors	Pathways to cost reduction	Identified limits
Components made of titanium (cell frame, screen pack, porous plate)	Reduce use of titanium in components. Make bi-polar plates of steel plus titanium coating instead of full titanium. Increase current density.	Titanium (high material and processing cost) expected to remain as the material of choice for 'acidic' electrolysers
Electrode catalysts	Material changes using advanced catalyst support structures, mixed metal oxides and nano-structured catalysts.	Precious metal cost and catalyst activity for acceptable efficiency. Goals are: - 0.3mg/cm² Iridium - Anode - 0.1mg/cm² Pt - Cathode
Supplied membrane	High volume orders and/or dedicated production	Costly fluorine chemistry in Nafion production

At the GW scale electrolysis plant, centralized BOP system might lead to a lower system cost.

Cost contributors	Pathways to cost reduction
Power supply	100MW+ electrolyzers mean lower engineering cost for each individual rectifier. ~20 MW rectifier units are common in other industries (aluminium smelters, chlor-alkali electrolysis)
Gas/liquid separator / KOH Scrubber	Integrated KOH scrubber with gas/liquid separator will reduce the overall cost
H2 booster compressor	Pressurized stack design will eliminate the H2 booster compressor
Deoxo unit	Select low temperature catalyst will help reduce the vessel material cost as well as reduce the H2 gas cooling unit cost. Differential pressure PEM design can eliminate need for de-oxo unit
H2 dryer	Thermal swing adsorption dryer will have higher H2 gas output (not consume H2 in regeneration step) which is more important in the large scale applications

Conclusions

‘Expert-predicted’ cost reductions seem plausible and could make electrolysis much more competitive

- Alkaline system and PEM system have broadly similar system costs at the high capacity applications
  - Alkaline cost reduction is quite sensitive to volume production (reduce the process costs) and increased current density
  - PEM routes to cost reduction include volume production, system scale-up, reduction of expensive materials, and increased current density
- PEM could ultimately be lower cost than Alkaline, but PEM is less mature so future cost is sensitive to a number of uncertain technology development assumptions
- BoP costs (mainly power supply) start to dominate system cost at high production volumes, when other cost components have been compressed already
- Other technology may be interesting to analyse, for example SOEC

Thank You!

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