Cost Analysis: Near-Term and Future Projections of Installation Costs for Low-Temperature Water Electrolysis

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Strategic Analysis Inc.

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Strategic Analysis Company Background

- Program Management
- Scientific & Technical Consulting
- Conference Planning
- Executive Conference Center
- Information Technology
- Graphics and Multimedia
- National Security and Intelligence
- Systems Engineering
- Policy Research and Studies

- Strategic Analysis Inc.
  - ~180-person consulting firm located in Washington DC area
  - Serving Federal Government and Commercial Clients
  - **Energy Analysis Services Division**
    - Expertise in Techno-Economic Analysis (TEA) of emerging energy systems
      - Specializing in fuel cells, H_2 production/storage, DFMA cost analysis, LCA, TCO, market studies, technical due diligence, and product/technology benchmarking

Overview

- SA developed detailed bottom-up project cost model for low temperature electrolyzers including direct costs and overhead construction costs
  - Cost models for following electrolyzer plants:
    - Alkaline Low Pressure (LP)
    - Alkaline High Pressure (HP)
    - Proton Exchange Membrane (PEM)
    - Anion Exchange Membrane (AEM) not included in this presentation
    - Solid Oxide Electrolysis (SOEC) not included in this presentation
  - Stack costs derived from Strategic Analysis bottom-up DFMA* analysis
  - Levelized cost of hydrogen (LCOH) is calculated for these cases but not the focus of this study

- **Focus of this presentation is on installation of electrolyzers**
  - Includes installation of equipment and piping, and indirect costs
  - Stack costs and LCOH deemphasized in this talk

*Design for Manufacture and Assembly (DFMA®)

Techno-Economic Analysis (TEA) Methodology

Techno-Economic Analysis (TEA) is a tool to evaluate an entire system; evaluating the interactions between technical performance and cost.

Create System Model

-Process Flow Diagram

-Identify key process steps and variables

→

Conduct Mass/Energy Balance

-Identify product feed, and product output

→

Identify Key Processes and Key Equip. Info.

-Unit capacity volume production

-Process Equipment pricing

→

Estimate System Capital Cost

-Use DFMA®* to evaluate cost for materials, manufact., & labor for key components

→

Evaluate Cost of H_2

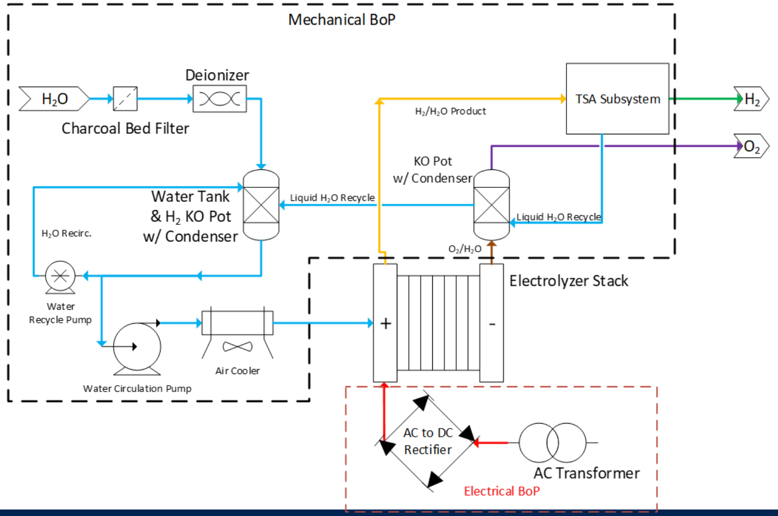
-Input capital cost, operating cost, efficiency, etc. into H2 Analysis (H2A) tool

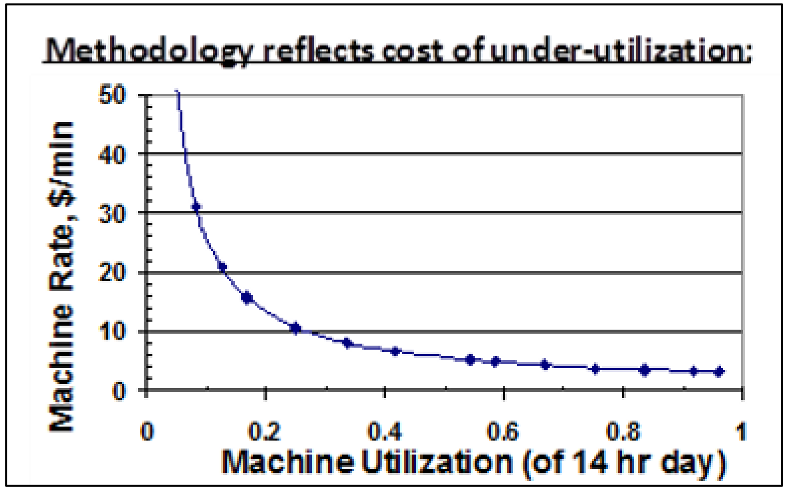
→

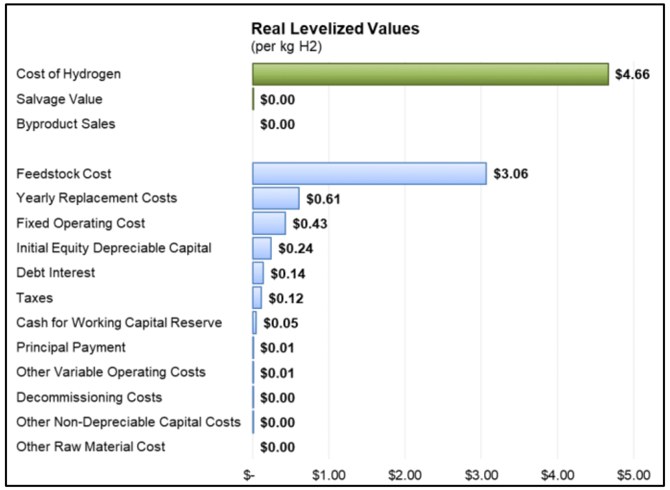
Post Analysis Process

-Review results

-Conduct sensitivity analysis







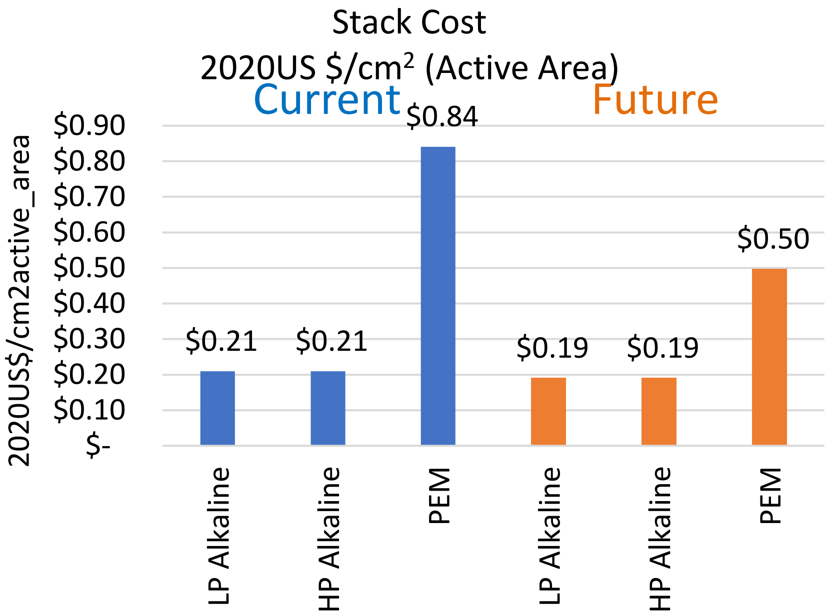
*Design for Manufacture and Assembly (DFMA®)

Electrolysis Process Overview

Electrolyzer Design & Performance Comparison

(Optimized operating points shown in table.)

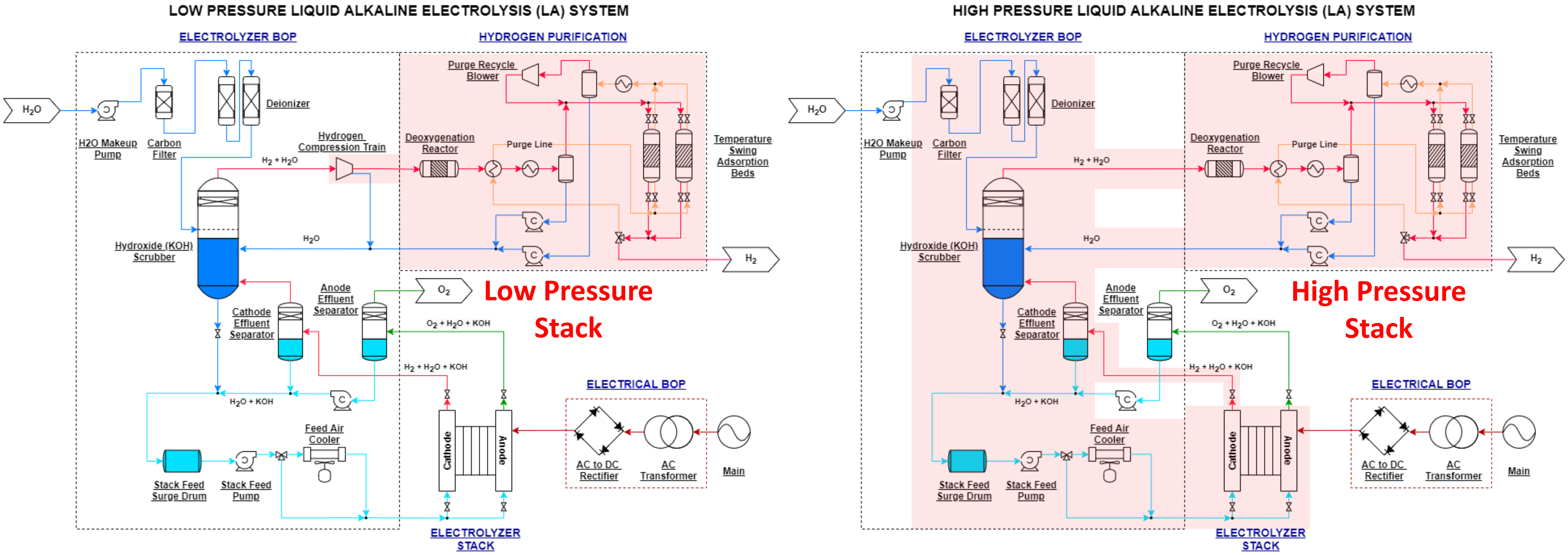
		LP Alkaline		HP Alkaline		PEM	
Parameter	**Units**	**Current**	**Future**	**Current**	**Future**	**Current**	**Future**
Performance							
Current Density (BOL Rated)	**A/cm²**	*0.7*	*1.0*	*0.7*	*1.0*	*2.0*	*3.0*
Voltage (BOL Rated)	**V/cell**	*2.0*	*1.7*	*2.0*	*1.7*	*1.9*	*1.8*
Current Density (BOL, optimal)	**A/cm²**	0.30	0.53	0.31	0.53	1.48	1.56
Voltage (BOL, optimal)	**V/cell**	1.70	1.62	1.71	1.62	1.82	1.71
Current Density (EOL, optimal)	**A/cm²**	0.30	0.53	0.31	0.53	1.48	1.56
Voltage (EOL, optimal)	**V/cell**	1.82	1.69	1.83	1.69	1.88	1.75
Degradation Rate	**mV/khrs**	3.20	1.40	3.20	1.40	1.50	1.00
Stack Durability	**years**	10	10	10	10	7	10
Specifications							
Cell Active Area	**cm²/cell**	10,000	10,000	10,000	10,000	2,980	2,980
Nominal Pressure (Anode/Cathode)	**bar / bar**	1 / 1	1 / 1	30 / 30	30 / 30	30 / 30	30 / 30
Operating Temperature	**°C**	90	90	90	90	90	90
KOH Concentration	**M**	7	7	7	7	-	-
Nominal Stack							
EOL Power (DC)	**MW**	4.2	4.7	4.2	4.7	4.3	4.8
Hydrogen Production	**kgH_2/day**	2,083	2,500	2,083	2,500	2,083	2,500
# of cells	**#**	765	520	741	520	521	597



- Stack Cost from SA DFMA analysis
- Assumes 1 GW/year manufacturing rate
- Includes 30% manufacturing markup
- ~2020US $163,969 / kg for Ir
- ~2020US $49,191 / kg for Pt

Process Diagram
LP Alkaline vs HP Alkaline Electrolysis

Red shading denotes High Pressure (~30 bar)

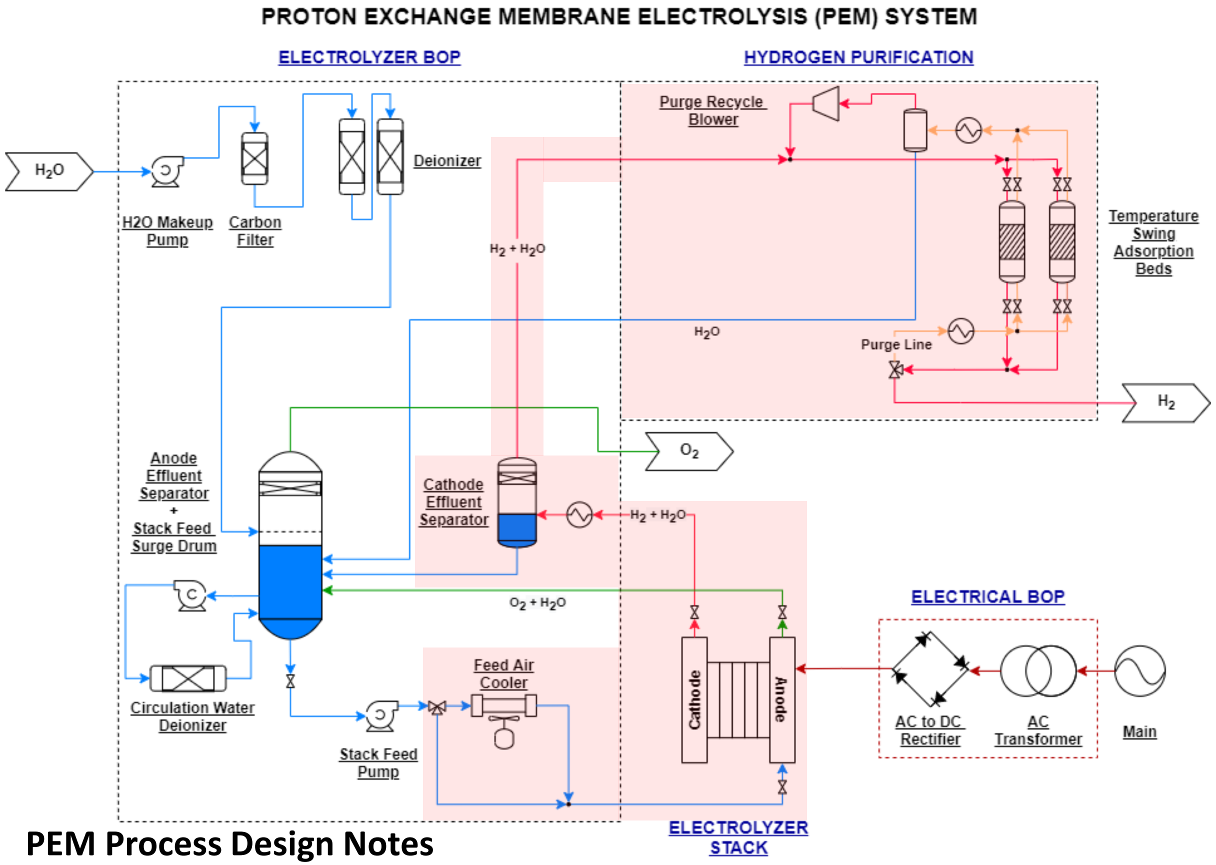


Alkaline Process Design Notes

- KOH solution split 50-50 between cathode and anode
- Low Pressure Stack: Both Cathode and Anode are assumed to be near-atmospheric
- High Pressure Stack: Both Cathode and Anode are assumed to be pressurized. Anode effluent separator is depressurized to release oxygen from solution

Process Diagram
PEM Electrolysis

Red shading denotes
High Pressure
(~30 bar)



PEM Process Design Notes

- DI water only enters anode and diffuses to cathode. Cathode effluent separator only contains trace amounts of water
- Both Cathode and Anode are assumed to be pressurized.
  - Many commercial PEM stacks only pressurize the cathode. Hydrogen concentration in anode managed by sufficient sweeping by liquid flow rate

Project Technical Parameters

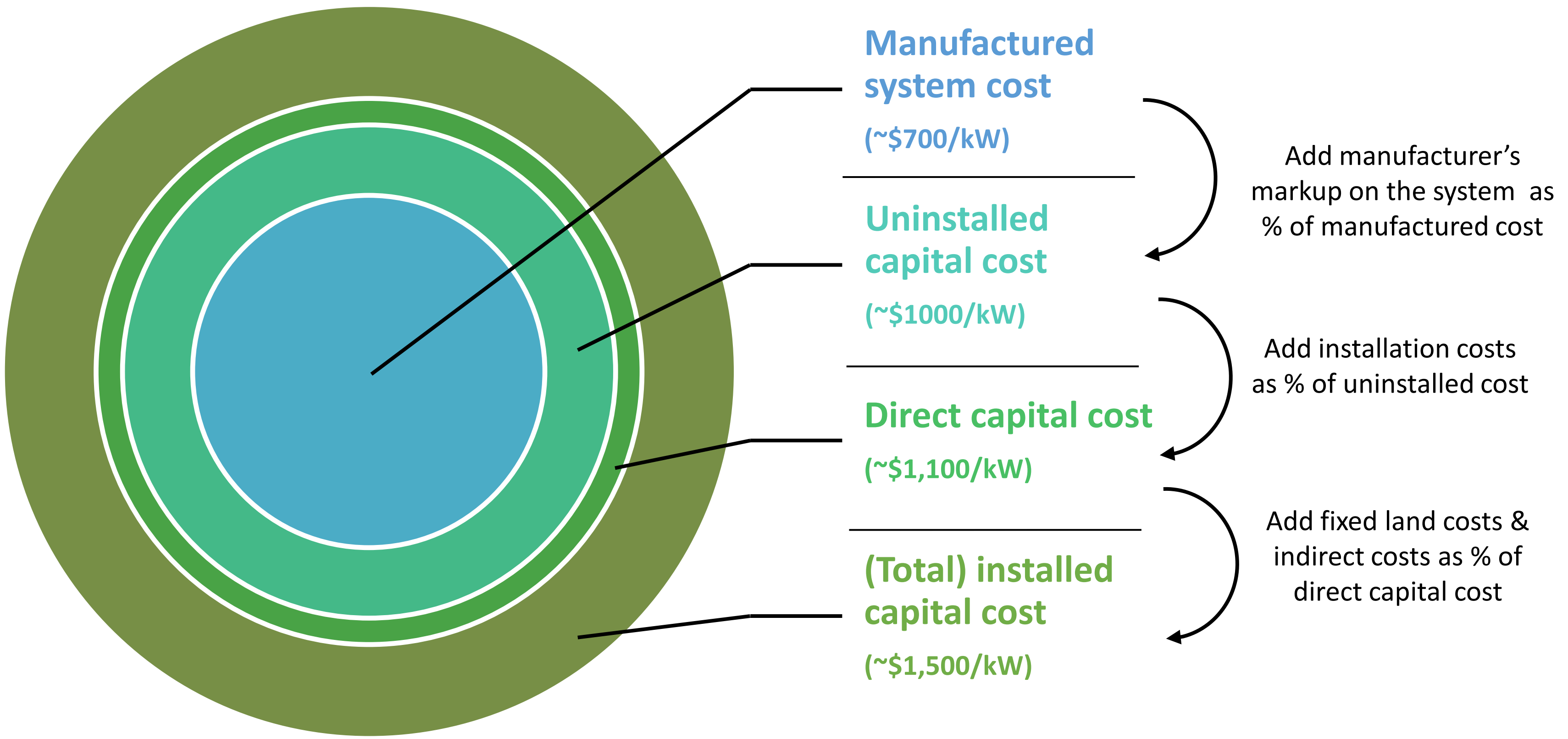
		LP Alkaline		HP Alkaline		PEM	
Parameter	**Units**	**Current**	**Future**	**Current**	**Future**	**Current**	**Future**
Plant Specifications							
Plant Capacity	kg H_2/day	50,000	50,000	50,000	50,000	50,000	50,000
Electrolyzer Power (System, BOL Rated)	MW	122	102	119	98	116	106
Number of Modules per Plant	#	4	2	4	2	4	2
Total Electrical Usage (BOL Rated)	kWh/kg	58.6	49.0	57.0	47.0	55.8	51.0
Stack Electrical Usage (BOL Rated)	kWh/kg	53.2	45.2	53.2	45.2	50.5	47.8
Total Electrical Usage (Average, optimal)	kWh/kg	52.2	47.8	50.8	45.8	54.5	49.1
Stack Electrical Usage (BOL, optimal)	kWh/kg	45.2	43.0	45.4	43.0	48.3	45.4
Stack Electrical Usage (EOL, optimal)	kWh/kg	48.3	44.9	48.7	44.8	50.0	46.6
BOP Electrical Usage	kWh/kg	5.4	3.8	3.8	1.9	5.3	3.2
Output Pressure	bar	30	30	30	30	30	30
Hydrogen Purity	%	99.99	99.99	99.99	99.99	99.99	99.99

Project balance of plant equipment sized using EOL conditions, during which the most heat is generated
ΔT across stacks limited to 10 °C

CAPEX and OPEX co-optimization results in Alkaline stacks being more efficient than PEM stacks at the selected operating points.

Cost Model

Cost Scope



Costs to the electrolyzer owner/operator:

- **Uninstalled capital cost** = Manufactured cost + manufacturer's mark-up
- **Direct capital cost** = Uninstalled capital cost + installation (transporting, placing, connecting, commissioning)
- **Total installed capital (TIC) cost** = Direct capital cost + indirect costs (construction, engineering/design, licensing, permitting, land)

Mechanical and Electrical BOP Component Cost Overview

- Balance of Plant (BOP) can be broken down into two sub-components:
  - **Mechanical BOP:**
    - Consists of **equipment, piping, valves, and instrumentation**
    - Cost basis
      - **Major BOP Equipment**: Aspen-generated cost estimates based on technical specifications
      - **Piping**: Aspen-generated cost estimates based on sizing and materials specifications
      - **Valves**: Published cost curves from Plant Design and Economics for Chemical Engineers, Fifth Edition, 2003
      - **Instrumentation**: Published quotes from Plant Design and Economics for Chemical Engineers, Fifth Edition, 2003
        - Includes temperature, pressure, flow, and level indicators
  - **Electrical BOP:**
    - Consists of **rectifier and housing; electrical wiring; and electrical infrastructure**
    - Cost basis
      - **Rectifier**: Quote from Rectifier vendor
      - **Transformer**: Estimate from 2013 engineering study
      - **Electrical Wiring**: Estimated using Craftsman methodology
      - **Electrical Infrastructure**: Estimated from publicly available price estimates

Scope of Supply

Conventional plant installation

All plant components except stacks procured by EPC

Electricity Feed Utilities Plant Control System
Water Inlet and Purification Balance of Stack and Water Circulation Hydrogen Compression (LP Alkaline) Hydrogen Purification
Rectifiers / Transformers
Stack | Stack | Stack | Stack

SA model assumes conventional plant approach without stacks modularized into skids

EPC Supplied

Electrol. OEM Supplied

Common Electrolyzer Scope of Supply

Skid modules for stacks, balance of stack

Rectifier often supplied by electrolyzer supplier

Additional plant components procured by EPC

Electricity Feed Utilities Plant Control System	
Water Inlet and Purification Hydrogen Compression (LP Alkaline) Hydrogen Purification	
Skid Module: Stack(s) Balance of Stack Rectifier / Transformer	Skid Module: Stack(s) Balance of Stack Rectifier / Transformer

Many electrolyzer suppliers preferentially offer stacks pre-packaged with the "balance of stack", which includes knock-out drums, recirculation pump, heat exchangers, and associated piping

Electrolyzer suppliers commonly only report cost numbers for <u>their scope of supply</u>

Estimation of Uninstalled Costs

(Cost as delivered to the field)

Cost Category	Scope	Estimation Method for SA Model
Mechanical BOP		
Equipment	Uninstalled equipment	Aspen-generated cost estimates based on technical specifications
Piping	Bare piping	Aspen-generated cost estimates based on sizing and materials specifications
Valves	Uninstalled costs	Published cost curves from Plant Design and Economics for Chemical Engineers
Instrumentation	Uninstalled costs	Published quotes from Plant Design and Economics for Chemical Engineers
Electrical BOP		
Rectifier	Uninstalled equipment	Quote from Rectifier vendor
Transformer	Delivered module	Estimate from 2013 engineering study
Electrical Wiring	Bare costs of wiring, conduits, and miscellaneous components	Estimated using Craftsman methodology
Electrical Infrastructure	Installed distribution lines to edge of production site	Estimated from publicly available price estimates
Stack	Uninstalled costs	Bottom-up SA cost estimate (Assumes stack is delivered and installed on site.)

For large scale projects, most electrolyzer companies supply stacks bundled with the “balance of stack”, which includes knock-out drums, recirculation pump, heat exchangers, and associated piping

Estimation of Installation Costs

Cost Category	Scope	Estimation Method for SA Model
Mechanical BOP		
Equipment	Installation cost	Aspen-generated cost estimates based on technical specifications
Piping	Installation and insulation costs	Estimated installation cost of pipe racks, field installation, equipment, engineering, contractor's expenses and insulation based on historic data[1] -Primarily a function of pipe diameter and pipe material
Valves	-	Assumed to be included in piping installation
Instrumentation	-	Assumed to be included in piping installation
Electrical BOP		
Rectifier	Installation cost	5% of uninstalled rectifier cost
Transformer	Installation of wiring costs	Estimated using Craftsman methodology[2] -Based on labor time and rate
Electrical Wiring	Installation costs of wiring, conduits, and miscellaneous components	Estimated using Craftsman methodology[2] -Based on labor time and rate
Electrical Infrastructure	-	None assumed in scope of project
Stack	Installation cost	Bottom-up estimate based on 1 day installation time per stack with 4 FTE's, shipping, and equipment rental

[1] Ulrich, G. D.; Vasudevan, P. T. Short-Cut Piping Costs: This Method Saves Precious Time in Preparing Estimates for Pre-Design and Other Approximated Analyses. Chemical Engineering 2006, 113 (3), 44+.
[2] Tyler, M. C. (2019). 2020 National Electrical Estimator. Craftsman Book Company.

Estimation of Indirect Costs

Cost Category	Scope	Estimation Method for SA Model
Site Preparation	Site Clearing, Site Grading, Site Foundation, Asphalting, Buildings, Cost Contingency	Bottom-up estimate using Craftsman methodology including material cost, equipment cost, labor time, and labor rate
Construction Overhead		
Engineering and Design	EPC activities	Baseline estimate of \$7.8M for a 100 MW Facility with 0.25 scaling factor[1] -Only includes indirect costs including engineering and fees. Field activities bookkept under installation costs
Up-Front Permitting Costs	Legal and permitting costs	Baseline estimate of \$4.3M for a 100 MW Facility with 0.2 scaling factor[2]
Project Contingency	-	15% of direct costs
Land	Total land usage	Based on bottom-up module and plant sizing: \$50,000/acre

[1] Holst, M. Aschbrenner, S. Smolinka, T. Voglstter, C. and Grimm, G. (2021). ”Cost Forecast for Low Temperature Electrolysis – Technology Driven Bottom-up Prognosis for PEM and Alkaline Water Electrolysis Systems,“ Fraunhofer Institute for Solar Energy Systems ISE, October.

[2] Based on 2022 DOE H2A case for a ~100 MW SOEC facility

Typical Installation Cost Ranges

Total Installed Capital Costs

Direct Costs

	Fluid Process Plant Grass-Roots		PEM Current Central, 50 MTD (~120MW)		PEM Current Distributed, 50 MTD (~120MW)	
Source	**(Peters et al. 2003)**		**H2A 2018**		**H2A 2018**	
Cost Category	**% of Purchased Equipment Cost**	**% of Total Installed Capital Cost**	**% of Purchased Equipment Cost**	**% of Total Installed Capital Cost**	**% of Purchased Equipment Cost**	**% of Total Installed Capital Cost**
Uninstalled Costs						
Purchased Equipment	-	15-40		62		63
Installation Costs						
Mechanical BOP						
Equipment installation	30-70	6-14	14	9	17	10
Piping	40-50 (Labor) 15-25 (Insulation)	4-17				
Instrumentation (Including valves)	26	2-12				
Electrical BOP	15-30	2-10				
Indirect Costs						
Site Preparation		12-53	2	1.4	18.9	14
Construction Overhead						
Engineering and Design		10-33	8	6	1	1
Up-Front Permitting Costs		1-3	15	11	1	1
Project Contingency		5-15	15	11	15	11
Land		1-2		0.2		0.2
TIC / Direct Cost Ratio		**~2x**		**~1.4x**		**~1.4x**

TIC: Total installed capital cost

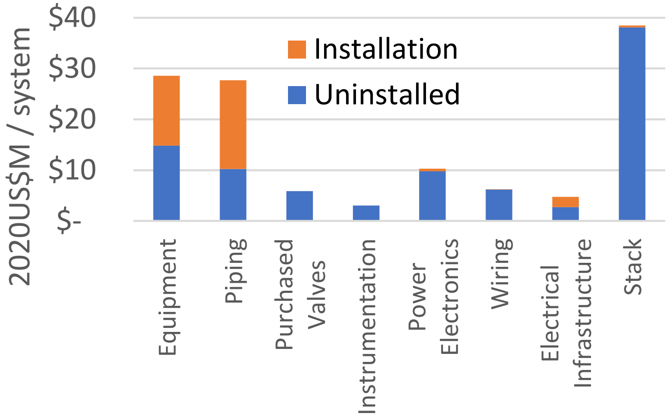
- **1.4x to 2x TIC to Direct Cost ratio** is a reasonable range for a project
- In general,
  - First-of-a-kind (FOAK) systems might be closer to 2x
  - Nth-of-a-kind (NOAK) systems might be closer to 1.4x

Peters, Timmerhaus, and West. Plant Design and Economics for Chemical Engineers, Fifth Edition, 2003

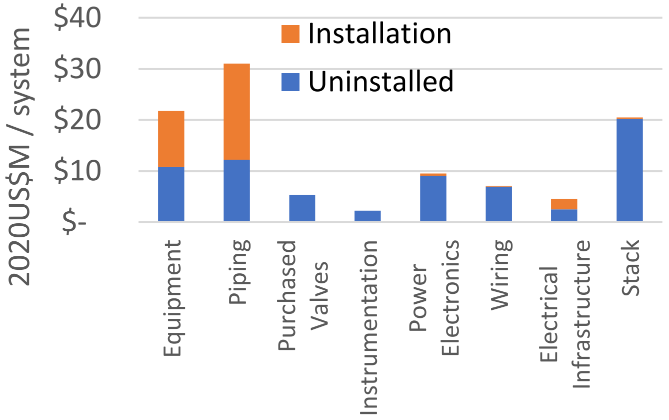
SA Model – Direct Costs and Total Installed Capital Costs

Low Pressure Alkaline

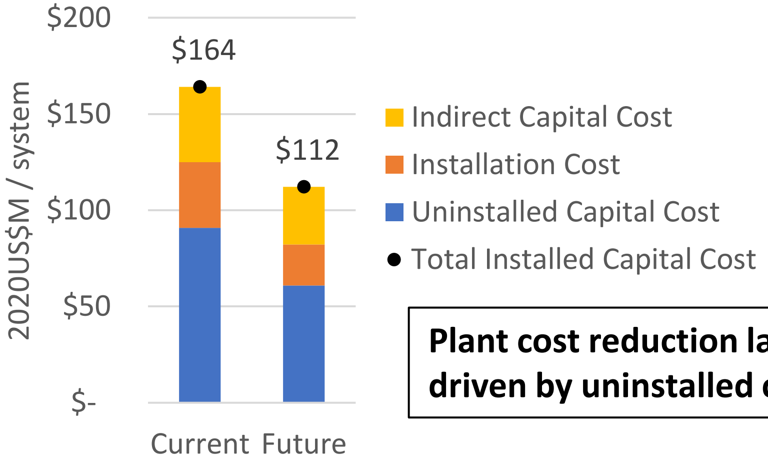
Direct Costs
Current LP Alkaline
50 MTD Plant, 4 modules



Direct Costs
Future LP Alkaline
50 MTD Plant, 2 modules



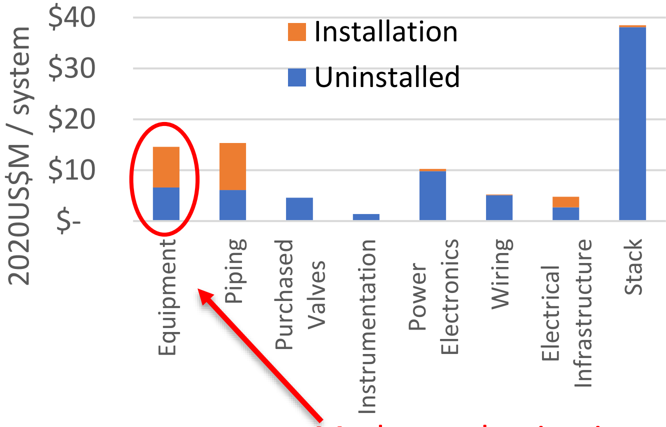
Total Installed Capital Cost
LP Alkaline - 50 MTD Plant



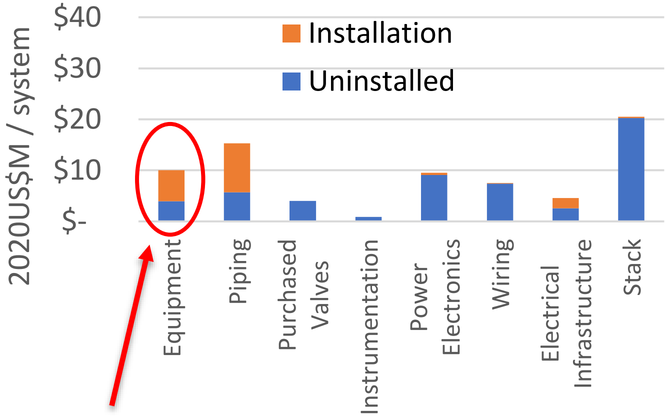
Plant cost reduction largely driven by uninstalled capital cost

High Pressure Alkaline

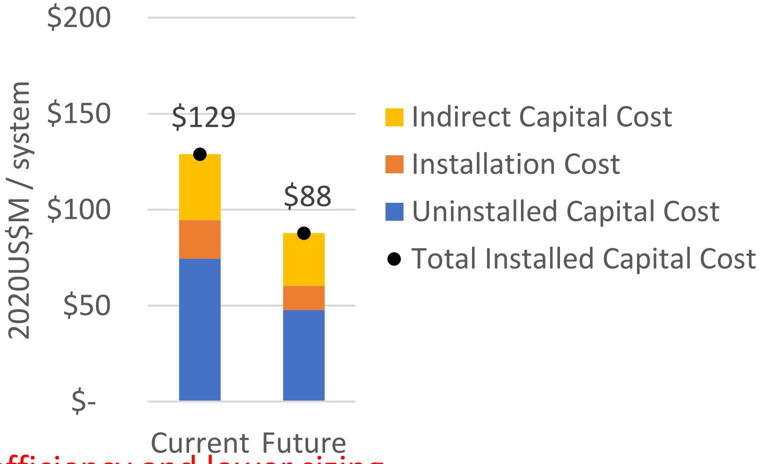
Direct Costs
Current HP Alkaline
50 MTD Plant, 4 modules



Direct Costs
Future HP Alkaline
50 MTD Plant, 2 modules



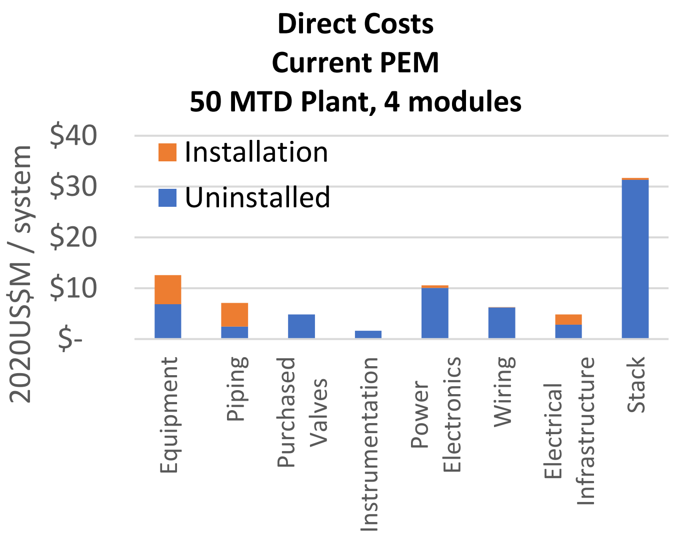
Total Installed Capital Cost
HP Alkaline - 50 MTD Plant

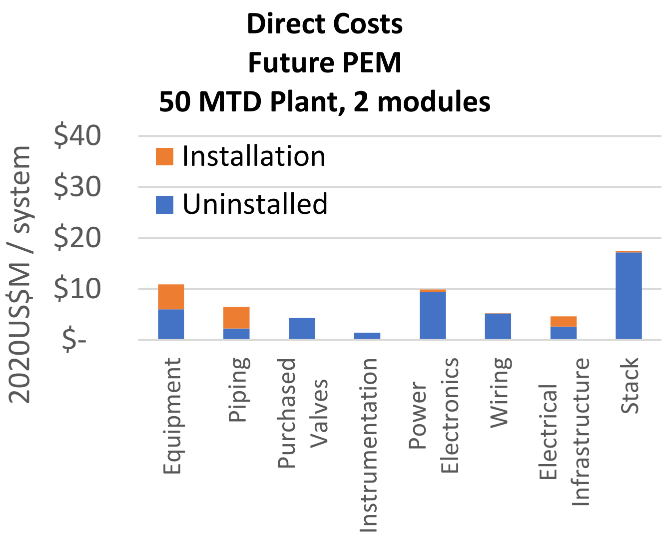


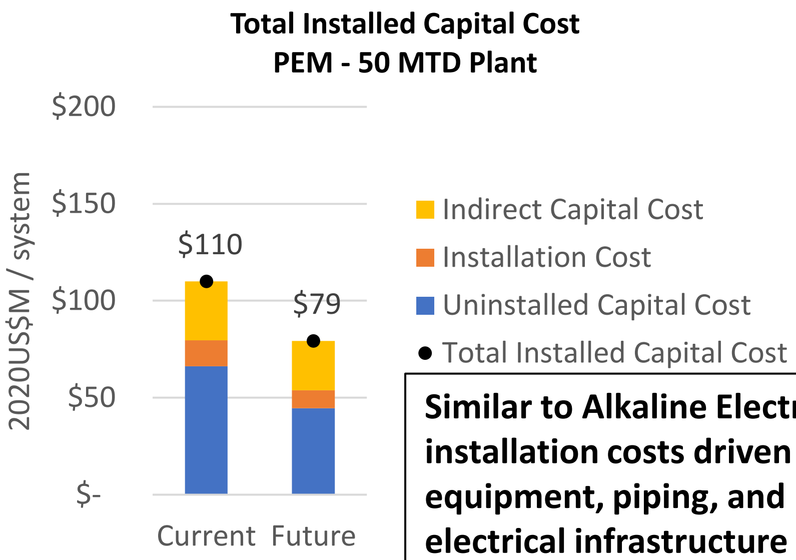
Modest reduction in equipment installation cost expected due to greater efficiency and lower sizing

SA Model – Direct Costs and Total Installed Capital Costs

PEM







Similar to Alkaline Electrolysis, installation costs driven by equipment, piping, and electrical infrastructure

Very little reduction in equipment and piping installation costs expected between Current and Future cases

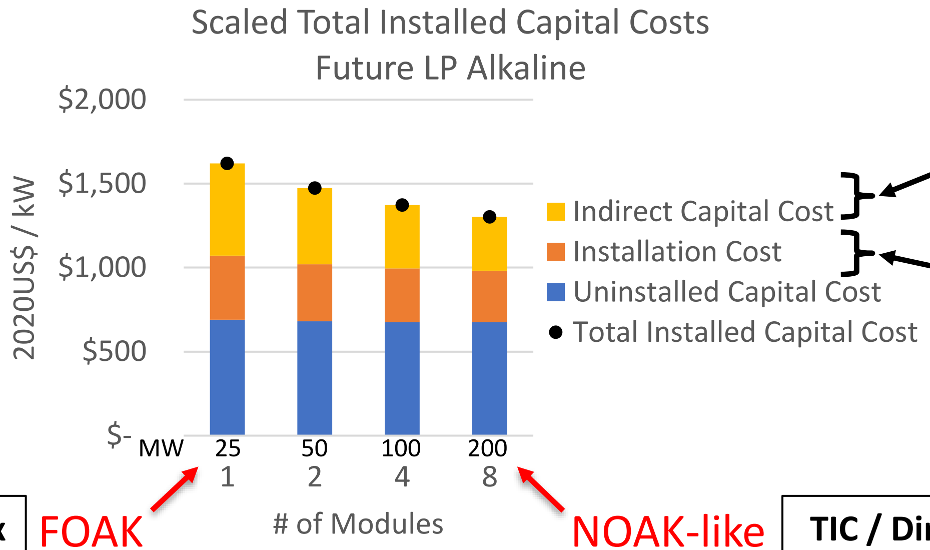
Note that assumed PEM stack production rate, stack lifetime, and Iridium spot price may not reflect current market status

		Model Assumption	Status Today
PEM Stack Production Rate	-	1 GW/year	Commonly < 500 MW/year
Stack Lifetime	Year	7 (Current), 10 (Future)	Performance degradation limits lifetime
Iridium Price	2020US $k / kg	$163k	$160 - $215k Increasing prices expected

Scaling Number of Identical Modules

12.5 MTD Modules
(~25 MW)

Low Pressure Alkaline



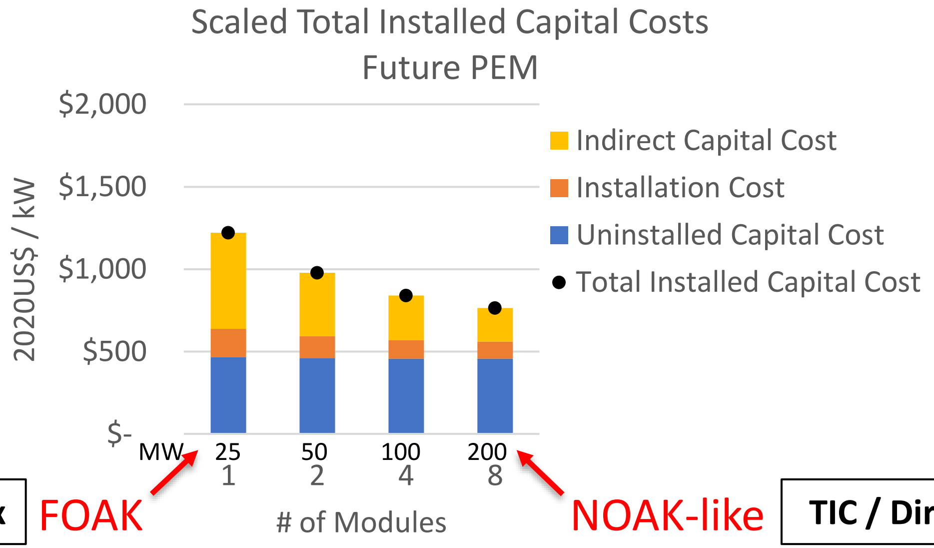
Flat scaling of EPC and up-front permitting costs accounts for reduction of indirect costs for large scale projects
- Modularization of plants should reduce engineering costs

Modest reduction in installation costs due to economies of physical size, and economies of manufacturing rate

TIC / Direct Cost Ratio: ~1.6x FOAK

NOAK-like **TIC / Direct Cost Ratio: ~1.3x**

PEM



HP Alkaline trends are similar to PEM

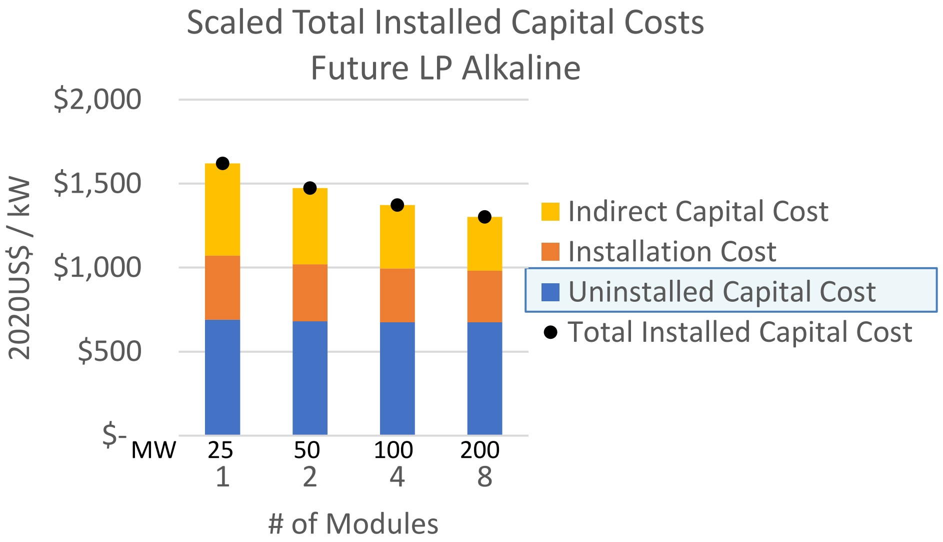
TIC / Direct Cost Ratio: ~1.9x FOAK

NOAK-like **TIC / Direct Cost Ratio: ~1.4x**

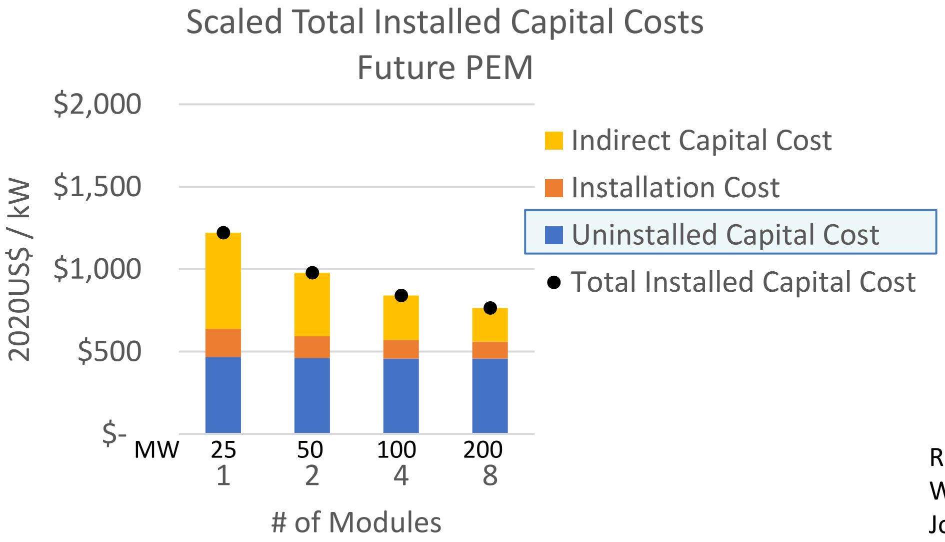
Comparison to Currently Reported Uninstalled Prices

Publicly available prices frequently omit installation and should be multiplied by 1.5x-2x to account for indirect costs

Low Pressure Alkaline



PEM



Uninstalled Prices Only
Scope of Supply: Stacks, balance of plant, power electronics
Omitted: Compressors, civil works, installation costs

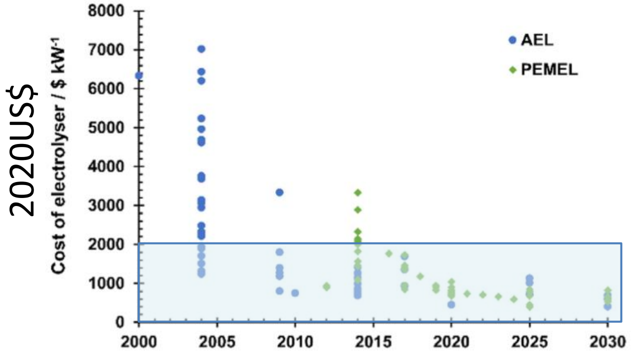


Fig. 2 – Literature data for electrolyser costs from 2000 until 2030, based on references [21–35].

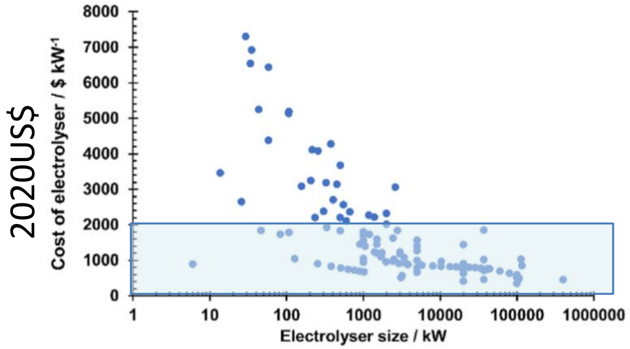


Fig. 3 – Literature data for electrolyser costs from 2000 until 2030, based on references [21–35].

- SA model estimates for **uninstalled costs** largely in line with historical publicly available prices and future predicted costs
- **Uncertain or limited scope of supply complicates the use of historical data for validation**
- Most data points are pre-2018 or projections
- Assumed kW for the plant depends on BOL and EOL conditions

Reksten, A. H.; Thomassen, M. S.; Møller-Holst, S.; Sundseth, K. Projecting the Future Cost of PEM and Alkaline Water Electrolysers; a CAPEX Model Including Electrolyser Plant Size and Technology Development. International Journal of Hydrogen Energy 2022, 47 (90), 38106–38113. https://doi.org/10.1016/j.ijhydene.2022.08.306.

Cost Reduction Potential

Cost Category	Cost Reduction Drivers
Uninstalled Costs	
Purchased Equipment	Economies of (physical) size scale, economies of manufacturing rate scale will reduce uninstalled equipment costs
Piping	General improved designs (e.g., higher efficiency stacks reduces piping demand)
Installation Costs	
Mechanical BOP	
Equipment installation	Factory installation would increase installation speed and reduce costs
Piping	Factory installation would increase installation speed and reduce costs
Instrumentation and valves	Factory installation would increase installation speed and reduce costs
Electrical BOP	Economies of (physical) size scale, economies of manufacturing rate scale will reduce costs
Indirect Costs	
Site Preparation	Minor cost reductions due to smaller facility footprint needed in the future
Construction Overhead	
Engineering and Design	Modularity leads to lower design costs
Up-Front Permitting Costs	Higher adoption of electrolyzers or government support may reduce permitting costs
Project Contingency	Can reduce as project certainty increases and modularity increases
Land	

Mechanisms for Cost Reduction

- Economies of physical size, economies of manufacturing rate, factory-built vs field-erected
- Modularity leading to lower design costs
- General improved designs (e.g., higher efficiency stacks reduces piping demand)
    - Design for Assembly/Manufacturing/Installation/Maintenance

Conclusions and Outlook

Direct Costs

- Scaling-up module size will decrease equip. & piping costs associated with installation due to economies of (physical) size
- Scaling-up module manufacturing rate should decrease installation costs due to economies of manufacturing rate

Installation Cost

- Increased use of factory assembly will decrease installation cost
- "Nth of a kind" savings and "Design for Installation" philosophy will also reduce cost

Indirect Costs

- Overhead/Engineering & Design
  - Increasing modularization and deployment volumes should decrease overhead costs, including engineering & design
- Project Contingency
  - Project contingency will continue to remain high in the short term as EPC's and electrolyzer suppliers learn how to deploy large-scale facilities
- Up-Front Permitting and Deployment Time
  - Improvements in electrical grid integration and electrolyzer deployment policy may lead to lower permitting costs in addition to a general reduction in deployment lag associated with renewable energy and electrolyzer installations

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- **Idaho National Labs**
- **National Renewable Energy Laboratory**

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