Towards Zero-Emission Shipping
-with Fuel Cells and Model-Based Design
30+ years of R&D activities

1988
- Founded by Odd Dahl

1991
- Mjøllner: 10kW SOFC project for Statoil
- Initiation of SOFC for Mars Project by ESA

2004
- Regenerative H2/O2 Fuel Cell & Hydrogen for ESA
- High Temperature PEM Fuel Cell
- RSOFC for Mars by ESA
- CHEOP Project with industrial partners Shell and Statoil
- ZEG Power 20kW module developed

2006
- Green Fish Farm concept established

2010
- H2/O2 Fuel Cell & Hydrogen for ESA

2014
- CHEOP Project with industrial partners Shell and Statoil
- ZEG Power 20kW module developed

2015
- Artiaga: 10kW SOFC project for Statoil
- Initiation of SOFC for Mars Project by ESA

2016
- CHEOP Project with industrial partners Shell and Statoil
- ZEG Power 20kW module developed

2018
- Clean Power AS established
- Clean Power AS launched from Clara Venture Labs

2019
- EU-funded ShipFC: Zero-Emission Ammonia Fuel Cell
- ZEG Power 20kW module developed

2020
- Clean Power AS launched from Clara Venture Labs

2021
- EU-funded ShipFC: Zero-Emission Ammonia Fuel Cell
- Clean Power AS launched from Clara Venture Labs
- Aker signs agreement to acquire Prototech

2021
- Clean Power AS launched from Clara Venture Labs
- EU-funded ShipFC: Zero-Emission Ammonia Fuel Cell
Problem:

No viable clean power solution for *deep-sea* shipping

*90% of global fleet

Total annual greenhouse gases emissions from international shipping to be reduced with at least 50% by 2050 compared to 2008.
What is a Solid Oxide Fuel Cell (SOFC)?

- High temperature (700 – 800 C) allows for internal cracking or reformation
- Available heat at high temperature (high value)
- High efficiency of electricity generation

**Hydrogen**

Ammonia (NH3)
Methane (CH4)
Methanol (CH3OH)

**Oxygen**

Air

**Electric Current**

Fuel In → e⁻ → Air In

H₂ → e⁻ → O₂

H₂O → e⁻ → Unused Gases Out

Anode → Electrolyte → Cathode

Excess Fuel and Water
SOFC solve the two main challenges related to decarbonization

**SIGNIFICANTLY HIGHER ENERGY EFFICIENCY**

<table>
<thead>
<tr>
<th></th>
<th>ICE</th>
<th>SOFC</th>
<th>SOFC future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Efficiency</td>
<td>40-50%</td>
<td>65%</td>
<td>70%+</td>
</tr>
</tbody>
</table>

**COMPATIBLE WITH FUTURE DEEP-SEA FUELS**

<table>
<thead>
<tr>
<th>FUEL</th>
<th>TECHNOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOFC</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>✓</td>
</tr>
<tr>
<td>Future deep-sea fuels Methanol, Ammonia</td>
<td>✓</td>
</tr>
<tr>
<td>Transition fuels LNG, LPG</td>
<td>✓</td>
</tr>
<tr>
<td>Traditional fuels Diesel, VLSFO</td>
<td>?</td>
</tr>
</tbody>
</table>

**MULTIPLE OTHER BENEFITS**

- **Low maintenance** with no moving parts
- **Silent** and **no vibrations**
- **Modularity** enables new ship design possibilities
- **Carbon capture** potential (high CO₂ concentration)
In-house early-stage venture lab

Clara Venture Labs in brief

Established >30 years ago, Clara Venture Labs is a venture lab delivering technology innovation, R&D projects, and venture support services.

Impressive track record of building breakthrough technology ventures from discoveries in the lab, including carbon capture, hydrogen production, and fuel cell technology solutions.

Systematically developing new innovations in partnership with Atoma Capital and leading institutions.

>3,600 m² of laboratories and testing facilities

Materials Characterization Lab

Lab Scale Experimentation Facility

Manufacturing Facilities

Energy Lab
Thermodynamics

\[ \Delta H, S, C_p \]


coder.extrinsic('py.CoolProp.CoolProp.PropsSI')
**Fuel cell - Thermodynamics**

\[
2NH_3 \rightarrow 3H_2 + N_2 \quad \text{Endothermic}
\]

\[
CH_4 + H_2O \rightarrow CO + 3H_2 \quad \text{Endothermic}
\]

\[
CO + H_2O \rightarrow CO_2 + H_2 \quad \text{Exothermic}
\]

\[
2H_2 + O_2 \rightarrow 2H_2O \quad \text{Exothermic}
\]
Fuel cell - Electrochemistry

\[ E_{\text{tot}} = E_{\text{rev}} - E_\Omega - E_{\text{cons}} - E_{\text{act}} \]

\[ E_{\text{rev}} = \frac{\Delta G_0}{4F} - \frac{TR}{4F} \cdot \ln \left( \frac{p_{H_2O}^2}{p_{H_2} \cdot p_{O_2}} \right) \]

\[ E_\Omega = \frac{I}{\text{area}} \cdot \left( ASR_{Tref} \cdot \exp \left( 1.08 \cdot \frac{F}{R} \left( \frac{1}{T} - \frac{1}{T_{\text{ref}}} \right) \right) + ASR_{\text{time}} \right) \]

\[ E_{\text{cons}} = -\frac{RT}{ZF} \ln \left( 1 - \frac{I}{I_L} \right) \]

\[ E_{\text{act}} = a \cdot \log(I) + b \]
Fuel cell - Measurements

\[ \text{Power} = \text{electric current} \cdot \text{potential} \]

All other energy is transformed to thermal energy.

Hence you can find the temperature of the fuel and air out from your fuel cell.
Data flow
Different utilisation of MATLAB/Simulink though projects
Example of modelling in the start and end of a project

If $T_{out}^{hot}$ is set, you know how much heat the cold fluid gets if we assume no losses:

$$Q = \Delta H \cdot \text{mass} = (\Delta H_{out} - \Delta H_{in}) \cdot \text{mass}$$

And you can calculate

$$T_{out}^{cold} = T_{in}^{cold} - \frac{Q}{c_p^{cold} \cdot \text{mass}}$$

Heat exchanger

$$Q = \epsilon \cdot C_{min}(T_{fuel} - T_{water})$$

$$\epsilon = \frac{1 - \exp(-N \cdot (1 - C))}{1 - C \cdot \exp(-N(1 - C))}$$

$$N = \frac{h}{C_{min}}$$

$[W/K]$

Dependent on
- area
- material
Additional work

- Make our own Gas mixture
- Include their thermodynamic properties
- Calculations of reaction rates

Azure DevOps

- Large system with many people with different areas of expertise
- Important to be able to test new code with code written by other experts

Git

Custom Libraries
What have we gotten out from our MATLAB/Simulink models?

1. **Prediction**: Give new investors and customers good estimates of future systems efficiencies, fuel utilization and available heat.

2. **Techno-economic insights** for downsizing components and selecting commercial off-the-shelf (COTS) products.

3. **Simplified** component manufacturing by setting mass flow, pressure, and temperature early on in the project.

4. **Leveraging value in test data**: Learn from lab tests, implement the data in our models for improvement to the next model.
Thank you for your attention

- 30+ years fuel cell experience
- Competent and capable organization
- Platform backed by Aker and ICP
- Maritime DNA
- Future proof technology