CEDREN Seminar on
Large Scale Balancing from Norwegian Hydropower

Julian Sauterleute
SINTEF Energy Research

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Simulating Pumped Storage Operation in Reservoirs Used for Balancing of Wind Power

Julian Sauterleute¹, Julie Charmasson¹, Atle Harby¹, Ånund Killingtveit², Eivind Solvang¹

¹ SINTEF Energy Research, Trondheim, Norway
² NTNU Norwegian University of Science and Technology, Trondheim, Norway
Pumped storage model

- Reservoir pairs in Southern Norway
- Balancing power capacity in addition to installed capacity
- Operation of existing power station remains unchanged
- Balancing power operation within current reservoir regulations
- Input data
  - Simulated wind power time series from North Sea
  - Observed reservoir water level and volume
    - Current operational regime
    - Natural inflow
- Time step: 1 day
Background

Increasing balance power capacity in Norwegian hydroelectric power stations – A preliminary study of specific cases in Southern Norway
Solvang, E. et al. (2011)

- **20.000 MW possible by 2030**
- Hydro storage + pumped storage
- Existing dams and reservoirs
- Outlet into reservoir or fjord/sea
Model purpose

1. Simulate magnitude of water level fluctuations

2. What determines the amount of balancing power?
   1. Turbine capacity
   2. Reservoir capacity

3. Basis for assessment of environmental impacts
Balancing power operation

Generation:
- Q determined by wind power

Pumping:
- Available Q in upper reservoir
- Available Q in lower reservoir
- Free Q in lower reservoir
- Free Q in upper reservoir
- Maximum Q technically handled by the HP

Current operation

Q transferred due to balancing power

Observed records of
- Stage H
- Volume Q

Equations for computation: Q–H-relationship

Future operation

Volume, stage at time step t

Volume, stage at time step t-1

Q transferred without balancing power

Q transferred due to balancing power
**Example cases**

**Holen (Urarvatn–Bossvatn)**

- **Svartevatn**
  - Volume: 1398 mill. m³
  - HRV = 899
  - LRV = 780

- **Gravatn + Tjamor kraftverk**

- **Urarvatn**
  - Volume: 253 mill. m³
  - HRV = 1175
  - LRV = 1141

- **Vatnedalsvatn**
  - Volume: 1150 mill. m³
  - HRV = 840
  - LRV = 700

- **Bossvatn**
  - Volume: 296 mill. m³
  - HRV = 551
  - LRV = 495

- **Holen**
  - Volume upper reservoir: 253 mill. m³
  - Volume lower reservoir: 296 mill. m³

- **Holen1-2**
  - Volume upper reservoir: 1064 mill. m³
  - Volume lower reservoir: 204 mill. m³

**Rjukan (Møsvatn–Tinnsjø)**

- **Møsvatn**
  - Volume: 1064 mill. m³
  - HRV = 1175
  - LRV = 1141

- **Kålholmen**
  - Volume: 256 mill. m³
  - HRV = 1087
  - LRV = 1075

- **Mårvatn**
  - Volume: 321 mill. m³
  - HRV = 1121
  - LRV = 1100

- **Tinnsjø**
  - Volume: 204 mill. m³
  - HRV = 191
  - LRV = 187

- **Kallhovd**
  - Volume: 256 mill. m³
  - HRV = 1087
  - LRV = 1075

- **Møsvatn**
  - Volume: 1064 mill. m³
  - HRV = 1175
  - LRV = 1141

**Holen**

- Volume upper reservoir: 253 mill. m³
- Volume lower reservoir: 296 mill. m³

**Rjukan**

- Volume upper reservoir: 1064 mill. m³
- Volume lower reservoir: 204 mill. m³
Assumptions

- **Power stations**
  - Reversible turbines
  - Energy equivalent $[m^3/kWh]$ adapted to nominal head
  - Efficiency 0.9

- **Installed capacity**
  - **Holen**: 1400 MW
  - **Rjukan**: 2800 MW
  - Percentage of total balancing load: 7% for Holen, 14% for Rjukan

- **Wind power to balance**
  - Above or below 7-days moving average
Balancing power needs

Daily wind power generation and 7-days moving average

- Generation
- Pumping

10^4 MW

Daily average
Moving average - 7 days
Water level fluctuations

**Stage Holen - upper reservoir**

- Strong increase in rates of change in water level
- Shorter periods with high WL
- Longer periods with low WL

**Stage Rjukan - upper reservoir**

- Moderate increase in rates of change in WL
- Same seasonal cycle

### Holen - upper reservoir

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Simulated</th>
<th>HRWL</th>
<th>LRWL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>0.05</td>
<td>0.12</td>
<td>1.10</td>
<td>1.23</td>
</tr>
<tr>
<td>P90</td>
<td>0.21</td>
<td>0.26</td>
<td>3.40</td>
<td>3.56</td>
</tr>
</tbody>
</table>

### Rjukan - upper reservoir

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<th>LRWL</th>
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<tbody>
<tr>
<td>Median</td>
<td>0.07</td>
<td>0.07</td>
<td>0.22</td>
<td>0.21</td>
</tr>
<tr>
<td>P90</td>
<td>0.26</td>
<td>0.10</td>
<td>0.50</td>
<td>0.63</td>
</tr>
</tbody>
</table>
Water level fluctuations

- Strong increase in rates of change in water level
- Longer periods with higher WL

- Strong increase in rates of change in WL
- Different seasonal cycle
Number of changes in stage

Holen

Current vs. balancing power operation

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Current</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urarvatn (upper)</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>Botsvatn (lower)</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

Rjukan

Current vs. balancing power operation

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Current</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Møsvatn (upper)</td>
<td>8</td>
<td>38</td>
</tr>
<tr>
<td>Tinnsjøen (lower)</td>
<td>16</td>
<td>40</td>
</tr>
</tbody>
</table>

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Necessity for seasonal regulations?

Monthly mean rate of change in WL – Holen
- **Upper reservoir**

- Current Rate of Change
- Simulated rate of change

Monthly mean rate of change in WL – Rjukan
- **Upper reservoir**

- Current Rate of Change
- Simulated rate of change

Monthly mean rate of change in WL – Holen
- **Lower reservoir**

- Current rate of change
- Simulated rate of change

Monthly mean rate of change in WL – Rjukan
- **Lower reservoir**

- Current rate of change
- Simulated rate of change
Limiting factors for providing balancing power demand

**Holen**

- **Balancing demand can be met**: 77%
- **Turbine capacity**: 12%
- **UPPER reservoir**: 4%
- **LOWER reservoir**: 7%

**Rjukan**

- **Balancing demand can be met**: 76%
- **Turbine capacity**: 12%
- **UPPER reservoir**: 1%
- **LOWER reservoir**: 11%
Limiting factors for providing balancing power demand

Required balancing power can be provided on

77% of all days

76% of all days
Conclusions

• Simulated courses of reservoir filling similar to current patterns
• Speed of water level changes increases
• Higher number of changes from increasing to decreasing water level and vice versa
• Seasonality of water level rates may change
• Limiting for provision of balancing power for these cases
  – Turbine capacity during pumping
  – Lower reservoir or turbine capacity during generation
Thank you for your attention!

julian.sauterleute@sintef.no

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