Water consumption from hydropower production
Water consumption - what raised the attention?


- What is the potential for renewable sources to replace fossil-based fuels? Lenke mal

- The different technologies benchmarked with respect to various criteria, including ‘water needed to produced 1 MWh electricity (water consumption)’
Water $\Rightarrow$ energy $\Rightarrow$ GHG footprints

- an inter-related system!
Water consumption from electricity generation: 
**Source:** IPCC SRREN, 2011

Wide range between minimum and maximum of estimates

- **209 m$^3$/MWh**
- **~0 m$^3$/MWh**
Water consumption from electricity generation:  
**Source:** IPCC SRREN, 2011

Main source of water losses: evaporation from reservoir surfaces

- 209 m$^3$/MWh
- ~0 m$^3$/MWh
Very few data points (n = 2) from 4 sources, i.e. Gleick, 1993; LeCornu, 1998; Torcellini et al., 2003 & Mielke et al., 2010.
IPCC SRREN (2011) states

• Upper values for hydropower result from few studies measuring gross evaporation values, and may not be representative.

• Research may be needed to determine the net effect of reservoir construction on the evaporation in the specific watershed.

• Allocation schemes for determining water consumption from various reservoir uses in the case of multipurpose reservoirs can significantly influence reported water consumption values.
On-going scientific debate

- Bakken et al. (2013) claims the methodological framework is immature and presents a biased picture. Has received support from e.g. Demeke et al. (2013), Chenoweth et al. (2014).

- Some claim hydropower production is globally a large water consumer, e.g. Gerbens-Lenes (2009), Mekonnen and Hoekstra (2012), Liu et al. (2015).

- High water consumption values can be observed in water-stressed regions, but this is also where the reservoirs are most needed (Weichert, 2013).

- Reservoirs are needed to mitigate the effects of climate change on the water resources (e.g. IPCC, 2008)
Comparison of environmental performance

Energy pay-back ratio (EPR)

Water consumption

Small HP, large HP & wind

Review

Review and critique of concept

Development & demonstration of improved methodology

Allocation water loss

Article: ‘Falkenmark’

Full LCA

Assessment regionalization factors

IAHS-article

HESS-article

Article: ‘Falkenmark’

Full LCA

Assessment regionalization factors
Development & demonstration of improved methodology

Water loss and availability

Improved use of water resources

Allocation water loss

Turkey study

Indices for water availability & the role of reservoirs

BBM applied on water allocation

HESS-article

Full LCA

Assessment regionalization factors

• 2 masters Ethiopia (HPD)
• Søren Weichert master
• Master evaporation
• UiO’s work
• SINTEF report
Highlights - results
Results from our review documented in:


Single-plant studies – Gross values

![Graph showing water consumption and lake evaporation for various hydropower plants and countries.](image-url)
Findings from our review of published values

• The presented estimates are based on different methodological approach. The dominating approach is the gross evaporation divided on production.

• Some of the newly published estimates are far beyond the earlier published maximum values by IPCC (2011).

• Only three studies report both gross and net evaporation. In these cases the net evaporation was 10-60 % of gross evaporation (water consumption).

• Some studies are single-plant studies, while others have a very large geographical extent, 'smoothening out' large variations in water consumption values.

• "No way" around the fact that HP has a large water consumption in some regions, given the current approach (gross evaporation) of calculating water consumption/footprint.
Critique: Methodological problems

1. Values are given as gross evaporation from the reservoir area. For dams constructed on desert land, the net evaporation will be equal to the gross values, but in most cases evaporation will be less, especially for dams in wetland areas and areas with vegetation where the net increase may be very limited.

2. Water stored in reservoirs is often used for multiple purposes; thus the evaporation losses should not all be assigned to the hydropower production.

3. Impacts from the water consumption/footprint is ‘ignored’.

4. Construction of dams is a very common way to improve the availability of/access to water. Are reservoirs in arid regions not feasible due to high water footprints?
5. How to set the right system boundaries in space and time?

- One reservoir might serve several hydropower plants
- The production might vary a lot during the year and from year to year – what is the temporal resolution and span?

[Diagram showing locations of Logna HPP, Smeland HPP, Skjerka HPP, Håverstad HPP, Bjølland HPP, and Laudal HPP with a map overlay.]

[Graph showing Water consumption vs Power production with a trend line indicating a decreasing water consumption as power production increases.]
6. What about the use of existing lakes as reservoirs – should all evaporation losses be assigned to the hydropower production?

7. Withdrawal versus consumption?
Recent study in China – Product water footprint of hydropower

Source: Liu et al., 2015
Max values very high!

<table>
<thead>
<tr>
<th>Study area</th>
<th>Hydroelectric PWF [m$^3$ GJ$^{-1}$]</th>
<th>Hydroelectric PWF [m$^3$ MWh$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States average</td>
<td>4.7</td>
<td>17</td>
</tr>
<tr>
<td>United States average – 120 largest plants</td>
<td>19</td>
<td>68</td>
</tr>
<tr>
<td>Arizona, United States</td>
<td>31.6</td>
<td>413.9</td>
</tr>
<tr>
<td>California, United States</td>
<td>Min: 0.04 Median: 1.5 Max: 58</td>
<td>Min: 0.04 Median: 5.4 Max: 209</td>
</tr>
<tr>
<td>California</td>
<td>Mean: 1.5 Median: 7.2</td>
<td>Mean: 5.4 Median: 26</td>
</tr>
<tr>
<td>“All plants” in Northern New Zealand</td>
<td>6.1</td>
<td>21.8</td>
</tr>
<tr>
<td>Norway</td>
<td>1–1.2</td>
<td>3.8–4.4</td>
</tr>
<tr>
<td>Ethiopia Omo-Ghabe River</td>
<td>Min: 9.4 Median: 34 Max: 82</td>
<td>Min: 11</td>
</tr>
<tr>
<td>Ethiopia (Blue Nile)</td>
<td>Mean: 27.5 Max: 38</td>
<td></td>
</tr>
<tr>
<td>Sudan Roseires and Sennar irrigation reservoirs</td>
<td>Min: 381 Mean: 411 Max: 978</td>
<td>Min: 1371 Max: 3521</td>
</tr>
<tr>
<td>Austria, Ethiopia, Ghana, Egypt and PDR Laos</td>
<td>Max: 1736 Max: 6250</td>
<td></td>
</tr>
<tr>
<td>Global average</td>
<td>22</td>
<td>80</td>
</tr>
<tr>
<td>Worldwide, 35 plants</td>
<td>Min: 0.3 Median: 1.08 Max: 846</td>
<td>Min: 0.001 Min: 0.0036 Max: 3.6</td>
</tr>
<tr>
<td>China from this study</td>
<td>Mean: 3.6 Max: 4234</td>
<td>Mean: 13 Max: 15244</td>
</tr>
</tbody>
</table>

Source: Liu et al., 2015

IPCC

Min: 0.04
Median: 5.4
Max.: 209

Min.: 0.0036
Mean: 13
Max.: 15244
Results from Canada on net effect

Implications for water footprint (WF) calculations:

- Large uncertainties in evaporation leads to large uncertainty in WF
- Important to be able to diversify between land use/cover types, but difficult hydrological
- Assessment of net evaporation difficult with good precision
- The difference is smaller than the uncertainty?
- If limited difference in evapotranspiration between area types, net WF will always be (close to) zero.

As the reservoir is periodically a drawdown reservoir, they argue that the net change is negative (reduced evaporation)

Source: Tremblay et al., 2014
Allocation recommendations for multipurpose reservoirs

Water losses - m³/year

Water use in the reservoir

Functions of the reservoir
Lack of allocation methodology

IPCC SRREN (2011, Chapter 5, page 44) states that ‘allocation schemes for determining water consumption from various reservoir uses in the case of multipurpose reservoirs can significantly influence reported water consumption values’.

Problem confirmed in scientific literature (e.g. Mekonnen and Hoekstra, 2012; Pfister, 2011, Demeke et al., 2013; Bakken et al., 2013, Liu et al. 2015).

ISO Standard of Water Footprint (ISO 14046) suffers from clear guidelines on allocation.

The work will also be useful for other environmental indices/parameters (e.g. GHG)
4 case studies
Allocation results

Mullaroya, Spain

- Flood control
- Industrial uses (excl. hydropower)
- Irrigation
- Water supply
- Power generation

Porma, Spain

- Flood control
- Ecological flow
- Irrigation
- Water supply
- Power generation

Sri Ram Sagar Project, India

- Irrigation
- Water supply
- Power generation

Aswan High Dam, Egypt

- Flood control
- Navigation
- Irrigation
- (Domestic) water supply and industries
- Power generation

CEDREN
Centre for Environmental Design of Renewable Energy
Recommendations

• We consider volume allocation to be the most robust approach in multipurpose reservoirs.

• We recommend that data should preferably be gathered from one source for all functions, to ensure a consistent calculation approach.

• The system boundaries should follow boundaries defined by the hydraulic system, but case-by-case adjustments will be needed to the site-specific character of the projects.
It is assumed that the water footprint of hydropower is dominated by the operative phase (Inhaber, 2004; Fthenakis & Kim, 2010; Pfister et al., 2011; Mekonnen & Hoekstra, 2012). This is, however, not properly documented.

How is the ratio between the water footprint in the operational phase versus the construction phase in an area with limited evaporation, a small reservoir, etc?
Case studies Norway

Trollheim HPP and Foldsjøen

Embretsoss 4 (ROR)

Known

Unknown

Known

Construction of plant

Operation of plant

Decommission of plant
The two case studies
First results – non-categorized results

Water footprint of hydropower
Life cycle inventory results

CEDREN
Centre for Environmental Design of Renewable Energy
First results – categorized results/ratio

Water footprint of hydropower
LCI and water scarcity results (net evaporation)

Embretsfoss 4  Trollheim

- Infrastructure, tunnels
- Infrastructure, dam
- Infrastructure, gates
- Infrastructure, station hall
- Infrastructure, turbine
- Infrastructure, generator
- Infrastructure, transformer
- Infrastructure, internal net
- Infrastructure, roads
- Maintenance
- Annual reinvestment
- Evaporation from reservoir

CEDREN
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ICOLD-database

ICOLD:
World Register of Dams

Contain information on a large number of dams > 15 meters

Holds information such as installed capacity, energy production, dam characteristics, country of location and purpose
  • single versus multi
  • main purpose
  • secondary purpose

Non-complete in terms of properties

Other sources estimate the total number of dams > 15 meters to be around 45 000 world-wide (ICOLD-web: ~ 50 000)

n=39188 by June, 2014
n=39064 for our study
Irrigation, flood control, hydropower and water supply are all common functions.
Reservoir purpose (Single and Main) and water scarcity

Falkenmark indicator
- Extremely scarce areas <500 m³/capita/year
- Scarce areas, 500-1000 m³/capita/year
- Stressed areas 1000-1700m³/capita/year
- Adequate areas 1700-6000 m³/capita/year
- Plentiful areas >6000 m³/capita/year

Source: Bakken et al., 2015
Reservoir purpose (Single and Main) and water scarcity

<table>
<thead>
<tr>
<th>Scarcity level</th>
<th>Hydro-power</th>
<th>Flood Control</th>
<th>Irrigation</th>
<th>Navigation</th>
<th>Recreation</th>
<th>Water Supply</th>
<th>Unknown</th>
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</thead>
<tbody>
<tr>
<td>Extremely scarce areas &lt;500 m³/capita/year</td>
<td>S</td>
<td>M</td>
<td>S</td>
<td>M</td>
<td>S</td>
<td>M</td>
<td>S</td>
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<tr>
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<td>3</td>
<td>2</td>
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<td>Scarce areas, 500-1000 m³/capita/year</td>
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<td>24</td>
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<td>Stressed areas 1000-1700 m³/capita/year</td>
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<td>Adequate areas &gt; 1700 m³/capita/year</td>
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<td>S</td>
<td>M</td>
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<tr>
<td></td>
<td>4842</td>
<td>1306</td>
<td>2624</td>
<td>1835</td>
<td>6250</td>
<td>3275</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Bakken et al., 2015
Inflow & outflow
Lake Nasser (HAD) (Egypt)

Trade-off: Increased availability versus reduced annual volumes

Strzepek et al., 2008
Summed up

• More studies are now published

• The data on hydropower is still very inconsistent, the old methodology frequently used

• Methodological problems investigated, solutions proposed, but not fully adopted by other scientists or the business

• Still an emerging topic in the industry/sector

• ISO standard on Water footprint (ISO 14046) now in place (?)

• Should a larger initiative be made among leading scientists, similar to on GHG?
External activity

+ meetings, seminars, conferences