Thermal Energy Grid Storage Using Multi-Junction Photovoltaics (TEGS-MPV)

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What is Thermal Energy Grid Storage (TEGS)?

Electricity $\rightarrow$ Heat (storage) $\rightarrow$ Electricity

System with thermal storage and conversion

Electricity in
Electricity out
Like a battery
Electricity \rightarrow \text{Heat (storage)} \rightarrow \text{Electricity}

Why would anyone ever do this?
Storing heat can be 10-100X cheaper than storing electricity!

System with thermal storage and conversion

Can be 100% efficient going from lower to higher entropy

Can never be 100% efficient going from higher to lower entropy
Why is it so cheap? – Atomistic Insight

Low concentration of active species
Large energy per active atom
Special, pure, organized materials
Impurities and byproducts are bad

100% concentration of active species
Low energy per active atom
Disordered, simple scrap material
Impurity tolerant

$250-695$ kWh/m$^3$ $\$150-400$/kWh

$300-600$ kWh/m$^3$ $\$4-77$/kWh

\[ \Delta G = \frac{1}{2} m v^2 \]
Simple Estimate

Liquid silicon storage

\[ \begin{align*}
  \text{Cp} &= 950 \text{ J kg}^{-1} \text{ K}^{-1} \\
  \text{Cost} &= $1.5/\text{kg} \\
  \Delta T &= 500^\circ\text{C} \\
  \text{Cost/Energy} &= \frac{\text{Cost}}{(\text{Cp} \times \Delta T)} = \frac{$1.5}{(950 \times 500)} = $11.4/\text{kWh} \\
  \text{At 50% efficiency} \\
  \text{Cost/Energy} &= \frac{$11.4}{0.5} = $22.8/\text{kWh-e}
\end{align*} \]

Liquid iron storage

\[ \begin{align*}
  \text{Cp} &= 444 \text{ J kg}^{-1} \text{ K}^{-1} \\
  \text{Cost} &= $0.11/\text{kg} \\
  \Delta T &= 500^\circ\text{C} \\
  \text{Cost/Energy} &= \frac{\text{Cost}}{(\text{Cp} \times \Delta T)} = \frac{$0.11}{(444 \times 500)} = $0.18/\text{kWh} \\
  \text{At 50% efficiency} \\
  \text{Cost/Energy} &= \frac{$0.18}{0.5} = $0.36/\text{kWh-e}
\end{align*} \]
Heat Leakage?

**Volume to surface area ratio**

\[ \tau = \frac{m\cdot C_p\cdot R}{\rho\cdot V\cdot C_p\cdot L/kA} \]

For tanks of order 10 m

\[ \tau \text{ on the order of months} \]

Lose \( \leq 1\% \) of energy stored per day
What about corrosion? The hotter the faster/worse!

Si melts at 1414°C
Fe melts at 1538°C

Molten metal dissolves metal
Like Sugar water dissolves sugar

Key New Idea = Liquid Metal + Ceramics
“Sun in a Box” TEGS-MPV

Electricity → Heat → Electricity

Liquid Silicon Hot Tank
~2400°C

Any Electricity Source Powers the Heaters

Liquid Silicon “Cold” Tank
~1900°C

MPV Panels Can Be Mechanically Retracted For Load Following

Krypton Gas in the Gap

Tungsten Foil Fins Cover Graphite Pipes to Block Sublimation

High Quality Single Crystal III-IV Multi-junction PV (MPV) Cells

Active Water Cooling Of Cells ~ 35°C

Multi-Junction Photovoltaics (MPV)
How Are You Going To Pump It?

Pumping at 1350°C

C. Amy et al., Nature 550, 199–203 (2017)
What About The Tank (2400°C)?

- Graphite + Si(l) react to form SiC
- Dense graphite forms protective SiC layer
- Tank cannot be monolithic piece
- Use sections that are bolted
- Carbon fiber bolts
- Use grafoil gaskets to seal
- Tested successfully > 2000°C

C. Amy et al., Energy & Environmental Science, 12, 334 (2019)
Why Use MPV Instead of a Turbine?

- **Turbine**
  - Doesn’t currently exist
  - **Large barrier to new turbine deployment**
  - > $100M of R&D
  - New materials + New HXs
  - Min-Hour response time to full load

- **MPV**
  - **Much lower barrier to deployment**
  - **Lower cost < $0.5/W-e**
  - Similar efficiency (50-55%)
  - Fast response time (seconds)
  - Fundamentally new cost/learning curve
  - Lower maintenance
Why Multi-Junction Photovoltaics?

[Graph showing modeled efficiencies of 1- and 2-junction cells as a function of junction bandgap for several different emitter temperatures.]

B – Optimal top-junction bandgap for the 2-junction cells as a function of the bottom junction bandgap.

C. Amy et al., Energy & Environmental Science, 12, 334 (2019)
System Efficiency & Cost

Efficiency = \( \frac{\text{Power}_{\text{out}}}{\text{Q}_{\text{total}}} = \frac{123}{(123 + 89.4 + 18.7 + 4.6)} = 52\% \)

- \( Q_{\text{blackbody}} = 1.95 \text{ MW/m}^2 \)
- Tungsten has low emissivity in the IR
- \( Q_{\text{tungsten}} = 689 \text{ kW/m}^2 \)
- \( Q_{\text{above BG}} = 213 \text{ kW/m}^2 \)
- \( Q_{\text{below BG}} = 476 \text{ kW/m}^2 \)
- \( Q_{\text{gen}} = 89.4 \text{ kW/m}^2 \)
- \( Q_{\text{below BG}} = 18.7 \text{ kW/m}^2 \)

Cost per unit energy = CPE
Cost per unit power = CPP

\[ \text{Cost} = \text{CPE} \times \text{time} + \text{CPP} \]

C. Amy et al., Energy & Environmental Science, 12, 334 (2019)
Centrifugal pump ~ 1 ft diameter

Graphite double wall
Carbon fiber bolts
Porous graphite insulation
Aluminum silicate insulation

System at Scale
Charge/discharge 100 MW
10 hrs of storage (1 GWh)
What’s Next?

- ARPA-E Project
- Build a prototype
- Pumping
- 2500°C Heaters
- Emitter evaporation/deposition
- Cell redesign/optimization + fabrication
- High current density
- High reflectivity (> 98%)
- High efficiency (≥ 50%)
- Long term testing
Commercialization Pathway

- Finish existing ARPA-E project
  - [scale = 1 kWh, 300 W]
  - Fully functioning prototype
  - Cell performance demonstrated
  - Pumping demonstrated
  - Actuation demonstrated
  - Deposition prevention demonstrated

- Pilot demonstration
  - [scale = 1 MWh, 300 kW]
  - Demonstrate > 40% efficiency
  - Demonstrate cycles with no degradation
  - Develop maintenance procedures
  - ARPA-E Pilot program
  - [up to $10M + 50% cost share] - $6M estimated
  - Need to raise cost share
  - Create/lead a startup company

- Full scale
  - [scale = 1 GWh, 100 MW] - $200M
  - Secure a utility as a customer
  - DOE Loan guarantee program
  - Demonstrate > 50% efficiency
  - Demonstrate cycle life and low cost
Questions?