# Annexure

## How Can India Indigenise Hydrogen Electrolyser Manufacturing?

Quantifying the Potential for Indigenising Electrolysers using a Bottom-up Cost Assessment

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We reviewed literature and compiled data from various sources, including previous studies, patents, technical reports, data sheets, websites, and e-marketplaces, to comprehensively understand the cost parameters influencing the stack and system cost. This allowed us to develop assumptions for different manufacturing process studies in our analysis. The key parameters used to establish the bottom-up study are summarised here.

**Annexure 1: Parameters and assumptions for PEM electrolysers**

Table A1 lists the major components, sub-components, and the respective material(s) used in the study to assess the bottom-up cost of PEM electrolysers.

**Table A1 Components and materials for PEM electrolysers**

| Main component | Sub-component | Material(s) |
|---|---|---|
| Electrolyser stack | Anode | Iridium |
| | Cathode | Platinum on carbon black |
| | Separator | Perfluorosulphonic acid (PFSA) membranes (i.e., Nafion) |
| | PTL (anode) | Gold-coated sintered porous titanium |
| | PTL (cathode) | Sintered porous titanium or carbon cloth |
| | BPP (anode) | Gold-coated stainless steel |
| | BPP (cathode) | Gold-coated stainless steel |
| | Frames and sealing | Polytetrafluoroethylene (PTFE); PTFE with 40% reinforced glass fibre |

*Source: Authors' compilation from Mayyas, Ahmad, Mark Ruth, Keith Wipke, Bryan Pivovar, and Guido Bender. 2019.* "Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers". *Golden, Colorado: US National Renewable Energy Laboratory (NREL).*

Table A2 lists the raw materials used in PEM manufacturing and their respective costs. The table also details the key material costs of the cell and stack assembly.

**Table A2 Material cost assumption for PEM electrolysers**

| Sr. No. | Material | Cost | Unit | Reference |
|---|---|---|---|---|
| 1 | Platinum | 32.28 | USD/g | (Metalary 2018) |
| 2 | Iridium | 31.19 | USD/g | (Metalary 2018) |
| 3 | Titanium powder | 35 | USD/kg | (NREL 2019) |
| 4 | Gold | 43.54 | USD/g | (Metalary 2018) |
| 5 | Ionomer | 1.53 | USD/g | (NREL 2019) |
| 6 | Carbon black | 1 | USD/kg | (Indiamart 2022) |
| 7 | Carbon cloth | 350.00 | USD/$m^2$ | (NREL 2019) |
| 8 | Solvent in CCM | 10 | USD/gallon | (NREL 2019) |
| 9 | Ethanol | 1.20 | USD/kg | (Indiamart 2022) |
| 10 | Binder | 1.50 | USD/kg | (Indiamart 2022) |
| 11 | PPS-40%GF resin | 15.40 | USD/kg | (NREL 2019) |
| 12 | Stainless steel 316L | 0.00372 | USD/g | (Sachiya Steel 2022) |

*Source: Authors' compilation*

**Annexure 2: Parameters and assumptions for alkaline electrolysers**

The assumptions we considered for alkaline electrolysers included a detailed analysis of components and sub-components essential for the process as shown in Table A3.

**Table A3 Components and materials for alkaline electrolysers**

| Main component | Sub-component | Material |
|---|---|---|
| Electrolyser stack | Anode | Nickel-coated perforated stainless steel |
| | Cathode | Nickel-coated perforated stainless steel |
| | Electrolyte | 30–40% potassium hydroxide (KOH) |
| | Separator | $ZrO_2$ stabilised with PPS mesh (Zirfon) |
| | PTL (anode) | Nickel foam |
| | PTL (cathode) | Nickel foam |
| | BPP (anode) | Nickel-coated stainless steel |
| | BPP (cathode) | Nickel-coated stainless steel |

| | | |
|---|---|---|
| | Frames and sealing | PTFE, PFSA 40% reinforced glass fibre |

*Source: Authors' compilation from Mayyas, Ahmad, Mark Ruth, and Margaret Mann. 2017.* "Manufacturing Competitiveness Analysis for PEM and Alkaline Water Electrolysis Systems." *Presented at the 2017 Fuel Cell Seminar and Energy Exposition, November 6–9, 2017. Long Beach, California.*

The material costs for an alkaline electrolyser are primarily determined by the cost associated with key materials such as nickel for electrodes, zirconium for membranes, and metals used for cell frames as shown in Table A4.

**Table A4 Material costs assumed for alkaline electrolysers**

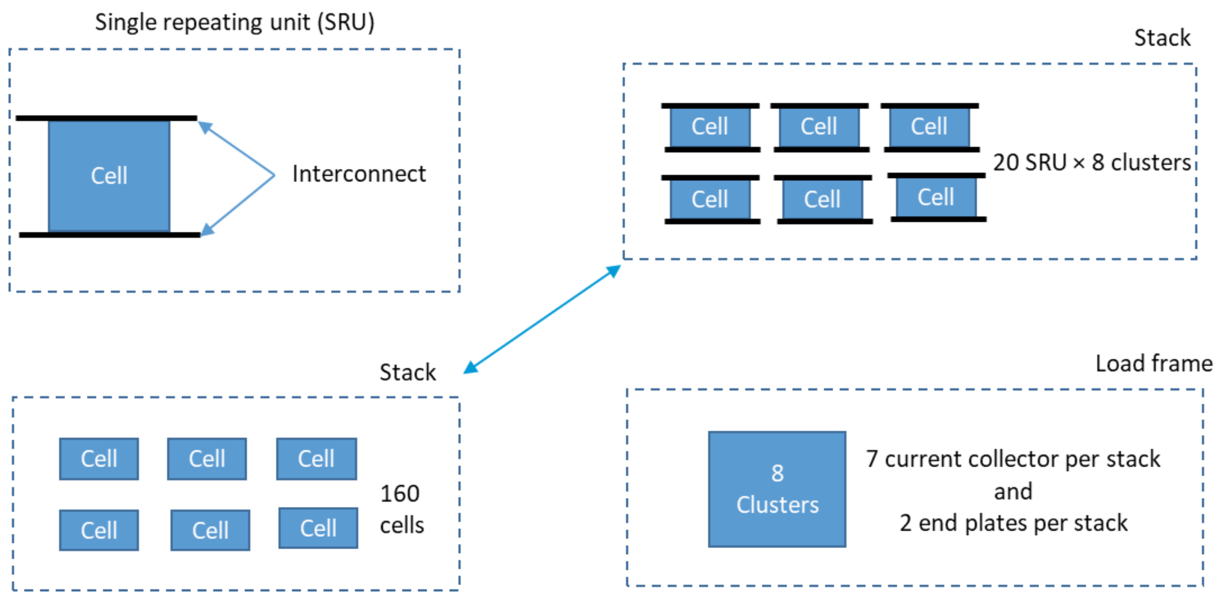
| Sr. No. | Material | Value | Unit | Reference |
|---|---|---|---|---|
| 1 | Nickel | 23.92 | USD/kg | (Nornickel 2019) |
| 2 | Average raney nickel | 0.044 | USD/kg | (Indiamart 2022, Indiamart 2022) |
| 3 | Steel | 3.72 | USD/kg | (Steel Tubes India 2022) |
| 4 | PPS-40GF resin | 8.85 | USD/kg | (Alibaba 2022) |
| 5 | PTFE gasket | 10 | USD/kg | (Made in China 2022) |
| 6 | Zirfon | 60 | USD/$m^2$ | (Kazemi 2014) and quotation from Agfa, 2022 |
| 7 | Expanded/woven nickel mesh | 64.15 | USD/$m^2$ | (Made in China 2022, Alibaba 2022) |
| 8 | Nickel foam | 21.70 | USD/$m^2$ | (Made in China 2022) |
| 9 | Molybdenum powder | 50.87 | USD/kg | (Ministry of Commerce n.d.) |

*Source: Authors' compilation*

**Annexure 3: Parameters and assumptions for SOEs**

The cells in SOEs are arranged in a stack configuration to maximise efficiency and output. Each cell is sandwiched between interconnects that facilitate electrical conductivity and gas flow. The stack configuration typically includes repeating units of anode–electrolyte–cathode assemblies known as SRU. Figure A1 shows a typical cell and stack arrangement for an SOE.

**Figure A1 Arrangement of the cell and stack for SOEs**




*Source: Authors' analysis*

Table A5 lists key components and materials for SOEs, including materials used for anodes, cathodes, electrolytes, and interconnects.

**Table A5 Components and material for SOE**

| Main component | Sub-component | Material |
|---|---|---|
| Electrolyser stack | Cathode | Nickel oxide + ceria gadolinium oxide (CGO) |
| | Electrolyte | Scandia-stabilised zirconia (SSZ) |
| | Anode | lanthanum strontium cobalt ferrite (LSCF) |
| | Current collector | Stainless steel with manganese cobalt oxide (MCO) coating |
| | Sealing gasket | Lanthanum oxide (LO) and borosilicate glass (BSG) |
| | Interconnect | Ferritic steel with MCO coating (Crofer 22 APU) |

*Source: Authors' compilation from Anghilante, Régis, David Colomar, Annabelle Brisse, and Mathieu Marrony. 2018. "Bottom-Up Cost Evaluation of SOEC Systems in the Range of 10–100 MW."* International Journal of Hydrogen Energy, *43 (45): 20309–22.*

Table A6 lists the key parameters that we used for the bottom-up cost assessment of SOEs, including cell size, stack configuration, specifications, operating conditions, and efficiency metrics.

**Table A6 Parameters assumed for the bottom-up cost assessment *of SOEs***

| Sr. No. | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Cell length | 15.83 | cm |
| 2 | Cell width | 10.55 | cm |
| 3 | Overall scrap rate for cell-making | 10–15% | |
| | **Anode (LSCF)** | | |
| 4 | Thickness | 0.0025 | cm |
| 5 | Density of LSCF | 6.21 | $g/cm^3$ |
| 6 | Mass of anode | 2.59 | g |
| | **Electrolyte (SSZ)** | | |
| 7 | Thickness | 0.013 | cm |
| 8 | Density of SSZ | 5.25 | $g/cm^3$ |
| 9 | Mass of electrolyte | 11.40 | g |
| | **GDL coating (CGO)** | | |
| 10 | Thickness | 0.0020 | cm |
| 11 | Density of CGO | 7.26 | $g/cm^3$ |
| 12 | Mass of coating | 2.42 | g |
| | **Cathode (NiO/CGO)** | | |
| 13 | Thickness | 0.0025 | cm |
| 14 | Density of NiO/CGO | 7.01 | $g/cm^3$ |
| 15 | Mass of cathode | 2.92 | g |
| | **Organic solvents** | | |
| 16 | Quantity required (scenario 1) | 24.5 | g |
| 17 | Quantity required (scenario 2) | 23.9 | g |
| | **General info: Interconnect (Crofer 22 APU)** | | |
| 18 | Margin for interconnect | 1 | cm |
| 19 | Interconnect plate length | 17.83 | cm |

| | | | |
|---|---|---|---|
| 20 | Interconnect plate width | 12.55 | cm |
| 21 | Interconnect plate thickness | 0.025 | cm |
| 22 | Crofer 22 APU / SS441 density (proprietary material) | 7.70 | $g/cm^3$ |
| 23 | Mass of interconnect plate | 43.07 | g |
| | **General info: Interconnect coating material (MCO)** | | |
| 24 | MCO coating thickness | 3.00E-04 | cm |
| 25 | MCO density | 1.41 | $g/cm^3$ |
| 26 | Volume of MCO coating | 0.135 | $cm^3$ |
| 27 | Mass of MCO coating | 0.19 | g |
| | **General info: Sealing (Ceradyne VIOX V1649) made of LO and BSG** | | |
| 28 | Sealing material thickness on a 1 cm margin | 148 | microns |
| 29 | Sealing material width | 0.80 | cm |
| 30 | Seal area | 0.0118 | $cm^2$ |
| 31 | Total sealing length | 323.36 | cm |
| 32 | Volume of seal material per cell | 3.83 | $cm^3$ |
| 33 | Density of seal material | 4.37 | $g/cm^3$ |
| 34 | Mass of seal material per cell | 16.73 | g |
| | **General info: Current collector (SS904L/SS441 with MCO)** | | |
| 35 | Current collector plate thickness | 0.025 | cm |
| 36 | Margin for current collector plate | 1.00 | cm |
| 37 | Current collector plate length | 19.83 | cm |
| 38 | Current collector plate width | 14.55 | cm |
| 39 | Current collector plate volume | 7.21 | $cm^3$ |
| 40 | Mass of collector plate | 58 | g |
| | **General info: Current collector coating material (MCO)** | | |
| 41 | MCO coating thickness | 3.00E-04 | cm |
| 42 | MCO density | 1.41 | g/cm3 |

| | | | |
|---|---|---|---|
| 43 | Volume of MCO coating | 0.194 | cm3 |
| 44 | Mass of MCO coating | 0.27 | g |
| | **General info: End plate (A560 stainless steel)** | | |
| 45 | Margin for end plate | 1.00 | cm |
| 46 | End plate length | 19.83 | cm |
| 47 | End plate width | 14.55 | cm |
| 48 | End plate thickness | 1.50 | cm |
| 49 | Volume of an end plate | 432.77 | $cm^3$ |
| 50 | Density of end plate material | 7.80 | $g/cm^3$ |
| 51 | Mass of end plate | 3376 | g |

*Source: Authors' compilation from Anghilante, Régis, David Colomar, Annabelle Brisse, and Mathieu Marrony. 2018. "Bottom-up Cost Evaluation of SOEC Systems in the Range of 10–100 MW."* International Journal of Hydrogen Energy*, 43 (45): 20309–22.*

Table A7 outlines the material costs associated with an SOE electrolyser consisting of rare earth materials, high-temperature ceramics, interconnect, and other key materials used in cell construction.

**Table A7 Material cost assumption**

| Sr. No. | Material cost | Value | Unit | Reference |
|---|---|---|---|---|
| 1 | LSCF (anode) | 53 | EUR/kg | (Anghilante, et al. 2018) |
| 2 | SSZ (electrolyte) | 256 | EUR/kg | (Anghilante, et al. 2018) |
| 3 | CGO (coating) | 42 | EUR/kg | (Anghilante, et al. 2018) |
| 4 | NiO/CGO (cathode) | 23 | EUR/kg | (Anghilante, et al. 2018) |
| 5 | Organic solvents | 10.6 | EUR/kg | (Anghilante, et al. 2018) |
| 6 | Sheet metal (Crofer 22 APU) | 25 | USD/kg | (Scataglini, et al. 2015) |
| 7 | Coating powder (MCO) | 300 | USD/kg | (Scataglini, et al. 2015) |
| 8 | Sealing (LO and BSG) | 24.25 | USD/kg | (Battelle 2016) |
| 9 | Current collector (LSCF) | 5.31 | USD/kg | (Battelle 2016) |
| 10 | End plate (A560 cast steel) | 7.95 | USD/kg | (Battelle 2016) |
| 11 | Benzyl n-butyl phthalate (Alfa Aesar) | 2.67 | USD/kg | (Indiamart 2022) |

| | | | | |
|---|---|---|---|---|
| 12 | n-butyl alcohol, 99.9% (Fisher Scientific) | 1.33 | USD/kg | (PNNL 2013) |
| 13 | Polyvinyl butyral, Butvar® B-79 | 19.75 | USD/kg | (PNNL 2013) |
| 14 | Phospholan™ PS-236 surfactant | 6.47 | USD/kg | (PNNL 2013) |
| 15 | Glass powder | 36.53 | USD/kg | (PNNL 2013) |
| 16 | Argon | 2.4 | USD/kg | (Indiamart 2022) |
| 17 | Nitrogen | 0.69 | USD/kg | (Indiamart 2022) |
| 18 | Hydrogen | 1.95 | USD/kg | (Alibaba 2022) |
| 19 | CuO | 11.3 | USD/kg | (Indiamart 2022) |
| 20 | Carbon pore former | 38 | USD/kg | (Alibaba 2022) |
| 21 | 2-butoxyethanol | 1.01 | USD/kg | (Indiamart 2022) |
| 22 | Inconel® 600 | 26.7 | USD/kg | (Steel Tubes India 2022) |
| 23 | $Al_2O_3$ substrate | 42.38 | USD/kg | (PNNL 2013) |
| 24 | Cr-steel support plate | 0.67 | USD/kg | (PNNL 2013) |
| 25 | Assembling cost (scenario 1) | 25.84 | EUR/kW | (Anghilante, et al. 2018) |
| 26 | Assembling cost (scenario 2) | 4 | EUR/kW | (Anghilante, et al. 2018) |

*Source: Authors' compilation*

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