1 GW Hydrogen Electrolyzer Plant Design and Cost Analysis

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November 7, 2019

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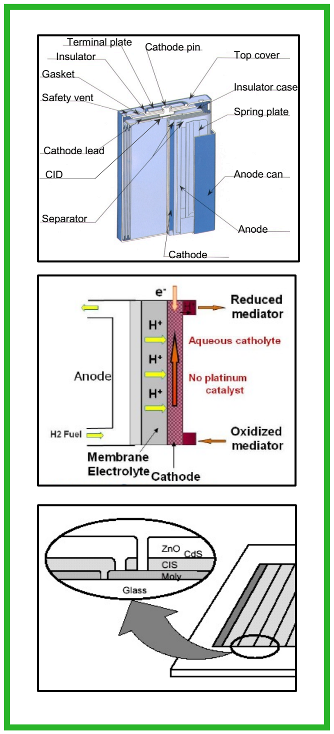
Austin Power Engineering LLC is an independent technology consulting company that focuses mainly on bottom-up technical cost modeling.

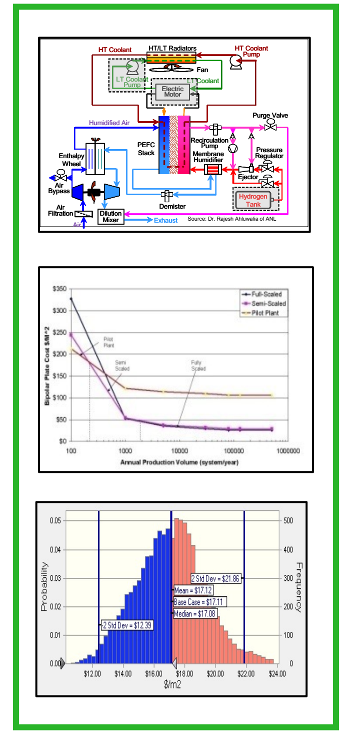


Hydrogen Electrolysis

Hydrogen Storage

Fuel Cell

Battery



Hydrogen & Fuel Cell Manufacturing Cost Modeling

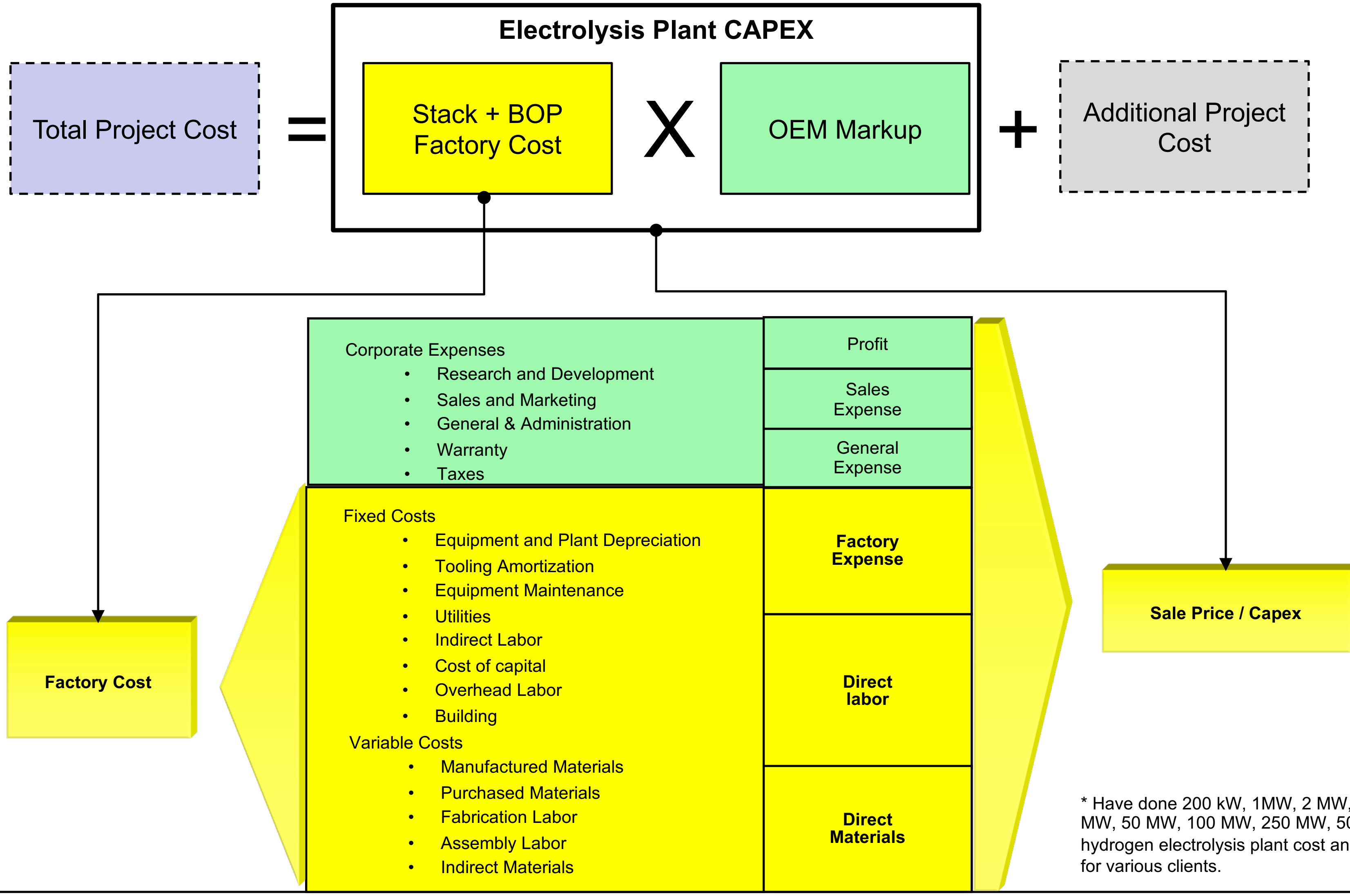
2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019

Arthur D Little / TIAX (2002–2008)

Austin Power Engineering (2008–2019)

Project Objective

We will analyze a 1 GW (200,000 Nm^3/hr / 500 ton H2 per day) hydrogen electrolysis plant capex.

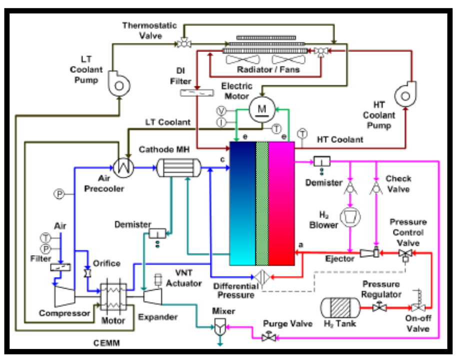


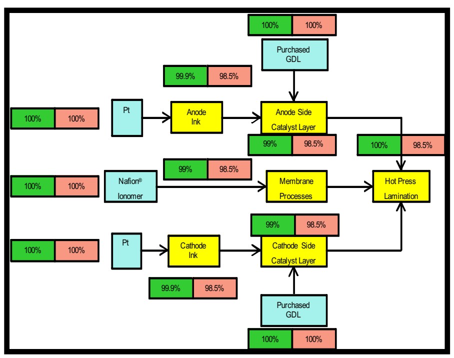
* Have done 200 kW, 1MW, 2 MW, 10 MW, 50 MW, 100 MW, 250 MW, 500 MW hydrogen electrolysis plant cost analysis for various clients.

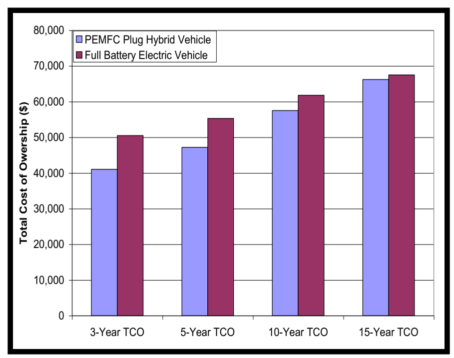
Approach Manufacturing Cost Modeling Methodology

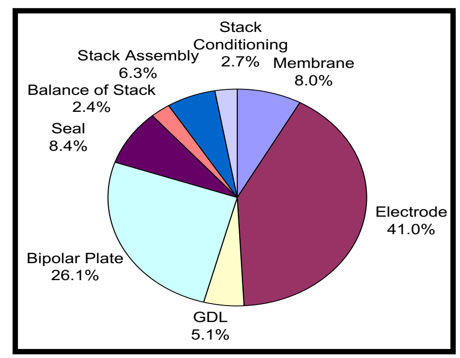
This approach has been used successfully for estimating the cost of various technologies for commercial clients and the DOE.

Technology Assessment	Manufacturing Cost Model	Scenario Analyses	Verification & Validation
• Literature research • Definition of system and component diagrams • Size components • Develop bill-of-materials (BOM)	• Define system value chain • Quote off-shelve parts and materials • Select materials • Develop processes • Assembly bottom-up cost model •Develop baseline costs	• Technology scenarios • Sensitivity analysis • Economies of Scale • Supply chain & manufacturing system optimization • Life cycle cost analysis	• Cost model internal verification reviews • Discussion with technical developers • Presentations to project and industrial partners • Audition by independent reviewers





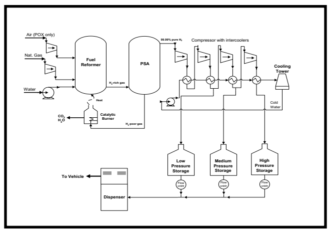




Approach Manufacturing Cost Modeling Methodology

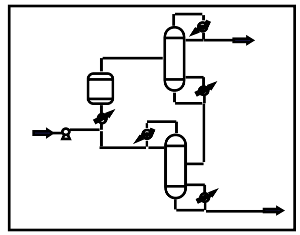
Combining performance and cost model will easily generate cost results, even when varying the design inputs.

Conceptual Design



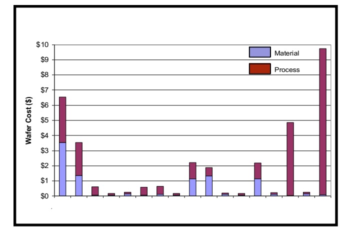
- System layout and equipment requirements

Process Simulation



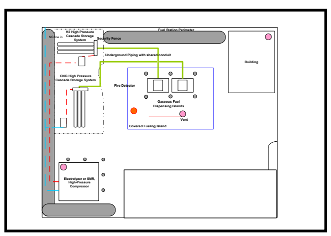
- Energy requirements
- Equipment size/ specs

Process Cost Calcs



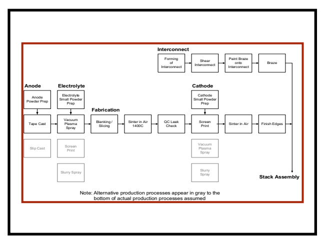
- Process cost
- Material cost

Site Plans



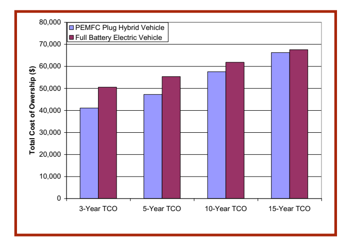
- Safety equipment, site prep, land costs

Capital Cost Estimates



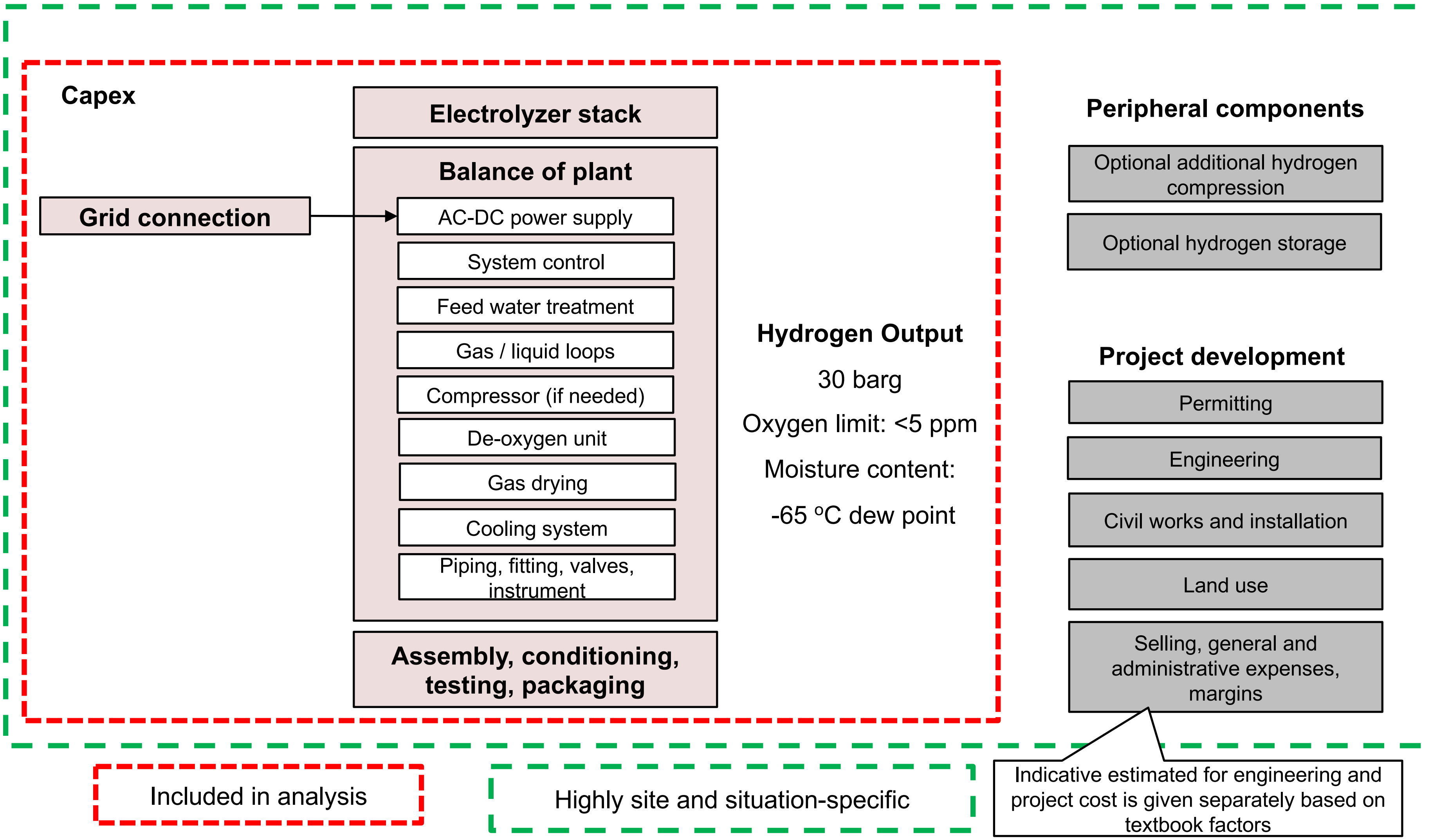
- High and low volume equipment costs

Product Costs



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

1 GW hydrogen electrolyzer plant boundary limits:



Comparing large scale hydrogen electrolysis plant with small hydrogen electrolyzer, cost reduction mainly comes from the following areas:

1. Improve stack performance
   - Increase current density
   - Simplify stack structure
   - Reduce precious metal loading
2. Large scale production
   - Process automation, etc.
3. Increase the stack size
   - Current 1~5 MW
   - Future 5~20 MW
4. System BOP optimization
   - Power supply
   - Mechanical compressors if apply
   - H2 gas purification
5. Low cost region manufacturing

Modular vs Integrated

- Capex
- Project cost
- O&M cost

We screened major electrolyzer manufacturer’s MW level electrolyzer stacks.

Alkaline electrolyzer

- Atm. pressure
- Pressurized

PEM electrolyzer

- Atm. pressure
- Pressurized

Hight temperature electrolyzer

- SOEC
- Proton Conductive SOEC

Commercial

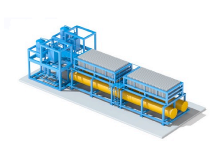
- NEL A485 2.3 MW

- McPhy 2 MW Module
- Chinese Manufacturers
  - Peric
  - Jingli
  - Tianjin Continental

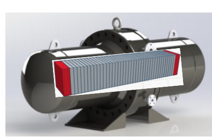
- Hydrogenics 3MW
- ITM Power 2MW Module
- NEL/Proton Onsite MW Module
- Giner EXL 1MW
- Siemens 1~2 MW

- Tubular
- Planar

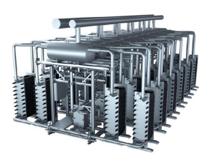
- ThyssenKrupp
- Asaki Kasei



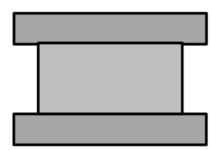
- NEL/GHW



- Siemens



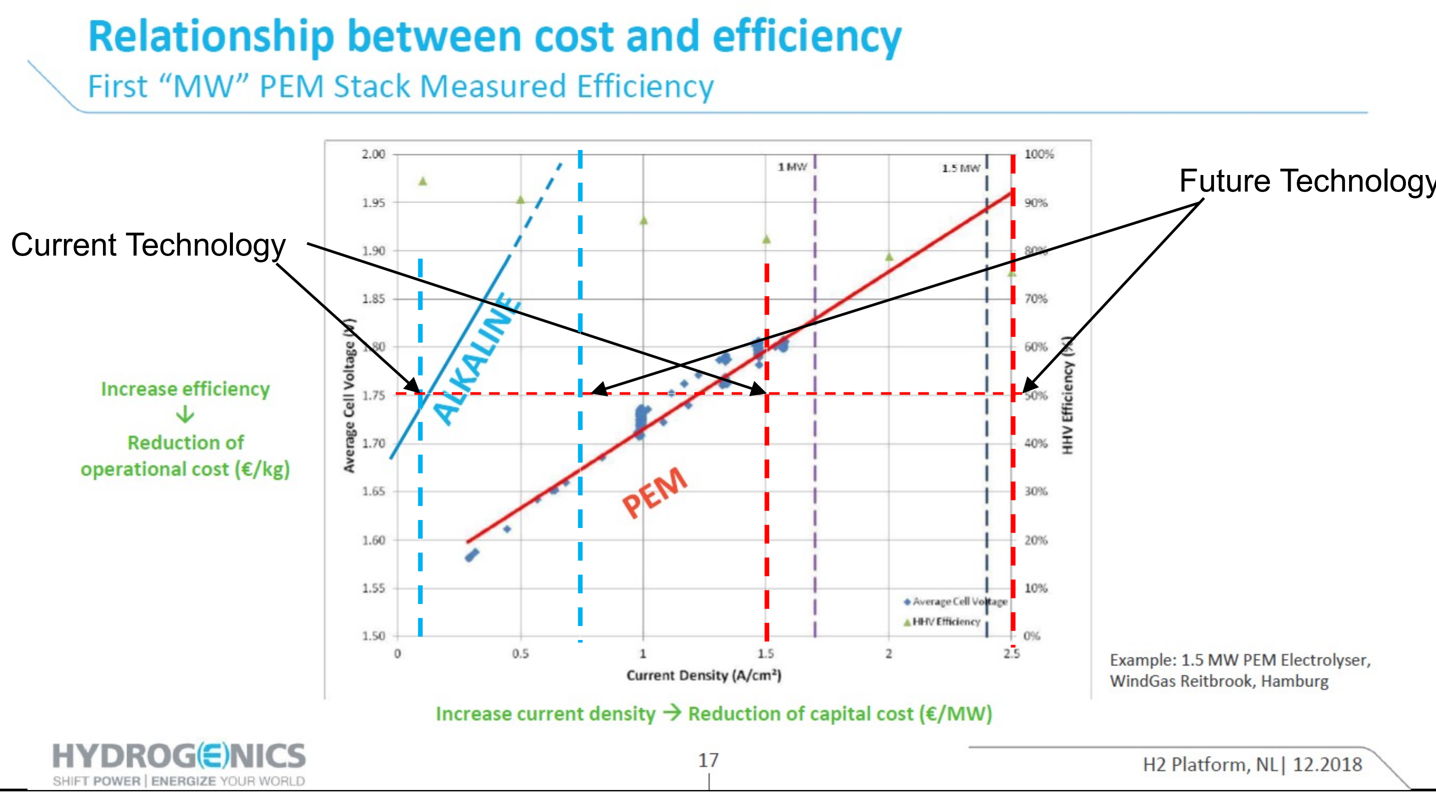
- >Potential 10 MW stacks



Pre-commercial

The chosen cell voltages and current densities are based on current technology status.

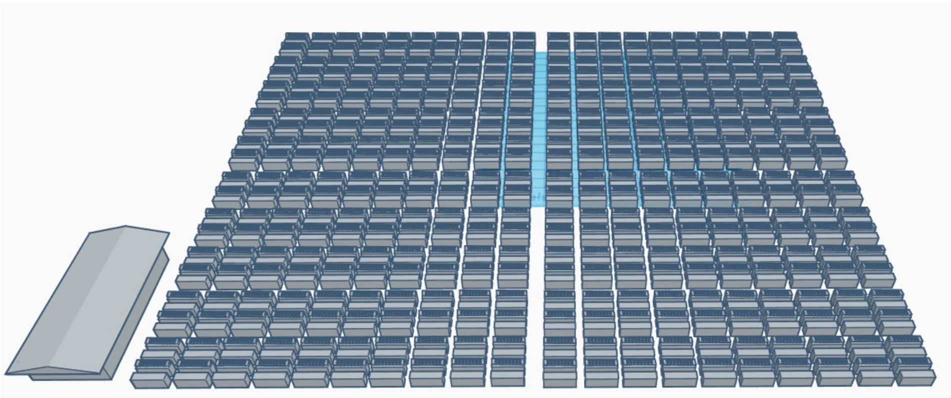
- The chosen cell voltage (1.75V) largely determines the cell efficiency (85% HHV)
- This low cell voltage is used to reflect that such large plants will be optimized for efficiency.
- Assume current atm. pressure alkaline electrolyzer current density is 175 mA/cm^2
- Assume current PEM electrolyzer current density is 1,500 mA/cm^2.



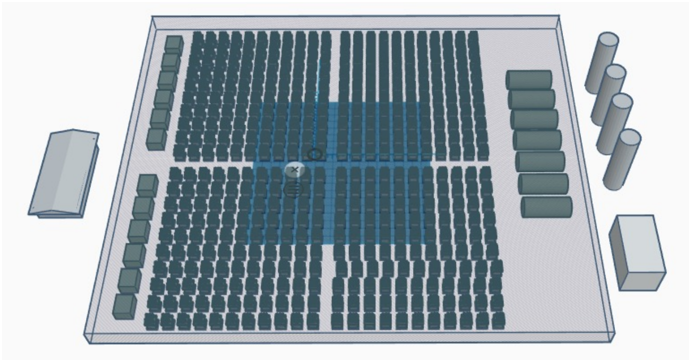
Approach BOP Options

We must consider the capex, project cost, as well as O&M cost when we design the electrolysis plant project.

BOP	Modular Design	Integrated Design
Capex	$$$	$$
Project Cost	$	$$$
O&M Cost	$$$	$$



Outdoor Modular Design



Integrated BOP Design

Design Scenarios 1 GW Hydrogen Electrolysis Plant Stack

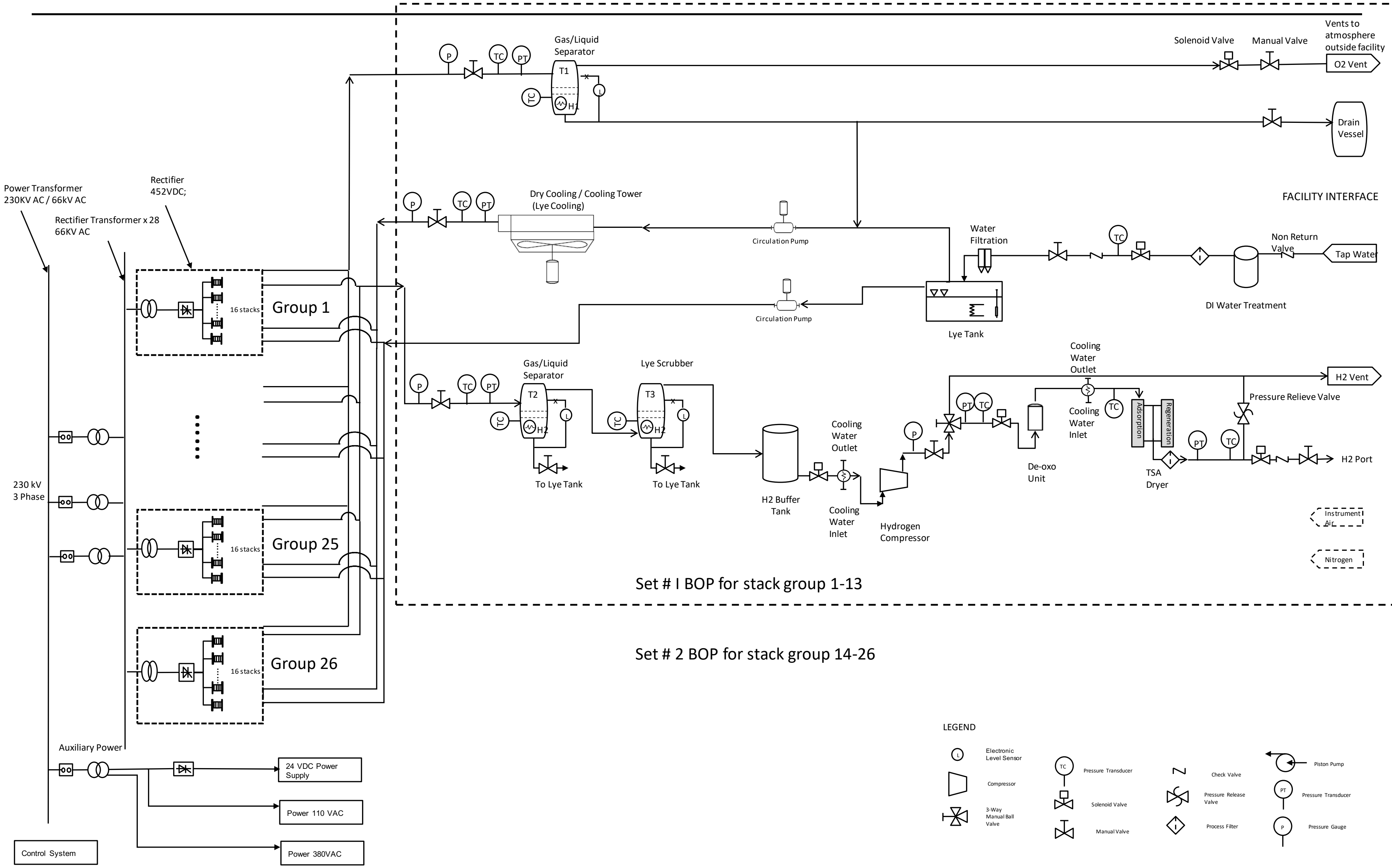
Major stack specifications summary:

Parameter	Alkaline Electrolyzer Current KPI	Alkaline Electrolyzer Future KPI	PEM Electrolyzer Current KPI	PEM Electrolyzer Future KPI
Plant size (MW, DC basis)	957	960	960	960
Stack size (MW)	2.3	10	2.5	10
# of stacks	416	96	384	96
Cell voltage (V)	1.75	1.75	1.75	1.75
Current density (A/cm^2)	**0.175**	**0.75**	**1.50**	**2.50**
# of cells	258	258	258	258
Stack voltage (VDC)	452	452	452	452
Stack Current (A)	5,088	22,124	5,531	22,124
Cell active area (cm^2)	29,077	29,499	3,687	8,850
Actual cell area (cm^2)	34,208	34,704	4,852	11,644
Operating Pressure (barg)	0.02	.06	30	30
Stack production volume (GW/year)	1	1	1	1
Purity (%)	99.99	99.99	99.99	99.99
Oxygen limit	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Moisture content	- 65 °C dew point	- 65 °C dew point	- 65 °C dew point	- 65 °C dew point

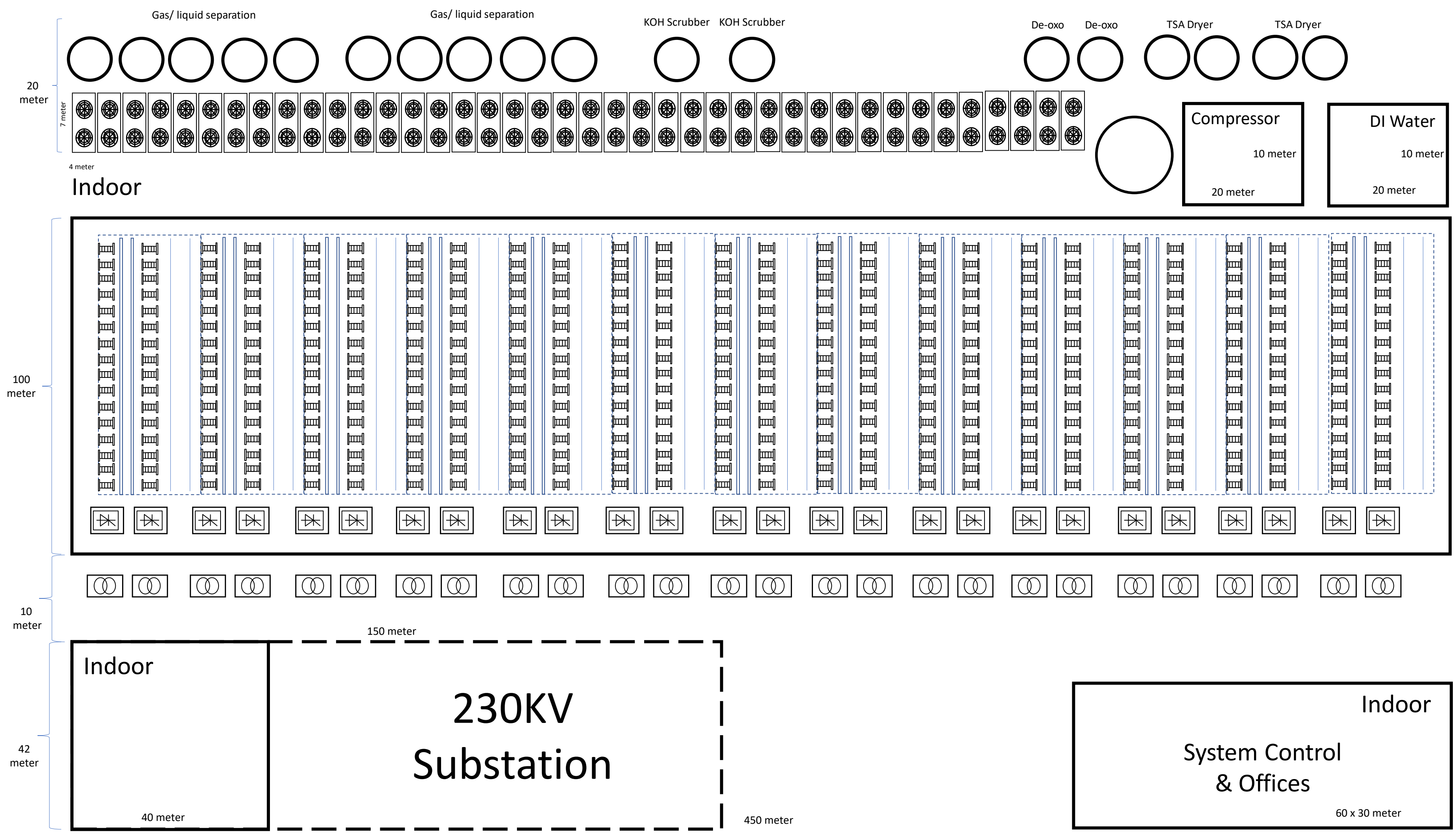
Major BOP components summary:

Parameter	Alkaline Electrolyzer Current KPI	Alkaline Electrolyzer Future KPI	PEM Electrolyzer Current KPI	PEM Electrolyzer Future KPI
Power supply	x	x	x	x
H2 gas/liquid separator	x	x	x	x
O2 gas/liquid separator	x	x	x	x
H2 gas lye scrubber	x	x		
H2 booster compressor	x	x		
De-oxo unit	x	x	x	x
TSA dryer	x	x	x	x
DI water system	x	x	x	x
Stack cooling system	x	x	x	x
H2 gas chiller before boost compressor	Included in the boost compressor cost	Included in the boost compressor cost	Included in the boost compressor cost	Included in the boost compressor cost
H2 gas chiller before TSA dryer	Included in the deoxo unit cost	Included in the deoxo unit cost	Included in the deoxo unit cost	Included in the deoxo unit cost
# set of BOPs in system	2	2	2	2

Current Alkaline: 1 GW Alkaline (2.3 MW stack), 2 sets of BOP, simplified P&ID

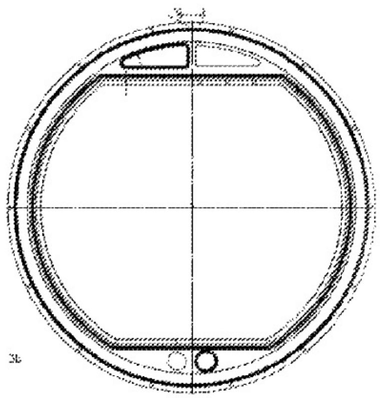


Current Alkaline 1 GW Plant Layout



Current Alkaline: Stack Overview

Atmospheric pressure alkaline electrolyzer design:



Illustrative

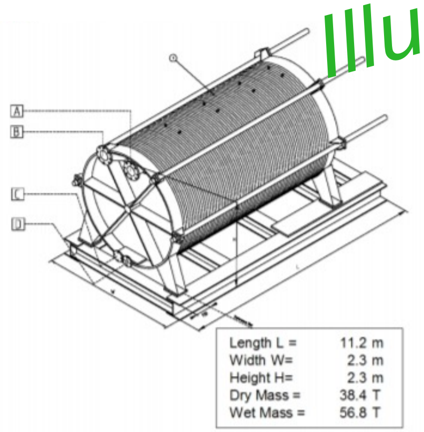


Figure 4 — Dimensional Details of the Selected Norsk Electrolyser Module.

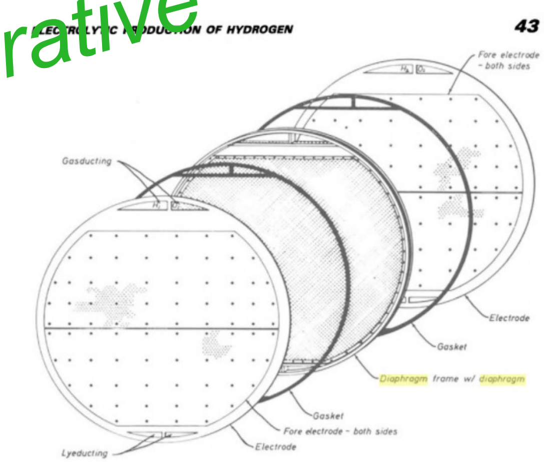


Figure 24. Norsk Hydro electrolyzer—exploded view of one electrolyzer cell (with permission from Norsk Hydro A.S.).

US patent: 9,556,529

Key Parameters

Diaphragm
- Zirfon Perl ® diaphragm
- 0.5 mm thickness

Anode Electrode
- Substrate: 0.3 mm Ni Mesh
- Coating: NiAl (56/44)wt; 90 µm

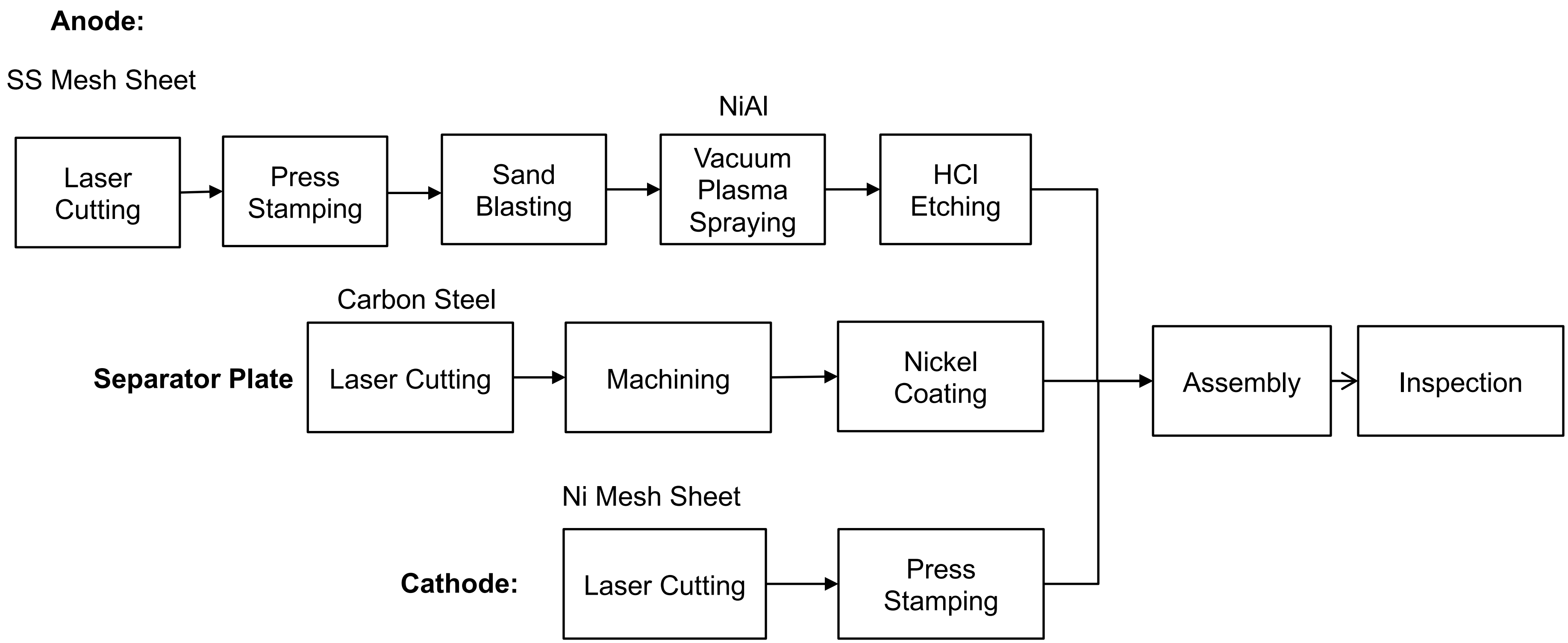
Cathode Electrode
- Substrate: 0.3 mm Ni Mesh

Frame / Structure Ring
- Machined Carbon steel with PTFE coating

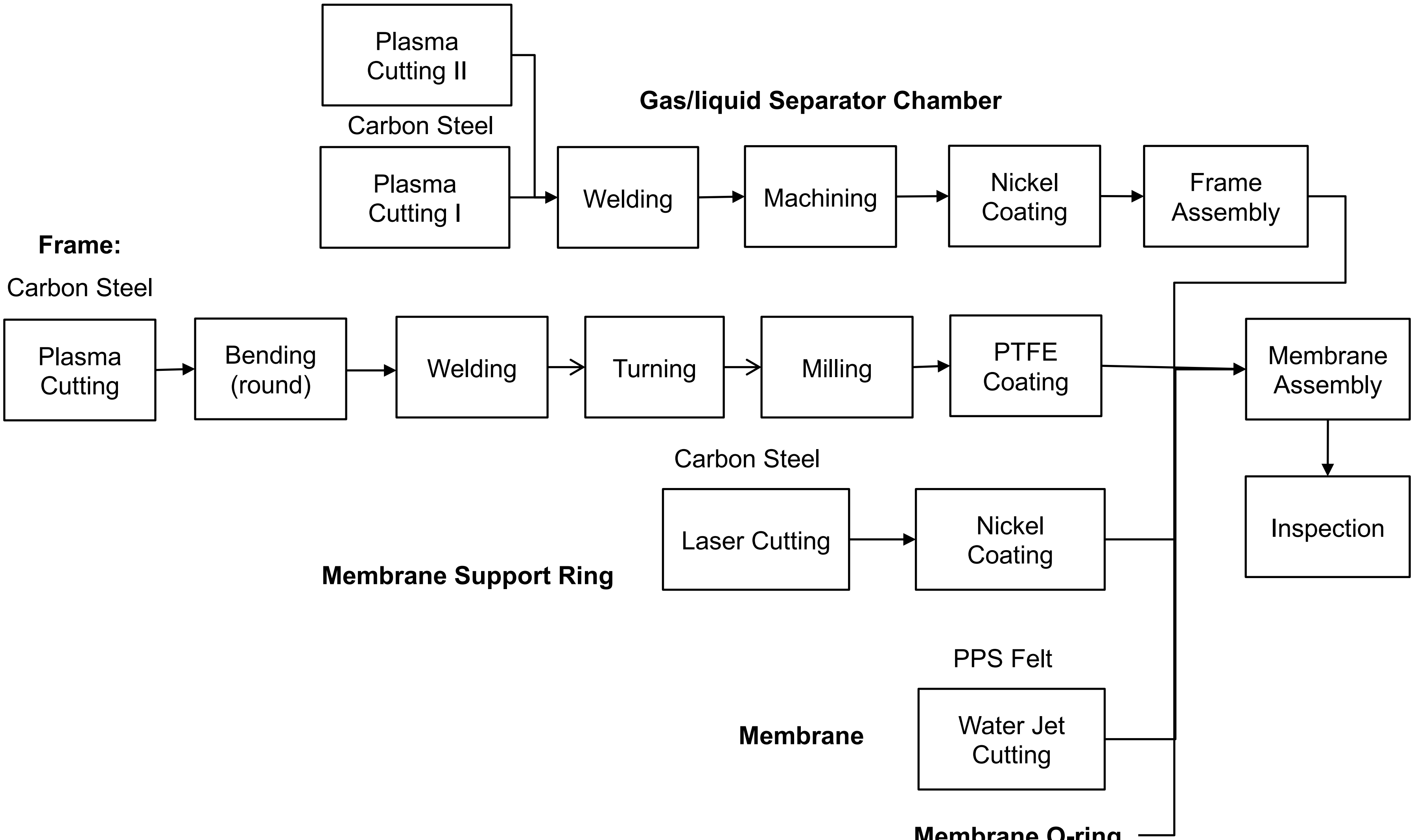
Cell gasket
- EPDM
- 1 mm thickness

Separator Plate
- Ni coated carbon steel
- 2 mm thickness

Anode, cathode, and bipolar plate fabrication processes:

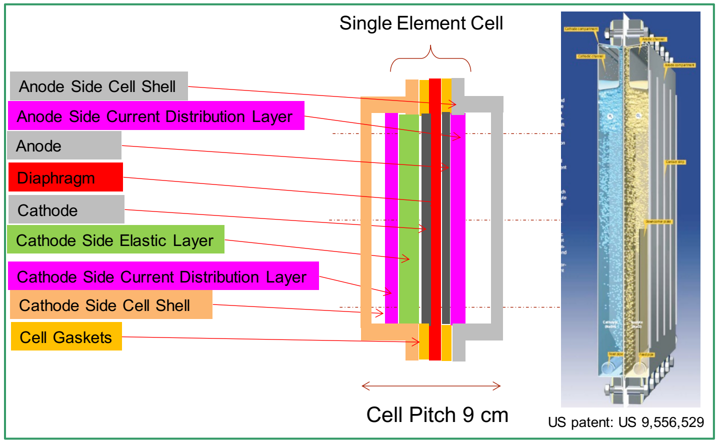


Diaphragm and cell frame fabrication processes:

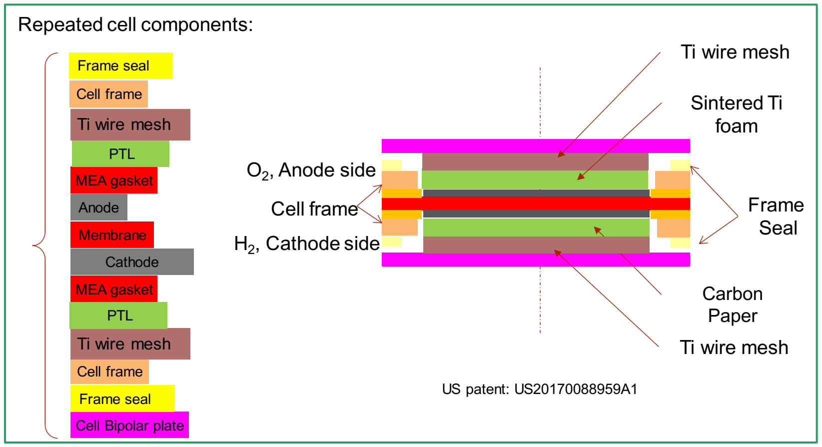


Other Stack Scenarios Overview

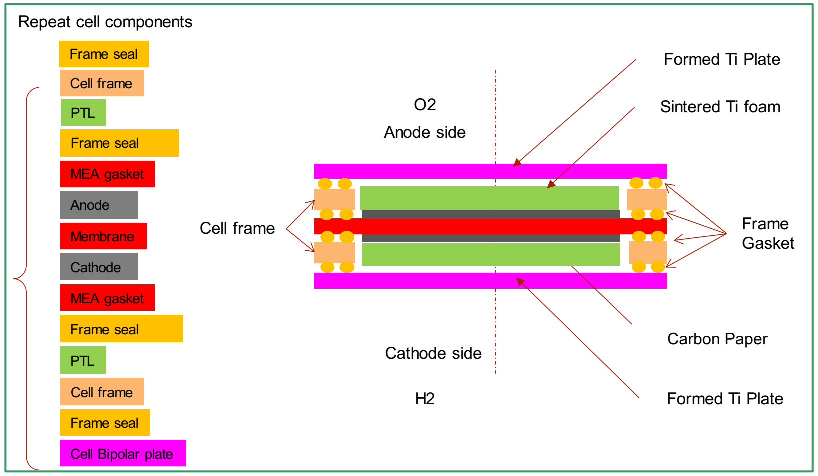
We designed the stacks based on patents and public available information, etc.



Future Alkaline Scenario:
10 MW Atm. Pressure Alkaline Electrolyzer Stack



Current PEM Scenario:
2.5 MW 30 Barg PEM Electrolyzer Stack

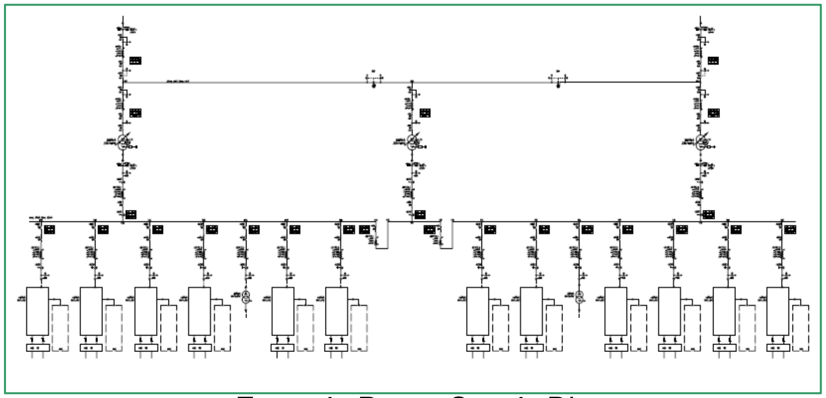


Future PEM Scenario:
10 MW 30 Barg PEM Electrolyzer Stack

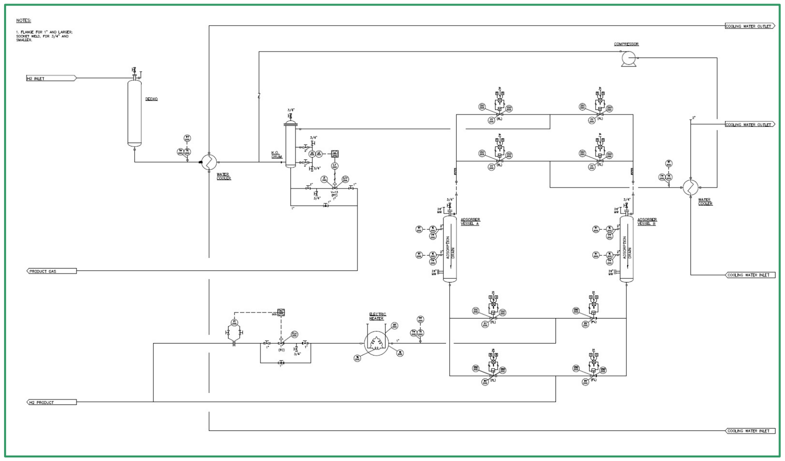
BOP Components

We assume there are two sets of BOP systems which make the system easy to maintain and give the benefit of resiliency.

Major BOP Components	Descriptions
Power supply	230KV Substation; N+1 transformer design
H2 gas/liquid separator	Integrated
O2 gas/liquid separator	Integrated
H2 gas lye scrubber	Integrated
H2 booster compressor	~20,000 HP x 2
De-oxo unit	Pt on Al2O3 pellets at 108 C^{o}
TSA dryer	UOP Molesieve pellets
DI water system	Electric conductivity, <1 Siemens/cm for PEM; <5 Siemens/cm for Alkaline
Stack cooling system	~20,000 cooling tons



Example Power Supply Diagram

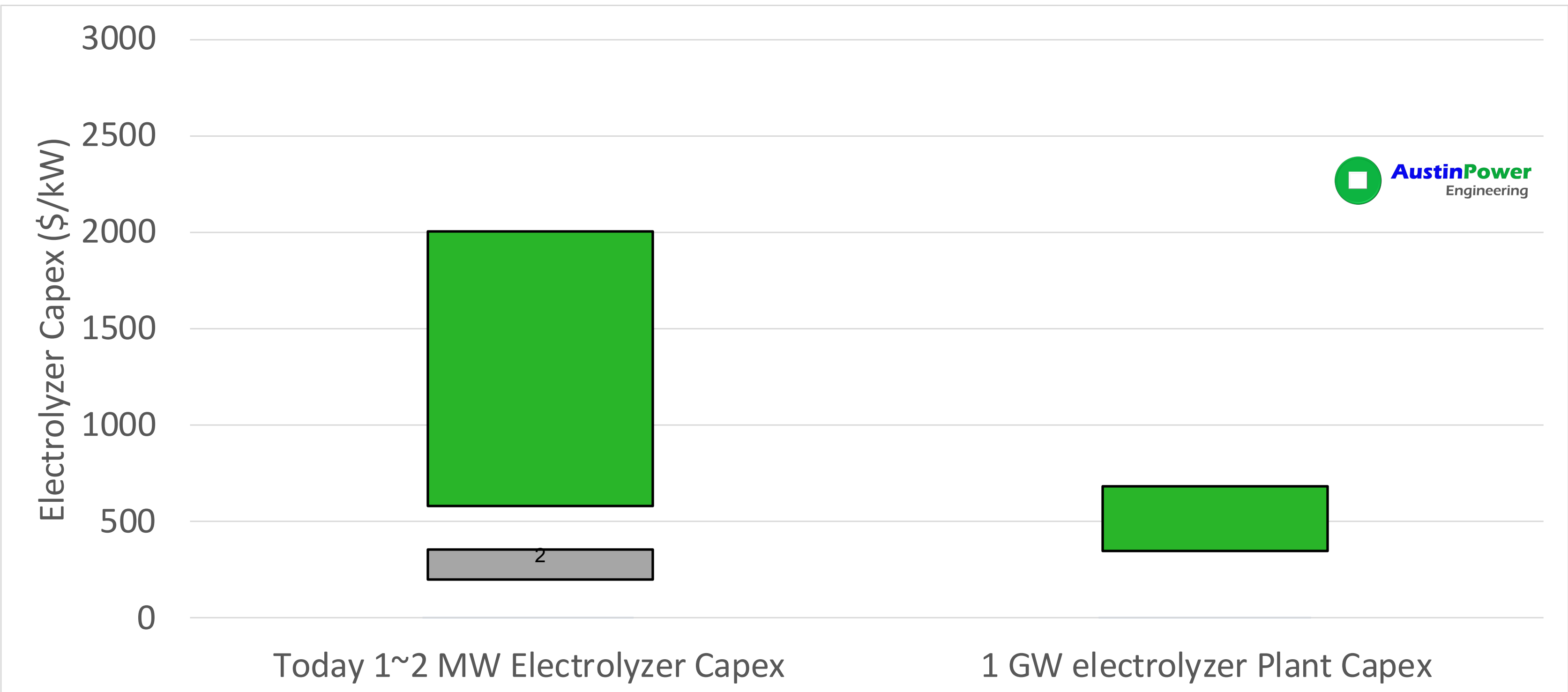


Example De-oxygen & TSA Dryer Diagram

Capex Summary

Estimated 1 GW electrolyzer plant capex fall into the range of between $400/kW and $600/kW.

- Today 1~2 MW electrolyzers' capex ranges from $600/kW to $2,000/kW
- Modelled 1 GW electrolyzers' capex ranges from $400/kW to $600/kW[1]



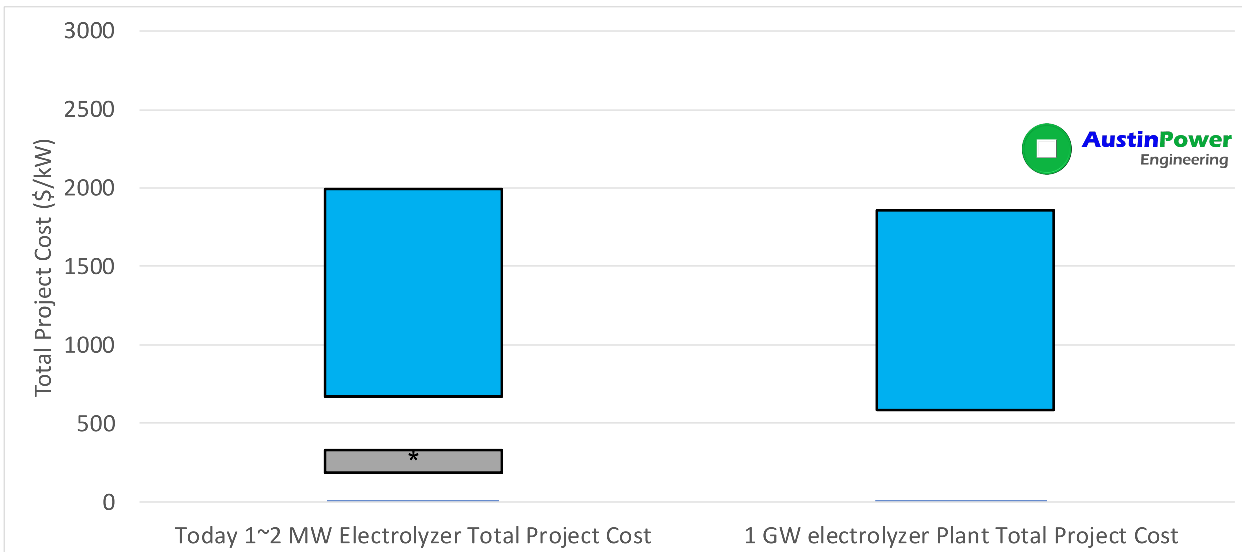
1. Made in US or western Europe countries; cell efficiency is about 85%; output H2 gas purity is 99.99% at 30 barg
2. Units made in China and sold in China only; as low as $200~300/KW

Total Project Cost Discussion

Total project cost also includes project "soft" cost which is highly site and situation specific.

- Container based 1~2 MW electrolyzers' project cost is minimum
- 1 GW electrolyzer plant total project cost ranges from \$600/kW to \$1,800/kW (additional 50%~200% project "soft" cost)

- Typical Project "Soft" Cost
  - Permitting
  - Building (including service facilities)
  - Engineering & supervision
  - Installation
  - Legal expense
  - Contract fee
  - Contingency



* Units made in China and sold in China only; as low as \$200~300/KW

Thank You!

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