Research Title
DYNAMIC MODELING OF A WIND-DIESEL-HYDROGEN HYBRID POWER SYSTEM

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Outlines

- Prospects of RE sources in Canada.
- Status of electrical generation and consumption at Ramea (HOMER based analysis).
- Modeling and simulations of WTs, hydrogen systems and diesel gensets.
- Transient analysis of Ramea hybrid power system.
- Conclusions.
- Future works.
Location of Ramea

- It is a small island 10 km from the South coast of Newfoundland.
- Population is about 700.
- Traditional fishery community
Canada is blessed with adequate wind resources. She has the longest coast-line and the second largest land mass. They are in a better position to deploy more number of WECS.

<table>
<thead>
<tr>
<th>Countries</th>
<th>Annual Mean Wind Speed (m/s)</th>
<th>Wind Power Density (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>5.5-7.0</td>
<td>200-400</td>
</tr>
<tr>
<td>Spain</td>
<td>5.5-8.0</td>
<td>200-600</td>
</tr>
<tr>
<td>USA</td>
<td>6.5-9.0</td>
<td>300-800</td>
</tr>
<tr>
<td>India</td>
<td>5.5-8.0</td>
<td>200-600</td>
</tr>
<tr>
<td>China</td>
<td>5.5-9.0</td>
<td>200-800</td>
</tr>
<tr>
<td>Canada</td>
<td>6.5-9.0</td>
<td>300-800</td>
</tr>
</tbody>
</table>
Ramea Electrical System (cont.)

4.16 kV Bus

- Six 65 kW Wind Turbines
- Three 925 kW Diesel Generators
- Three 100 kW Wind Turbines
- Electrolyzer
- Hydrogen Generator
- Hydrogen Storage
- Load
Ramea Electrical System

Load Characteristics
- Peak Load – 1,211 kW
- Average Load – 528 kW
- Minimum Load – 202 kW
- Annual Energy – 4,556 MWh

Distribution System
- 4.16 kV, 2 Feeders

Energy Production
- Nine wind turbines (6X65 kW and 3X100 kW).
- Three diesel generators (3X925 kW).
- Four hydrogen generators (4X62.5 kW).
# Ramea Power System simulation in HOMER

<table>
<thead>
<tr>
<th>Hybrid System Components</th>
<th>Capital Costs ($)</th>
<th>Replacement Costs ($)</th>
<th>O&amp;M Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>WM15S Wind Turbines</td>
<td>90,000</td>
<td>70,000</td>
<td>$1,200 per yr</td>
</tr>
<tr>
<td>NW100 Wind Turbines</td>
<td>550,000</td>
<td>480,000</td>
<td>$3,600 per yr</td>
</tr>
<tr>
<td>Diesel Generators</td>
<td>100,000</td>
<td>80,000</td>
<td>$5 per hr</td>
</tr>
<tr>
<td>Hydrogen Generators</td>
<td>50,000</td>
<td>37,500</td>
<td>$5 per hr</td>
</tr>
<tr>
<td>Electrolyzers</td>
<td>150,000</td>
<td>120,000</td>
<td>$600 per yr</td>
</tr>
<tr>
<td>Hydrogen Tanks</td>
<td>100,000</td>
<td>70,000</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Load Profile at Ramea

- Day-to-day variability – 8.14%.
- Time step-to-time step variability – 7.86%.
- Load factor – 0.448.
Wind Resource at Ramea

- Weibull shape factor – 2.02.
- Correlation factor – 0.947.
- Diurnal pattern strength – 0.0584.
Cost Summary of Ramea System

### Cash Flow Summary

![Cash Flow Summary Graph](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>Capital ($)</th>
<th>Replacement ($)</th>
<th>D&amp;M ($)</th>
<th>Fuel ($)</th>
<th>Salvage ($)</th>
<th>Total ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windmatic</td>
<td>540,000</td>
<td>108,536</td>
<td>83,906</td>
<td>0</td>
<td>-58,038</td>
<td>674,403</td>
</tr>
<tr>
<td>NorthWind 100</td>
<td>1,650,000</td>
<td>372,123</td>
<td>125,859</td>
<td>0</td>
<td>-198,989</td>
<td>1,948,993</td>
</tr>
<tr>
<td>925kW Diesel Gen</td>
<td>100,000</td>
<td>799,520</td>
<td>510,427</td>
<td>10,232,138</td>
<td>-1,474</td>
<td>11,640,613</td>
</tr>
<tr>
<td>250kW H2 Gen</td>
<td>200,000</td>
<td>57,216</td>
<td>40,904</td>
<td>0</td>
<td>-6,771</td>
<td>291,349</td>
</tr>
<tr>
<td>Electrolyzer</td>
<td>150,000</td>
<td>221,064</td>
<td>6,992</td>
<td>0</td>
<td>0</td>
<td>378,056</td>
</tr>
<tr>
<td>Hydrogen Tank</td>
<td>100,000</td>
<td>53,674</td>
<td>0</td>
<td>0</td>
<td>-6,449</td>
<td>147,225</td>
</tr>
<tr>
<td>System</td>
<td>2,740,000</td>
<td>1,612,133</td>
<td>768,087</td>
<td>10,232,138</td>
<td>-271,721</td>
<td>15,080,637</td>
</tr>
</tbody>
</table>
Electrical Performance of System Components (cont.)

Table: Electrical Characteristics of WM15S Wind Turbines

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total rated capacity</td>
<td>396 kW</td>
<td></td>
</tr>
<tr>
<td>Mean output</td>
<td>117 kW</td>
<td></td>
</tr>
<tr>
<td>Capacity factor</td>
<td>29.5%</td>
<td></td>
</tr>
<tr>
<td>Total production</td>
<td>1,022,662 kWh/yr</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum output</td>
<td>0 kW</td>
<td></td>
</tr>
<tr>
<td>Maximum output</td>
<td>396 kW</td>
<td></td>
</tr>
<tr>
<td>Wind penetration</td>
<td>23.9%</td>
<td></td>
</tr>
<tr>
<td>Hours of operation</td>
<td>6.832 hr/yr</td>
<td></td>
</tr>
<tr>
<td>Levelized cost</td>
<td>0.0566 $/kWh</td>
<td></td>
</tr>
</tbody>
</table>

Table: Electrical Characteristics of NW100 Wind Turbines

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total rated capacity</td>
<td>309 kW</td>
<td></td>
</tr>
<tr>
<td>Mean output</td>
<td>92 kW</td>
<td></td>
</tr>
<tr>
<td>Capacity factor</td>
<td>29.8%</td>
<td></td>
</tr>
<tr>
<td>Total production</td>
<td>805,500 kWh/yr</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum output</td>
<td>0 kW</td>
<td></td>
</tr>
<tr>
<td>Maximum output</td>
<td>308 kW</td>
<td></td>
</tr>
<tr>
<td>Wind penetration</td>
<td>18.8%</td>
<td></td>
</tr>
<tr>
<td>Hours of operation</td>
<td>7,003 hr/yr</td>
<td></td>
</tr>
<tr>
<td>Levelized cost</td>
<td>0.208 $/kWh</td>
<td></td>
</tr>
</tbody>
</table>
### Electrical Performance of System Components (cont.)

#### Table: Electrical Characteristics of 925 kW Diesel Generators

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours of operation</td>
<td>8,760</td>
<td>hr/yr</td>
</tr>
<tr>
<td>Number of starts</td>
<td>1</td>
<td>starts/yr</td>
</tr>
<tr>
<td>Operational life</td>
<td>1.14</td>
<td>yr</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>38.8</td>
<td>%</td>
</tr>
<tr>
<td>Fixed generation cost</td>
<td>31.0</td>
<td>$/hr</td>
</tr>
<tr>
<td>Marginal generation cost</td>
<td>0.229</td>
<td>$/kWh</td>
</tr>
</tbody>
</table>

- Electrical production: 3,141,887 kWh/yr
- Mean electrical output: 359 kW
- Min. electrical output: 278 kW
- Max. electrical output: 925 kW

#### Table: Electrical Characteristics of 250 kW Hydrogen Generators

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours of operation</td>
<td>702</td>
<td>hr/yr</td>
</tr>
<tr>
<td>Number of starts</td>
<td>702</td>
<td>starts/yr</td>
</tr>
<tr>
<td>Operational life</td>
<td>14.2</td>
<td>yr</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>2.41</td>
<td>%</td>
</tr>
<tr>
<td>Fixed generation cost</td>
<td>20.0</td>
<td>$/hr</td>
</tr>
<tr>
<td>Marginal generation cost</td>
<td>0.00</td>
<td>$/kWh</td>
</tr>
</tbody>
</table>

- Electrical production: 52,752 kWh/yr
- Mean electrical output: 75.1 kW
- Min. electrical output: 75.0 kW
- Max. electrical output: 93.6 kW

- Hydrogen consumption: 9,162 kg/yr
- Specific fuel consumption: 0.174 kg/kWh
- Fuel energy input: 305,384 kWh/yr
- Mean electrical efficiency: 17.3 %
Electrical Performance of System Components (cont.)

Table: Electrical Characteristics of the Whole System

<table>
<thead>
<tr>
<th>Production</th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbines</td>
<td>1,828,162</td>
<td>36</td>
</tr>
<tr>
<td>925 kW Diesel Gen</td>
<td>3,141,887</td>
<td>63</td>
</tr>
<tr>
<td>250 kW H2 Gen</td>
<td>52,752</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>5,022,801</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Consumption</th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC primary load</td>
<td>4,280,795</td>
<td>90</td>
</tr>
<tr>
<td>Electrolyzer load</td>
<td>482,333</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>4,763,128</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity</th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess electricity</td>
<td>259,549</td>
<td>5.17</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>302</td>
<td>0.01</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>704</td>
<td>0.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable fraction</td>
<td>0.374</td>
</tr>
</tbody>
</table>

Figure: Monthly Energy Production by Wind, Diesel and Hydrogen
Electrical Performance of System Components

Figure: Excess Electricity and Unmet Load of Ramea Hybrid Power System

- Excess energy – 259,549 kWh per year.
- Unmet load – 302 kWh per year.
- Capacity shortage – 704 kWh
WECS Components

Wind Energy Conversion
Torque and Speed Conversion
Mechanical to Electrical Energy Conversion

- Rotor Blades
- Shaft and Bearings
- Brakes
- Electrical Generator
- Transformer
- Capacitor Bank
Power Extraction from the Wind

\[ P_t = \frac{1}{2} \rho A C_p(\lambda, \beta) v_w^3 \]

\[ C_p(\lambda, \beta) = c_1 \left( \frac{c_2}{\lambda_1} - c_3 \beta - c_4 \right) e^{-\frac{c_5}{\lambda_1}} + c_6 \lambda \]

\[ \frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08 \beta} - \frac{0.035}{\beta^3 + 1} \]

\[ \lambda = \frac{\omega R}{v_w} \]

\[ T_t = \frac{1}{2} \rho A R \frac{C_p(\lambda, \beta)}{\lambda} v_w^2 = \frac{1}{2} \rho A R C_q(\lambda, \beta) v_w^2 \]

\[ C_q(\lambda, \beta) = \frac{C_p(\lambda, \beta)}{\lambda} \]
Modeling and Simulation of WM15S WT (cont.)
Modeling and Simulation of WM15S WT (cont.)

13 kW Generator in Operation

\[ v_w = 5 \text{ m/s} \]
\[ v_w = 6 \text{ m/s} \]
\[ v_w = 7 \text{ m/s} \]

0.25 kW Output  
1.48 kW Output  
3.05 kW Output
Modeling and Simulation of WM15S WT (cont.)

65 kW Generator in Operation

\[ v_w = 8 \text{ m/s} \]
\[ v_w = 9 \text{ m/s} \]
\[ v_w = 10 \text{ m/s} \]
\[ v_w = 11 \text{ m/s} \]

24 kW Output
32.9 kW Output
41.4 kW Output
48.9 kW Output
Modeling and Simulation of WM15S WT (cont.)

65 kW Generator in Operation

\[ v_w = 12 \text{ m/s} \]

55.3 kW Output

\[ v_w = 13 \text{ m/s} \]

60.2 kW Output

\[ v_w = 14 \text{ m/s} \]

63.7 kW Output

\[ v_w = 15 \text{ m/s} \]

65.8 kW Output
Modeling and Simulation of WM15S WT

Generator Rotational Speeds

\[ \omega_1 = 128 \text{ rad/s} \quad \text{and} \quad \omega_2 = 125 \text{ rad/s} \]
Modeling and Simulation of NW100 WT (cont.)

\[ \text{\(v_w\)} = 5 \text{ m/s} \]

\[ \text{\(v_w\)} = 6 \text{ m/s} \]

\[ \text{\(v_w\)} = 7 \text{ m/s} \]

\[ \text{\(v_w\)} = 8 \text{ m/s} \]

\[ \text{\(v_w\)} = 9 \text{ m/s} \]

\[ \text{\(v_w\)} = 10 \text{ m/s} \]

2.8 kW Output

14.1 kW Output

29.2 kW Output

46 kW Output

62.3 kW Output

76.1 kW Output
Modeling and Simulation of NW100 WT (cont.)

$v_w = 11 \text{ m/s}$  
$86.6 \text{ kW Output}$

$v_w = 12 \text{ m/s}$  
$93.4 \text{ kW Output}$

$v_w = 13 \text{ m/s}$  
$97.1 \text{ kW Output}$

$v_w = 14 \text{ m/s}$  
$98.2 \text{ kW Output}$

$v_w = 15 \text{ m/s}$  
$98.2 \text{ kW Output}$
Modeling and Simulation of NW100 WT

100 kW Generator Rotational Speed

\[ \omega = 183 \text{ rad/s} \]
Comparison of Actual and Simulated Power Curves

Power Curves of WM15S WT

Power Curves of NW100 WT
Modeling of Alkaline type Electrolyzer (cont.)

- 30% KOH is added to increase the conductivity level of the electrolyte.
- Anode made of Ni, Co & Fe and Cathode made of Ni & C-Pt prevent corrosion and ensure good conductivity.
- For the same reason diaphragm is made up of NiO.

Figure: Internal structure of an alkaline electrolyzer.
Modeling of Alkaline type Electrolyzer (cont.)

Figure: Simulink Model of 200 kW Electrolyzer.
Modeling of Alkaline type Electrolyzer (cont.)

- $H_2$ flow rate
- Cell voltage
- Faraday efficiency
- Energy efficiency

Figure: Electrochemical Model.
Modeling of Alkaline type Electrolyzer

- Heat generation
- Heat loss
- Cooling demand
- Temperature

Figure: Thermal Model.
Simulations of Alkaline type Electrolyzer (cont.)

Figure: Current & Power.

Figure: \( \text{H}_2 \) Generation.

Figure: Faraday & Energy Efficiencies.

Figure: Cell Voltage.
Simulations of Alkaline type Electrolyzer

Figure: Heat Generation.

Figure: Heat Loss.

Figure: Auxiliary Cooling.

Figure: Temperature.
Modeling of H₂ Tanks

Figure: Simulink Model of H₂ Tank.

Figure: Three Hydrogen Tanks of 1000 Nm³ combined Capacity.
Simulations of H₂ Tanks

Figure: Pressure Change in the H₂ Tank.
Modeling of H₂ Engines

- Throttle body dynamics
- Manifold dynamics
- Rotational dynamics

Figure: Simulink Model of H₂ Engines.
Simulations of H₂ Engines

Figure: H₂ Flow Input to Engines.

Figure: Mech. Power from Engines.

Figure: Synchronous Speed of the Engines.
Modeling of H$_2$ Generators

Figure: SimPower Model of H$_2$ Generator.
Simulations of H₂ Generator

Figure: H₂ Generator Output Power.

<table>
<thead>
<tr>
<th>Tank Output Flow Rate (mol/s)</th>
<th>Mechanical Power from Hydrogen Engine (kW)</th>
<th>Electrical Power Hydrogen Generator (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.472</td>
<td>70.70</td>
<td>68.5</td>
</tr>
<tr>
<td>1.300</td>
<td>62.50</td>
<td>60.5</td>
</tr>
<tr>
<td>1.150</td>
<td>55.25</td>
<td>53.5</td>
</tr>
<tr>
<td>1.000</td>
<td>48.00</td>
<td>46.5</td>
</tr>
<tr>
<td>0.850</td>
<td>40.83</td>
<td>39.6</td>
</tr>
<tr>
<td>0.700</td>
<td>33.63</td>
<td>32.6</td>
</tr>
<tr>
<td>0.550</td>
<td>26.42</td>
<td>25.6</td>
</tr>
</tbody>
</table>
Transient Analysis of Ramea Hybrid Power System

Figure: Ramea Hybrid Power System.
Modeling of Diesel Generators

Figure: SimPower Model of Diesel Generator.
Modeling of Dump Load

Figure: SimPower Model of Dump Load.
CS1: Simulation with Variable Load (1200/1600/1200 kW)

- Wind speed – 15 m/s.
- Dump load increases to minimize the effect of the main load declination.
- Secondary load current – 0.8 pu.
CS2: Simulation with Variable Wind Speed (15/10/15 m/s)

- Main load – 1200 kW.
- WTs respond to the wind speed change accordingly.
- In the second stage the additional load is met by diesel generator.
- SL has to increase as to minimize the effect of high wind generation.
- Secondary load current – 0.5 pu.
CS2: Simulation with Variable Wind Speed (7/8 m/s)

- Main load – 500 kW.
- WTs respond to the wind speed change accordingly.
- In the second stage the diesel power is reduced.
- SL has to increase as to minimize the effect of high wind generation.
- Secondary load current – 0.5 pu.
CS2: Simulation with Variable Wind Speed (12/13 m/s)

- Main load – 300 kW.
- WTs respond to the wind speed change accordingly.
- In the second stage the diesel power is reduced.
- SL has reached to its rated value.
- Secondary load current – 1 pu.
CS3: Simulation with Electrolyzer in Operation (cont.)

- Electrolyzer current – 160A.
- Electrolyzer power – 45 kW.
- H₂ production rate – 4.6 Nm³/hr.
- Faraday efficiency – 78%.

Figure: Current and Power.

Figure: H₂ Production.

Figure: Faraday Efficiency and Temperature.
CS3: Simulation with Electrolyzer in Operation

- Main load – 1200 kW.
- WTs and diesel generator are operating at rated conditions.
- Secondary load – 400 kW.
CS4: Simulation with HG in Operation

- Main load – 200 kW.
- WTs are operating below cut-in wind speed.
- Secondary load – 60 kW.
- Both diesel and H2 gensets are producing 130 kW individually.
CS5: Simulation with DG in Operation

- Main load – 500/700/500 kW.
- No wind generation
- No H₂ generation
- Diesel generation follows the load.
- SL increases to 200 kW.
- SL current – 0.5 pu.
Hydrogen Storage Dynamics

- 10-20 sec: Electrolyzer in operation.
- 20-25 sec: Both electrolyzer and H\textsubscript{2} generators are non-operating.
- 25-27 sec: H\textsubscript{2} generators in operation.
Conclusions

- Dynamic model of Wind-Diesel-Hydrogen based Ramea power system has been developed.
- Hydrogen as a storage medium is a novel approach adopted in this system.
- Introducing of new WECS is aiming at increasing the penetration level.
- The dump load used in this system played an important role in maintaining stability.
Future Works

- Introduce precise control mechanisms.
- Flywheel and pumped hydro as alternative storage systems.
- Design stand-alone energy systems for other remote communities.
- Energy consumed by the SL might be used for water heating, room heating, water pumping etc.
THANKS!

QUESTIONS?