Outline

1. Quick History of Electrolyzers
2. Hydrogen paving the way to Renewables
3. Principles of Alkaline Electrolyzers
4. Two Highlights to catalyze innovation (Diaphragm + Electrodes)
5. Trajectory vs. PEM Technology
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A Quick History of Water Electrolyzers

- How far ago?

A word can certainly change the interpretation, sometimes even the course, of history. The former seems definitely to be the case with the verb I used [1] referring to Nicholson and Carlisle’s experiment: ‘discovered’ (water electrolysis). I should have more appropriately (and more cautiously) used the word ‘observed’.

before Volta, electricity and chemistry ever met. This had occurred sporadically with the application of electrical sparks from Leyden jars to chemical substances. The oldest citation is that mentioning the experiments of Father Beccaria around 1750 (quoted by Priestley in 1772). Father Beccaria observed that an electric discharge could ‘revivify’ metals; he was thus
A Quick History of Water Electrolyzers
- Who are the main pioneers?

• **Volta´s Pile**
  – Continuous electrical current
  – Letter to Joseph Banks – 20.03.1800
  – Banks shows to Anthony Carlisle
  – Carlisle was the first to show that Volta was right
  – Carlisle shows to William Nicholson

• **William Nicholson and Anthony Carlisle**
  – Connected to Nicholson´s doubler
  – Observation of H2 and O2 gas evolution
  – 30 April 1800
  – Filled a small tube with water
  – Inserted Volta´s pile wire
  – Gases formed two inches apart
  – Electrolysis was discovered
A Quick History of Water Electrolyzers

- Alkaline Water Electrolyzers @Scale in the 20th Century

• Long established and well mature technology
• Robust, reliable and safe
• Significantly efficient
• The most extended technology at a commercial level
  – By 1902, more than 400 industrial alkaline electrolyzers
  – Primarily for ammonia production (fertilizer industry)
  – Plants based on low-cost hydroelectricity

Aswan Electrolyser (KIMA)
165MW - 37000 m³H₂/h

Aswan Dam – Egypt


Source: ELT
A Quick History of Water Electrolyzers

Alkaline Water Electrolyzers @Scale in the 20th Century

- 20th century – Ammonia from hydropower
  - Electrolyser plants in Canada, Chile, Egypt, Iceland, India, Norway, Peru and Zimbabwe

- Today only 3 are believed to be in operation
  - Cuzco, Peru
  - Aswan, Egypt
  - Que Que, Zimbabwe
  - 28 electrolysers
  - 165 MW
  - Type S-556
  - 37000 Nm³H₂/h
  - In use over 35 years

- Other industries are still on the market
- Companies acquired or merged with others
- Transferred technologies
- Information is very scarce and contradictory

Source: KIMA

Zimbabwe Electrolyser
165MW - 37000 m³H₂/h
A Quick History of Water Electrolyzers

- NEL Hydrogen paving the way to green Hydrogen!

1789 - Discovery of water splitting by A. Paets van Troostwijk und J.R. Deimann

1820 - M. Faraday defined the term electrolysis for “water splitting”

1900 - First industrial electrolyzer by O. Schmidt

1920–1930 - First electrolysis boom due to high ammonia demand (fertilizers)

1924 - J.E. Noeggenrath was to first to patent high pressure electrolyzer (100 bar)

1925 - M. Raney investigated the activity of catalysts to increase catalyst surface area.

1929 - Norsk-Hydro’s (NEL Hydrogen) started hydrogen via electrolysis with earliest bipolar technology

1948 - E.A. Zdansky demonstrated first high pressure industrial electrolyzer (Lonza)

1954-1957 - Winsel and Justi patented Raney-Nickel for Alkaline Electrolyzers

1956-1960 - Largest atmospheric pressure electrolyzer (40,000 Nm³/h H₂ (200 MW)) in Assuan – Egipt

1972-1974 - Largest high pressure electrolyzer (Lurgi) (21,000 Nm³/h H₂) in Zimbabwe (100 MW)
A Quick History of Water Electrolyzers

- NEL Hydrogen paving the way to green Hydrogen!

Såheim I&II, Rjukan: from 1929

Up to 16500 Nm³/h and 88 MWₑ
A Quick History of Water Electrolyzers

- NEL Hydrogen paving the way to green Hydrogen!

Rjukan, Norway (1927 – 1970s)

- Two largest electrolyser plants worldwide
- Capacity: 30,000 Nm3/h each
- Energy consumption: 135 MW each
- Electrolycity source: Hydropower

Glomfjord, Norway (1953 – 1991)
A Quick History of Water Electrolyzers

- NEL Hydrogen paving the way to green Hydrogen!

Vemork, Rjukan: from 1928 to 1971

25500 Nm³/h, 136 MW$_{el}$
A Quick History of Water Electrolyzers

NEL Hydrogen paving the way to green Hydrogen!

Glomfjord: from 1948 – 1993

27100 Nm³/h and 142 MW_{el}
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Hydrogen paving the way to Renewables
- US Department of Energy’s H2@Scale initiative

Source: B. Pivovar, DOE H2@Scale, www.energy.gov
Markets grow as unit scale increases

- Analytical Labs
- Weather Balloon Filling
- Industrial Processes
- Heavy Duty Vehicle Fueling
- Power Plant Cooling

Electrolysis has been sustained by applications with varying price points.
NEL Hydrogen – A key player in the generation of green hydrogen

- Iberdrola, Spain; Renewables $\rightarrow$ Green Hydrogen (20 MW PEM) $\rightarrow$ Ammonia

Nel and Aibel team for Iberdrola plant to kick off green hydrogen pact

Electrolyser maker and oil & gas services company to jointly develop and deliver large green hydrogen projects

Electrolyser maker Nel and oil & gas services company Aibel signed a framework agreement to work together on large-scale renewable hydrogen projects.

To kick-off their alliance the two Norwegian groups will work jointly to deliver a 20MW PEM hydrogen production plant to Iberdrola to provide green hydrogen for industrial use in a link-up with fertiliser group Feribertia that was first announced last summer by the Spanish utility.

“We are very excited to be announcing this collaboration with Aibel, a company with vast experience in delivering large scale, complex projects across industries,” Nel chief executive Jon André Leiske said.

Their in-house construction expertise and experience in fabrication and modularisation will add significant value to Nel’s global delivery and project execution abilities.”

Leiske added the partnership is a long-term commitment. Beyond the work for Iberdrola, Nel is phasing in Aibel on selected ongoing projects.

The agreement represents a strategic step in Aibel’s transformation towards renewable energy segments, the service provider’s CEO Mads Andersen said.

PEM Electrolyser
Containerized Solution
NEL Hydrogen – A key player in the generation of green hydrogen
- Sunline Transit, Renewables ➔ Green Hydrogen (2 MW PEM) ➔ Bus Refueling

**NEL ASA: Awarded USD 8.3 million Hydrogen Electrolyser Fueling Station Contract**

(Oslo, 25 September 2017) Proton Onsite (Proton) and Nel Hydrogen Solutions, divisions of Nel ASA (Nel, OSE:NEL), have received a purchase order of USD 8.3 million on a combined hydrogen PEM electrolyser and H2Station® fueling solution for SunLine Transit Agency (SunLine) in California. The combined solution will have a hydrogen capacity of up to 900 kg per day, making it the world’s largest combined hydrogen production and fueling facility currently being contracted. SunLine will use the solution for fueling of their growing fleet of Fuel Cell Electric Buses operating in the Palm Springs area in California.

“We are very pleased to have been awarded this contract to deliver a turnkey hydrogen production and fueling solution to SunLine that will provide zero-emission public transportation for the Palm Springs area and contribute to California’s climate efforts. This delivery highlights the combined strengths of Proton and Nel, using cutting-edge technology both within PEM electrolysis and heavy duty fueling solutions for buses,” says Jon André Løkke, Chief Executive Officer of Nel.

The facility will be delivered turn-key, consisting of one Proton PEM M400 electrolyser, and two H2Station® units from Nel. The awarded contract has a total value of just over USD 8.3 million, with expected delivery and installation during 2018.

“The project is strategically important for Nel and Proton, as it shows our joint capability in delivering unparalleled hydrogen production and fueling solutions. The combined organization is well-positioned to be part of current and future initiatives needed to achieve California’s long-term renewable energy goals,” says Løkke.

The project is supported by the Californian Air Resources Board (CARB) under the California Climate Investments (CCI) program.
NEL Hydrogen – A key player in the generation of green hydrogen
- Polysilicon (Malaysia), Renewables → Hydrogen (25 MW ALK) → Semiconductors

Using 100% green electricity from Hydroelectricity

Hydrogen supply is critical for the plant → reliability is paramount

24/7 operation

Biggest water electrolyser in operation globally

Offsetting ~43,000 Tons CO₂/y
NEL Hydrogen – A key player in the generation of green hydrogen

- HYBRIT - Sweden, Renewables → Green Hydrogen → Fossil-free steel project
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Principles of Alkaline Water Electrolyzers

- Alkaline vs. PEM

Anode: $4\text{OH}^- \leftrightarrow 2\text{H}_2\text{O} + \text{O}_2 + 4\text{e}^-$

Cathode: $4\text{H}_2\text{O} + 4\text{e}^- \leftrightarrow 2\text{H}_2 + 4\text{OH}^-$
Principles of Alkaline Water Electrolyzers

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PEM electrolyzers

Anode: \(2\text{H}_2\text{O} \leftrightarrow \text{O}_2 + 4\text{H}^+ + 4\text{e}^-\)

Cathode: \(4\text{H}^+ + 4\text{e}^- \leftrightarrow 2\text{H}_2\)

PFSA membranes: Ex. Nafion
Principles of Alkaline Water Electrolyzers

- OH\(^-\) vs. H\(^+\) Electrolytes

![Diagram of alkaline water electrolysis](image)

**Table 1.**

<table>
<thead>
<tr>
<th>Ion</th>
<th>(\lambda_{0}^{+}, \lambda_{0}^{-}/\Omega^{-1}) mol(^{-1}) cm(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(^+)</td>
<td>349.8</td>
</tr>
<tr>
<td>OH(^-)</td>
<td>197</td>
</tr>
<tr>
<td>K(^+)</td>
<td>73.5</td>
</tr>
<tr>
<td>NH(_4^+)</td>
<td>37.7</td>
</tr>
<tr>
<td>Rb(^+)</td>
<td>77.5</td>
</tr>
<tr>
<td>Cs(^+)</td>
<td>77</td>
</tr>
<tr>
<td>Ag(^+)</td>
<td>62.2</td>
</tr>
<tr>
<td>Na(^+)</td>
<td>50.11</td>
</tr>
<tr>
<td>Li(^+)</td>
<td>38.68</td>
</tr>
<tr>
<td>[Fe(CN)(_6^{3-})]</td>
<td>440</td>
</tr>
<tr>
<td>[Fe(CN)(_6^{3-})]</td>
<td>303</td>
</tr>
<tr>
<td>[CrO(_4^{2-})]</td>
<td>166</td>
</tr>
<tr>
<td>[SO(_4^{2-})]</td>
<td>161.6</td>
</tr>
<tr>
<td>I(^-)</td>
<td>76.5</td>
</tr>
<tr>
<td>Cl(^-)</td>
<td>76.4</td>
</tr>
<tr>
<td>Ca(^{2+})</td>
<td>119.6</td>
</tr>
<tr>
<td>NO(_3^-)</td>
<td>71.5</td>
</tr>
<tr>
<td>CH(_3)COO(^-)</td>
<td>40.9</td>
</tr>
<tr>
<td>C(_6)H(_5)COO(^-)</td>
<td>32.4</td>
</tr>
</tbody>
</table>
Materials and properties of alkaline electrolysers

- Electrolyte Concentration and Temperature of Operation

Points to consider:

- Responsible for great Ohmic losses
- Ionic transfer depends on electrolyte conc.
- Distance between the different layers
- Presence of bubbles (sizes)
- Viscosity/Surface tension (additives)
- Interaction with the diaphragm
- Temperature distribution
- Recirculation
- Leakage
- Advantages when monopolar conf. is used
- Evaporation
- Corrosion
- Safety issues
Past R&D Activities within Alkaline Water Electrolyzers

- Different types of diaphragms

Requirements for using diaphragms:
- High gas separation efficiency
- High chemical stability
- High mechanical and thermic stability

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Temperature [°C]</th>
<th>Thickness [µm]</th>
<th>Specific Resistance [Ωcm²]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain Asbestos</td>
<td>inorganic</td>
<td>&lt;100</td>
<td>2000 - 5000</td>
<td>0,74</td>
<td>hazardous</td>
</tr>
<tr>
<td>Polymer-reinforced Asbestos</td>
<td>composite</td>
<td>&lt;100</td>
<td>200 - 500</td>
<td>0,15 - 0,2</td>
<td>superior chemical resistance and mechanical stability in comparison to plain asbestos</td>
</tr>
<tr>
<td>PTFE-bonded potassium titanate</td>
<td>composite</td>
<td>120 - 150</td>
<td>300</td>
<td>0,1 - 0,15</td>
<td>shows excellent stability in hot caustic environment</td>
</tr>
<tr>
<td>Polymer-bonded zirconia</td>
<td>composite</td>
<td>&lt;160</td>
<td>200 - 500</td>
<td>0,25</td>
<td>ZrO₂ on polyphenylsulfon lattice</td>
</tr>
</tbody>
</table>
Past R&D Activities within Alkaline Water Electrolyzers

- Electrode Developments

- Circular bipolar plate (~1.8 m in diameter) with gas-ducts at top and lye ducts at bottom
- Electrodes on both sides fixed to bipolar plates with through connection bolts
- Rubber frames with inlet/outlet channels
- **Electrodes and bipolar plate of mild steel coated with nickel**
  - Nickel-plating key in production technology
- Anodes: activated nickel
- Cathodes: SU-coating
  - Developed by Norsk Hydro in 1950-1960's and increased production output by 30%
- Electrode activation and nickel-plating is core technology and carried out at Notodden, Norway
Past R&D Activities within Alkaline Water Electrolyzers

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• Anodes: activated nickel

• Cathodes: SU-coating
  • Developed by Norsk Hydro in 1950-1960’s and increased production output by 30%

• Electrode activation and nickel-plating is core technology and carried out at Notodden, Norway
World largest AEL plant in operation
- Tokyama plant 25 MW – 12 t/d
Largest AEL plant in operation in Europe 2020
- Akzo Nobel/Nouryon, Norway - Chemicals – 1.940Nm³/h - 9.2MW
- Commercial technologies

**Liquid KOH (base):**
- Catalysts are common metals
- Corrosive electrolyte
- Low output, high efficiency

**Proton exchange membrane (PEM/acid):**
- Catalysts are rare metals
- High output, benign electrolyte

**Technology Status**
- Commercial low temperature (50-80°C) – MW scale, demonstrated reliability

1 MW stack = ~20 m³

1 MW stack < ~0.5 m³

Commercial low temperature (50-80°C) – MW scale, demonstrated reliability
NEL HYDROGEN ELECTROLYSER

- Alkaline product scale

1 electrolyzer (2.2MW)
Built for future expansion up to any capacity size

176 electrolyzers (~400MW)
NEL HYDROGEN ELECTROLYSER

- PEM product scale

<table>
<thead>
<tr>
<th>M Series</th>
<th>Larger Installations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25-2.5 MW solution</td>
<td>5-25 MW solution</td>
</tr>
</tbody>
</table>
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Innovation within Alkaline Water Electrolyzers

- Alkaline vs. PEM – Thickness of the separator/membrane

![Graph showing the relationship between cell voltage ($U_{cell}$) and current density ($i$) for alkaline and acidic conditions. The graph includes two lines: one for alkaline conditions with a formula $T = 80^\circ C$, $p = 1$ bar, and another for acidic conditions. The graph highlights experimental data points.](image-url)
Innovation within Alkaline Water Electrolyzers

- Alkaline vs. PEM – Thickness of the separator/membrane

Experimental
Innovation within Alkaline Water Electrolyzers

**PBI based membranes coupled to Raney-Ni catalysts**

- Ion-solvating membranes

Raney-electrodes by perforated plates

Cells operated with strong supporting KOH
No ionomer needed

Prepared by DLR Stuttgart by VPS method

Raney nickel compositions
Cat.: Ni, Al, Mo
An.: Ni, Al

Innovation within Alkaline Water Electrolyzers

PBI based membranes coupled to Raney-Ni catalysts - Ion-solvating membranes

- 24 wt% KOH at 80°C for three different cells. Error bars represent variation across 2 or 3 cells.
- Cells are (cathode/seperator/anode): Raney-NiMo/40 µm m-PBI membrane/Raney-Ni anode.

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Innovation activities within PEM Electrolyzers

– can PEM components be an inspiration???

PEM CAPITAL COST

- Demonstrated cost evolution – scale

Cell Stack:
- Cost curve primarily driven by material utilization
- Improved bipolar plate format for 250 kW stack

Balance of Plant:
- Rule of six tenths seems to be supported by past scale up activities
Electrode integration: porous transport layers

- Gas diffusion layer needs to contact catalyst layer effectively while providing porosity
  - Typically involves a microporous layer (MPL) approach
  - Materials optimized for fuel cell, not electrolyzer
  - Wetproofing vs. wettability, gas vs. liquid flow
- Design and manufacturing maturity needs to catch up for electrolysis for both MEA and adjacent components

Gasteiger, ECS 2018

Friedrich, J. Power Sources 2016
HOW REALISTIC ARE LARGE COST REDUCTIONS?

- Example of 80% component cost reduction

Fundamental R&D to Prototyping

Products from kW to MW scale

Component modeling

Accelerated embrittlement

Plate manufacturing

Nel scale up and commercialization: MW stack based on same platform
THE IMPORTANCE OF AUTOMATION

- Example of advanced manufacturing

Roll to roll manufacturing already demonstrated for related fuel cell industry

Current: T-shirt printing like
Slow, moderate control, high labor

Future: Newspaper printing like
Fast, precision, low labor
Final Remarks

- Alkaline Electrolyzers:
  - Well established and mature at scale technology
  - Robust
  - Low-cost
Final Remarks

- Alkaline Electrolyzers:
  - Well established and mature at scale technology
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- High Potential for Innovation
  - Diaphragms
  - Electrodes
  - Porous Transport Layers and interfaces
  - Cell and Stack design for high pressure operation
Final Remarks

- **Alkaline Electrolyzers:**
  - Well established and mature at scale technology
  - Robust
  - Low-cost

- **High Potential for Innovation**
  - Diaphragms
  - Electrodes
  - Porous Transport Layers and interfaces
  - Cell and Stack design for high pressure operation

- **PEM Electrolyzers**
  - Significant achievements in cost and efficiency levels
  - Important steps towards automations (as with Fuel Cells, batteries) are on the making
ACKNOWLEDGEMENTS

Forschungszentrum Julich (IEK-14):
Martin Mueller
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Kathy Ayers
Egil Rasten
Everett Anderson

and you for the attention!!!
number one by nature
Heavy duty H$_2$ vehicles may be earliest market growth

- More synergistic with heavy transport vehicles like buses and shipping trucks – long range, fast fueling
- Fixed routes keep capacity high
- Larger stations reduce production cost