Round Trip Efficiency Formulation for Comparing Thermal Energy Storage Systems to Electrical Energy Storage Systems

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School of MEWES-NM-AIST: We train at MSc and PHD levels in

- Materials Science and Engineering
- Sustainable Energy Science and Engineering
- Hydrology and Water Resource Engineering
- Environmental Science and Engineering
- Environmental Management Information System
Program Specialties

- **Materials Science and Engineering**
  - Structural Materials
  - Energy Materials

- **Sustainable Energy Science and Engineering**
  - Sustainable Power Generation and Energy Utilization
  - Sustainable Renewable Energy Engineering
  - Sustainable Nuclear Power Engineering

- **Hydrology and Water Resources Engineering**
  - Hydrology and Climate studies
  - Water Resources Engineering and Management
  - Irrigation Engineering
  - Water Supply and Sanitation

- **Environmental Science and Engineering**
  - Environmental Science
  - Environmental Engineering
NM-AIST Constructed Wetland

- Established a constructed wetland for treating wastewater from Students Dormitory Block A
- It is a research, teaching and practical system – a true living laboratory
“GREEN CAMPUS” PROJECT

- **Main goal:** to show the feasibility of a Green Campus at the NM AIST on an ** economical, technical as well as cultural level.**
- **The project shall involve**
  - Design of renewable energies and their applications (solar farm, biogas systems, wind)
  - Concept of intelligent use of resources
  - Closed-cycle management of resources
- **Good precondition prevails at the NM AIST**
  - Concept has the full support of the University management
  - the study programs include *Sustainable Energy Science and Engineering* and *Environmental Science and Engineering.*
- **The approach to the concept is a transdisciplinary co-design and will cover technological, economic and social issues and is expected to be also translated in a teaching programme on sustainability sciences.**
Thermal Energy Storage Model

- The charging and discharging process of batteries, fuel cells, flywheels, and CAES including the discharging mechanism of thermal energy storage systems (TES) is well understood and defined from a physics standpoint in the context of comparing these systems.

- The challenge lays in comparing the charging process of batteries, fuel cells, flywheels, and CAES with the charging process of TES systems for CSP plants.

- The source of energy for all these systems is electrical energy except for the CSP plant where the input is thermal energy. In essence, the round trip efficiency for all these systems should be the ratio of electrical output to electrical input.

- The metric that is proposed for comparison is the round trip efficiency, which in this context is simply defined as the ratio of desired output to desired input i.e. $E_{out}/E_{in}$. 

CENTRE FOR RENEWABLE AND SUSTAINABLE ENERGY STUDIES
Charging and Discharging Processes of Batteries, Fuel Cells, Flywheels, CAES, and TES (Block Diagrams)

**Battery**
- **Charging**: $E_{in} \rightarrow E_{out}$
- **Discharging**: $E_{out} \rightarrow \text{Load}$

**Fuel Cell**
- **Charging**: $E_{in} \rightarrow H_2, O_2$
- **Discharging**: $H_2 + O_2 \rightarrow E_{out}, Q$

**Electrolysis**
- **Charging**: $E_{in} \rightarrow \text{Electrolysis}$
- **No Storage**: $E_{in} \rightarrow E_{out,ns}$

η = $E_{out} / E_{in}$

- **Battery** (Charging): η ≈ 70-90%
- **Fuel Cell** (Charging): η ≈ 20-50%

**Chemical Reactions**
- Anodic Reaction: $H_2 \rightarrow 2 H^+ + 2 e^-$
- Cathodic Reaction: $\frac{1}{2} O_2 + 2 H^+ + 2 e^- \rightarrow H_2O$

**Centre for Renewable and Sustainable Energy Studies**
Charging and Discharging Processes of Batteries, Fuel Cells, Flywheels, CAES, and TES (Block Diagrams)

**Charging Process of a CAES**

- $E_{in}$ → Compressor → Cavern/Vessel

**Discharging Process of a CAES**

- Cavern/Vessel $Q_{loss}$ → Turbine → Generator $E_{out}$ → Load

$\eta = \frac{E_{out}}{E_{in}} \approx 50-89\%$

*89% Advanced Adiabatic CAES

**Huntorf plant (42%), McIntosh plant (54%)**
Charging and Discharging Processes of Batteries, Fuel Cells, Flywheels, CAES, and TES (Block Diagrams)

Charging Process of a Flywheel Energy Storage

- $E_{in} \rightarrow$ Motor $\rightarrow$ Flywheel

Discharging Process of a Flywheel Energy Storage

- $E_{in} \rightarrow$ Flywheel $\rightarrow$ Generator $\rightarrow$ Load
  - $E_k = 0.5I\omega^2$
  - $\eta = \frac{E_{out}}{E_{in}} \sim 93-95\%$

$E_{in}, E_{out}$ - Electrical Energy

No Storage

$E_{in} \rightarrow E_{out,ns}$
Charging and Discharging Processes of Batteries, Fuel Cells, Flywheels, CAES, and TES (Block Diagrams)

TES System w/o storage

$E_{in}$

Generic CSP Receiver

Heat Exchanger

Power Block

Gen

Load

TES System with Storage

Generic TES $Q_{th}$

Heat Exchanger

Power Block

Gen

Load

$E_{out,ns} = \eta_0 E_{in}$

$E_{out} = E_{out,ws}$

$\eta = \frac{E_{out,ws}}{E_{out,ns}}$

Storage Efficiency

$E_{in}$ – Solar Energy, $E_{out}$ – Electrical Energy

Now you are comparing apples with apples
Sensible energy storage for the molten salt
Heat exchanger losses
Tank losses

\[ \eta = \frac{m_{salt} C_{p,salt} (T_{out,st} - T_{in,st}) \{2(1-\eta_{hx})\} - \int_{t_0}^{t_f} Q_{dotloss} dt}{m_{HTF} C_{p,HTF} (T_{out,HTF} - T_{in,HTF})(1-\eta_{hx})} \]

Sensible energy storage for the HTF
Heat exchanger losses

Thermal Energy Storage Performance measure currently used (shown below) cannot be compared to electrical energy storage technologies.

First Law Efficiency measure for molten salt storage systems is defined as the ratio of discharged energy to stored energy (\(\sim 93-95\%\)).
Results - Using Andasol 3 (50 MW) data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molten salt tank losses</td>
<td>2.5%</td>
</tr>
<tr>
<td>Heat exchanger losses</td>
<td>10%</td>
</tr>
<tr>
<td>Temperature hot tank</td>
<td>386°C</td>
</tr>
<tr>
<td>Temperature cold tank</td>
<td>296°C</td>
</tr>
<tr>
<td>HTF inlet temperature</td>
<td>293°C</td>
</tr>
<tr>
<td>HTF outlet temperature</td>
<td>393°C</td>
</tr>
<tr>
<td>Molten salt energy</td>
<td>125 MW</td>
</tr>
<tr>
<td>HTF energy</td>
<td>125 MW</td>
</tr>
<tr>
<td>Rate of Energy output with storage</td>
<td>97 MW</td>
</tr>
<tr>
<td>Rate of Energy output without storage</td>
<td>112.5 MW</td>
</tr>
<tr>
<td>Round trip efficiency</td>
<td>86%</td>
</tr>
<tr>
<td>Total project cost</td>
<td>400 million dollars</td>
</tr>
<tr>
<td>Annual O&amp;M cost</td>
<td>1.6 million dollars</td>
</tr>
<tr>
<td>Net electric output per annum</td>
<td>200 GWh</td>
</tr>
<tr>
<td>LCOE</td>
<td>216 $/MWh_e</td>
</tr>
</tbody>
</table>

Storage Efficiency

Total Cost of the Stored Electricity
## Results

<table>
<thead>
<tr>
<th>Technology</th>
<th>LCOE [$/MWh_e] (cost of stored electricity)</th>
<th>LCOE [$/MWh_e] based on conventional source</th>
<th>LCOE [$/MWh_e] based on renewable source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAES</td>
<td>275</td>
<td>352</td>
<td>372</td>
</tr>
<tr>
<td>Sodium sulphur</td>
<td>350</td>
<td>427</td>
<td>447</td>
</tr>
<tr>
<td>Advanced lead acid T1</td>
<td>625</td>
<td>702</td>
<td>722</td>
</tr>
<tr>
<td>Advanced lead acid T2</td>
<td>325</td>
<td>402</td>
<td>422</td>
</tr>
<tr>
<td>Zinc bromine</td>
<td>288</td>
<td>365</td>
<td>385</td>
</tr>
<tr>
<td>Vanadium redox</td>
<td>525</td>
<td>602</td>
<td>622</td>
</tr>
</tbody>
</table>

(EPRI, 2012)

**Cost of Electricity Output = Cost of Stored Electricity + Cost of Electricity Input**
Conclusion.

- The storage efficiency using this formulation is 86% using Andasol 3 data (previous slide). The efficiency of the thermal energy storage for Andasol 3 is 97.5% based on the first law efficiency (Thermal Energy Discharged / Thermal Energy Stored)
- The storage efficiency formulation compares well with the first law efficiency measure of TES which ranges from 93 – 99%
- The LCOE of molten salt storage system is significantly lower than the LCOE of vanadium redox, sodium sulphur, and compressed air energy storage
- Molten storage systems have both high energy and high exergy efficiency
Potential for Collaboration

- Development of thermal energy storage facilities and know-how between UD/USA-AFRICA
- Student/Faculty Exchange Programmes between UD and NM-AIST
- Battery manufacturing and technological know-how i.e. Developing Li-ion/VRB at Universities
- Towards developing an African Energy Storage Association – sharing knowledge from USA
- Possible collaborative partnerships between USA and East Africa both institutional and stakeholder