RENEWABLE POWER VIA ENERGY SHIP
AND GRAZ CYCLE

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Outline

- The Energy Ship Concept
- Hydro Turbine Experiment
- Graz Cycle
Transition to Renewable Energy

- David MacKay – University of Cambridge
  - “Sustainable Energy – without the hot air”
- Mark Jacobson – Stanford University, 2009
  - 4 million 5 MW wind turbines
  - 50,000 Concentrated Solar Plants
The Energy Ship Concept

- First proposed in 2009
- Performance and cost estimates
- 330,000 energy ship convoys needed to produce 1 TW of electric power
The Resource – Unlimited Wind

January

July

Wind Speed (meters/sec)
How does the ship work?

Wind

Sail

Electrolyser → H2 Storage

Generator (G)

Turbine

Offshore

Onshore

Power Plant

H2 Distribution

H2

Potable Water

Electricity
In More Detail...

Wind → Motion of Ship

Reverse Osmosis ← Onboard Generator ← Turbine or Oscillating Wing

Onboard Electrolysis → Onboard H₂ Storage
Energy Ship Concept

- Energy ship concept comprises a number of technologies:
  - large sailing ships equipped with modern rigid sails
  - hydro-turbines
  - sea water desalinators, electrolysers and hydrogen compressors
  - hydrogen-oxygen power plants
- Competitive concept due to the much higher capacity factors and wind speeds available to energy ships cruising in high-wind ocean areas
- Storable energy in the form of hydrogen is produced
- Most technology already relatively well developed; but further development is required
Experimental Study of a Small Hydroturbine

- Hydrodynamics Laboratory of the Naval Postgraduate School
- AmpAir Energy Ltd. turbine
- 3-bladed rotor of 312 mm diameter
- Test water speed range up to 1.7 m/sec
Test Setup for Power Measurement
• Max. measured power 27 W
• Max. design power 100 W
• A single energy ship delivers approx. 1.5 MW hydroturbine power
• This corresponds to 17.3 kg hydrogen per hour and 137.3 kg oxygen per hour
• The following proposed Graz Cycle of 139 MW requires 5644.8 kg hydrogen per hour
• This corresponds to 330 energy ships
Efficient Use of Hydrogen

- Energy ships deliver hydrogen H\textsubscript{2} and oxygen O\textsubscript{2} to storage tanks which feed new hybrid fuel cell/gas turbine plant

New Hybrid FC-GT Plant 140 MW, 74% therm. efficiency

High-pressure tanks

Source: www.power.statom.com
• High temperature Solid Oxide Fuel Cells (SOFC) up to 250 kWel were successfully built and operated. A unit power up to 2500 kWel seems feasible.

• Therefore a hybrid power plant with 12 fuel cells of 2.5 MWel arranged in parallel is proposed, leading to reasonable size of turbomachines.

• Fuel Cell electrical power about half of energy content of utilized hydrogen.

• Difference heats up steam flow through the fuel cell

Hybrid fuel cell/gas turbine plant

Source: Siemens Westinghouse, 100 kW SOFC
Hybrid Graz Cycle Power Plant

- Fuel Cells FC and Turbomachinery have the same working fluid: H2O (steam)

**Components:**
- **HTT1** - High Temperature Compressor Turbine
- **HTT2** - High Temperature Power Turbine
- **HPT** - High Pressure Steam Turbine
- **LPT** - Low Pressure Steam Turbine
- **C** - Steam Compressors
- **FC** - Fuel Cells
- **HRSG** - Heat Recovery Steam Generator

**Details:**
- **Electric Power**
  - **O2** → FC → H2O – hot steam
- **Start + Peak power**
  - **41 bar**
  - **600°C**
- **Combustion of H2 surplus**
  - **40 bar**
  - **1550°C**
- **Main Generator**
  - **870°C/40 bar**
- **Motor/Generator**
  - **1 bar**
  - **100°C**
- **Condenser**
  - **0.05 bar**

**Steam Flow:**
- **H2O – hot steam**
- **Steam Compressors**
- **41 bar**
- **620°C**
- **Steam**

**Heat Recovery Steam Generator (HRSG):**
- **1 bar**
- **670°C**
- **Electric Power**
- **Combustion of H2 surplus**
- **Deaerator**
- **Condenser**
- **Feed water**
### Power Balance

Hybrid FC/GT plants achieve high efficiencies

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Fuel input</td>
<td>1.568 kg/s H2, 12.44 kg/s O2</td>
</tr>
<tr>
<td>Total heat input (LHV)</td>
<td>188 MW</td>
</tr>
<tr>
<td>HTT power</td>
<td>123.1 MW</td>
</tr>
<tr>
<td>HPT power</td>
<td>22.4 MW</td>
</tr>
<tr>
<td>LPT power</td>
<td>14.3 MW</td>
</tr>
<tr>
<td>Compressor power</td>
<td>47.8 MW</td>
</tr>
<tr>
<td>Total pump power</td>
<td>0.7 MW</td>
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<tr>
<td>Generator power</td>
<td>109.6 MW</td>
</tr>
<tr>
<td>Fuel cell DC power</td>
<td>30 MW</td>
</tr>
<tr>
<td>Fuel cell AC power</td>
<td>29.1 MW</td>
</tr>
<tr>
<td>Net electrical power</td>
<td>138.7 MW</td>
</tr>
<tr>
<td><strong>Net efficiency</strong></td>
<td><strong>73.8 %</strong></td>
</tr>
</tbody>
</table>
Challenges for Turbomachinery Layout

- Unusual working fluid (steam) for HTT and compressor
- Enthalpy drop about twice as high as for air -> larger number of stages
- Higher speed of sound influences compressor design
- Risk of condensation
- Start-up and shutdown
Turbomachinery Layout

- Small mass flow demand high rotational speeds of free-running turbomachinery
- High Pressure Turbine HPT and one-stage High Temperature Turbine HTT1 drive the compressor running at **22432 rpm**
- Five-stage power turbine HTT2 runs at **9400 rpm** and is connected to generator via a gear box
- High rotational speed of 22432 rpm to achieve a reasonable enthalpy drop for the HTT1
- HTT2 at 9400 rpm: reasonable stage number of five at bearable disk stresses at the same time

Solid rotor design with blade lengths from 90 mm to 350 mm attached in fir-tree roots on small elongation disks on the rotor drum

Cooling of first stages with steam
Compressor and HPT

- **Compressor**: double flow rotor with two axial stages on each side connected to a radial disk
  Symmetric arrangement creates an optimal flow situation in the radial diffuser
  Axial stages: half of the compressor pressure head, first axial stages have a maximum tip Mach number of 1.4
- **HPT**: 50% reaction blading and multiple stages at low rotor diameter
  A balance piston is arranged in the usual way
• LPT in the form of a conventional low-pressure three-stage turbine
• The speed is 3000 rpm, the turbine is contributing about 14 MW to the power output
• The mean radius of the last stage is 1134 mm and the last blade length is 660 mm

Last blade: water droplet impingement protection (maximum wetness 12%).

Inlet Steam:
1 bar, 100°C

Last blade tip velocity: 460 m/s

Shaft connected to generator

3000 rpm
Conclusions

- Energy ships provide access to the vast ocean wind resources
- The production of hydrogen via the energy ship requires only known technologies
- The conversion of hydrogen into electricity can be done with existing power plants
- However, use of the Graz Cycle permits a very high efficiency
- Layout of the main turbomachinery components for the Graz Cycle shows its feasibility
- Current studies of the energy ship concept indicate that the hydrogen can be produced at a cost similar to that of off-shore wind turbines
MAHALO

Thank you