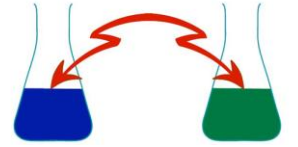




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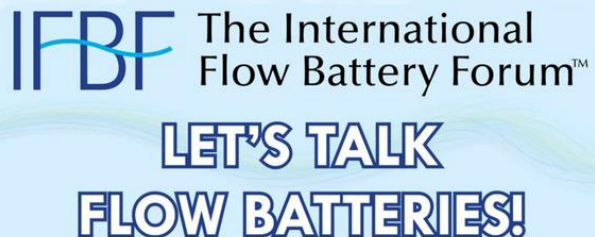
FB POTENTIALS AND COMPETITIVENESS IN THE SOARING MARKET OF LONG DURATION ENERGY STORAGE

Massimo Guarnieri

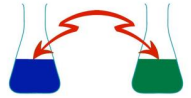
University of Padua, Padova, Italy

Giorgio Levi Cases Center for Energy Economy and Technology, Italy

E-Storage Engineering, Italy



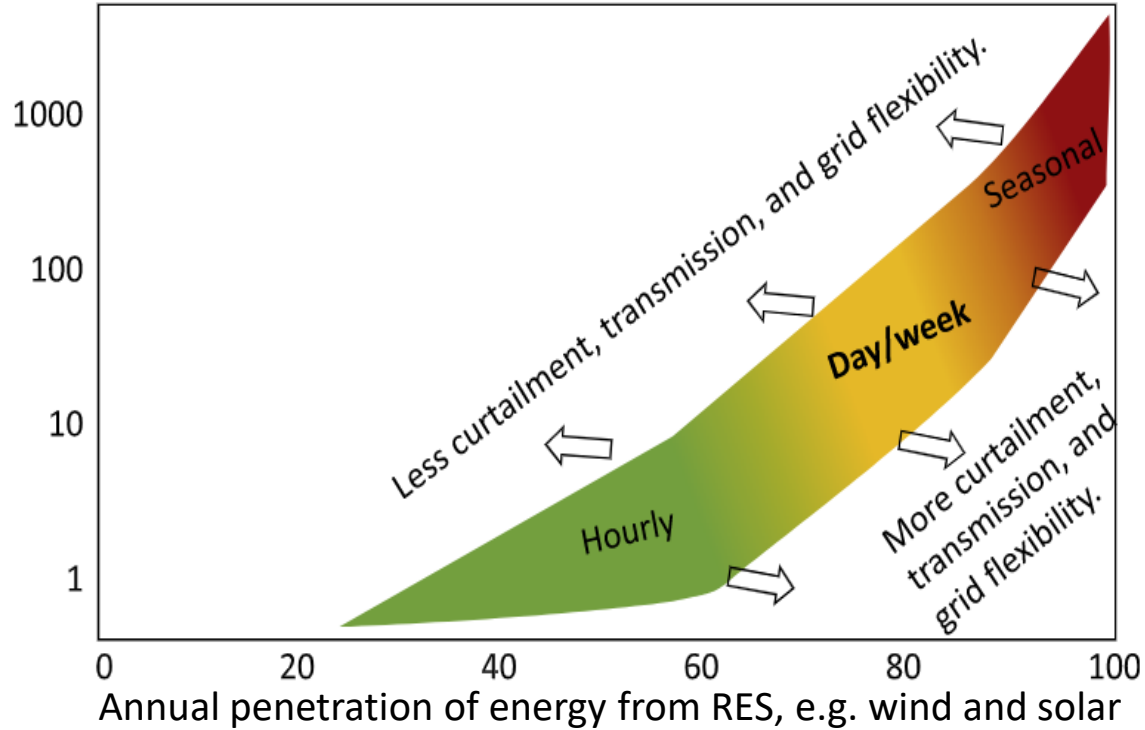
Vienna, 24 June 2025



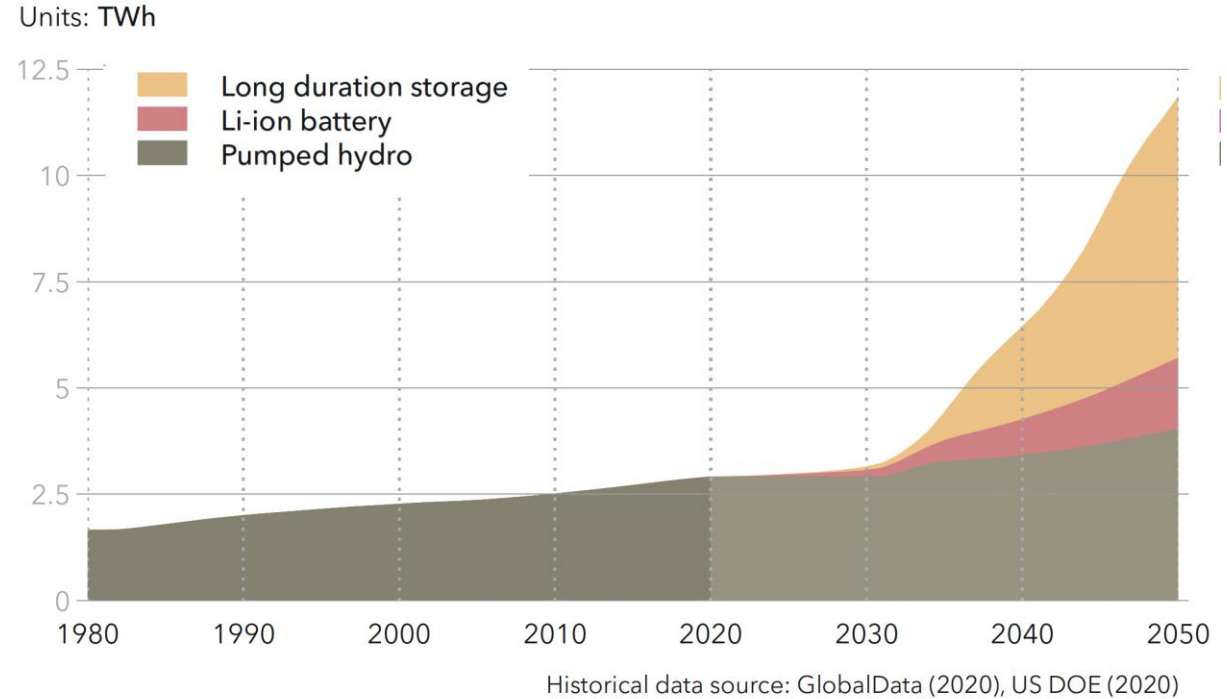
WHAT TO INVESTIGATE: LDES

LDES will be a must in future decarbonized grids (Net Zero)

Maximum required storage duration (hours at rated power)



World utility-scale storage capacity

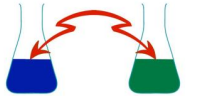


D. Engel, DNV energy transition outlook 2020: power supply and use – a global and regional forecast to 2050, DNV GL – Energy, 2020

P. Albertus, J. S. Manser, and S. Litzelman, Long-Duration Electricity Storage Applications, Economics, and Technologies, Joule, 4 (1), (2020) 21–32.

Several technologies are competing to gain this soaring market

CLASSIFYING ES AND LDES



Classifying ES 1

Energy Storage (ES) types

- Mobility oriented
- Stationary (STES)
 - grid-oriented services (GOES)
 - non-grid-oriented services (NGOES)

Classifying ES 3 (stationary grid-oriented ES – GOES)

- unidirectional ESTs = delay one-way electric energy delivery from a primary renewable source
- bidirectional ESs = charge/discharge from the grid
→ full storage capacity for intermittent, unpredictable renewable sources

LDES Definition for STES (both GOES, NGOES)

Duration can refer to:

- 1) ST = storage time or
- 2) DT = discharge time at rated power

Technically: $ST > DT$ – sometime $ST \gg DT$

Classifying ES 2

- LDES: usually $DT \geq 8$ hours

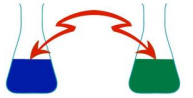
Emerging higher limits

- recent EU Horizon Europe and US DOE reports indicate $DT \geq 10$ hours
- 8–100 h: D. Hochschild's IFBF presentation this morning

Two levels of DT are also considered in LDES:

- mild LDES: $DT = 10$ – 20 hours (daily and multi-daily cycles)
- ultra LDES: $DT =$ week-months (seasonal)

HOW TO COMPARE TECHNOLOGIES: KPIs*



TP = top plant power

TE = top plant energy

DOD = depth of discharge: $= E_d / E_r$ (=100%) [E_d = discharged en.; E_r = rated en.]

DT = discharge time at rated power: E_r / P_r (should be E_d / P_r)

ST = storage time – depending on self-discharge rate (SDR) due to all internal losses in idle/off mode

RT = response time

CyL = cycle life: number of cycles to end of life (EOL)

CaL = calendar life: years to EOL independently of use

RTE = round-trip efficiency = E_{out} / E_{in} at system level

MTF = mean time to failure / MTR = mean time to repair

UPCE = unit power capital expenditure

UECE = unit energy capital expenditure

UOE = unit operational expenditure

LCOS = levelized cost of storage

UREC = unit capital cost of total net released energy (RTE, DOD, CyL)

ANL = ambient noise level

DOD, RTE, UECE, UREC depend on:

E_s = stored energy

E_r = rated energy $\leq E_s$

E_d = discharged energy $\leq E_r$

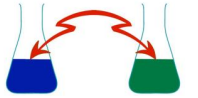
E_{out} = released energy $< E_d$

Different standards in different ESTs

RTE: very different in small exp. (TRL = 3)
and pilots/ind. syst. (TRL \geq 7) for the same EST

*KPIs consistent with Batteries Europe Secretariat “D3 .6 - KPIs Benchmarking & Target KPIs”

HOW TO EQUIPARE TECHNOLOGIES: MATURITY



According to the European Union Horizon Europe program, TRLs are:

- TRL1 Basic principles observed
- TRL2 Technology concept formulated
- TRL3 Experimental proof of concept
- TRL4 Technology validated in a lab
- TRL5 Technology validated in a relevant environment
- TRL6 Technology demonstrated in a relevant environment
- TRL7 System prototype demonstration in an operational environment**
- TRL8 System complete and qualified**
- TRL9 Actual system proven in an operational environment.**

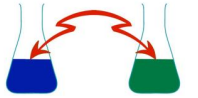
Maturity comparison standard:

TRL \leq 6 KPIs not reliable for final applications, critical extrapolation

TRL \geq 7 KPIs reliable for final applications

EARTO, The TRL Scale as a Research & Innovation Policy Tool, EARTO Recommendations, 30 Apr 2014. https://www.earto.eu/wp-content/uploads/The_TRL_Scale_as_a_R_I_Policy_Tool_-_EARTO_Recommendations_-_Final.pdf (accessed March 31, 2025)

M. Héder, From NASA to EU: the evolution of the TRL scale in Public Sector Innovation, The Innovation Journal: The Public Sector Innovation Journal, Volume 22 (2), 2017, # 3.



IHES = impoundment hydro energy storage

TES (CPS) = thermal energy storage in concentrated solar power

PHES = pumped hydro energy storage

HES = hydrogen energy storage

CAES = compressed air energy storage

LAES = liquid air energy storage

BES (Li) = battery energy storage – Li based

BES (Na-X) = battery energy storage – Na based

BES (Pb-A) = battery energy storage – Lead-acid

BES (MAB) = battery energy storage – Metal-air

FBES (V) = flow battery energy storage – vanadium based

FBES (Fe) = flow battery energy storage – iron based

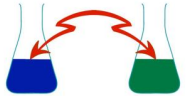
FES = flywheel energy storage

SMES = superconducting magnet energy storage

SCES = supercapacitor energy storage

GES = gravitational energy storage

PTES = pumped thermal energy storage



IHES = impoundment hydro energy storage

Unidirectional GOES

TRL = 9

most common type of hydropower facility

Three Gorges Dam (China): 22.5 GW / 3000 GWh

Tyssedal Power Station (Norway): 0.1 GW / 260 GWh

RT = Slow

DT \approx 100 days – seasonal (few!)

SDR = 0.5–3 % month⁻¹

ST = months – seasonal

RTE = 90–95 %

CyL \approx 20,000

UPCE = 1000–5000 \$/kW

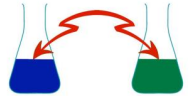
UECE = 1–100 \$/kWh

UREC = 0.01–1.1 c\$/kWh/n

ECO-impact = very high

Hazard = low





TES = thermal energy storage in CPS

High-T systems

$T_w = 280^\circ - 600^\circ \text{C}$ suitable for Rankine cycles

Unidirectional GOES

TRL = 9

Noor Complex (Morocco): 496 MW / 2890 MWh

RT = Slow

DT = 3 – 17.5 h

SDR = 1–2 % day^{-1}

ST = 1 day

RTE = 70 %

CyL \approx 12000

UPCE = 2700 \$/kWe

UECE = 400 \$/kWh

UREC = 9 c\$/kWh/n

ECO-impact = high

Hazard = low



Low-T systems

$T_w < 100^\circ \text{C}$ unsuitable for Rankine cycles

Unidirectional NGOES

TRL = 7

SDR = 0.5–1.0 % month^{-1}

ST = months (seasonal)

RTE = 97 %

Drake Landing Solar Community Alberta, Canada

High-T systems

$T_w = 280^\circ - 600^\circ \text{C}$

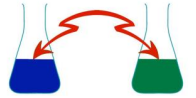
Bidirectional GOES – Carnot Battery

TRL = 2–3

SDR = 1–2 % day^{-1}

ST = days

RTE = 55–70 % ? (with heat pump)



PHES = pumped hydro energy storage

Bidirectional GOES

TRL = 9

Blasjo-Saurdal / Ulla-Førre (Norway): 0.64 GW 3331 GWh

Fengning (China): 3.6 GW / 40 GWh

Bath County (USA): 3.0 GW / 24 GWh

RT = Slow

DT > 200 days – seasonal (few!)

SDR = 0.5–3 % month⁻¹

ST = months – seasonal

RTE = 75–85 %

CyL ≈ 20,000

UPCE = 1000–4000 \$/kW

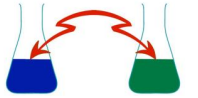
UECE = 20–200 \$/kWh

UREC = 0.1–3 c\$/kWh/n

ECO-impact = very high

Hazard = low





CAES = COMPRESSED AIR ENERGY STORAGE

Bidirectional GOES

TRL = 7–9

Feicheng ZCGN (China): 0.35 GW / 1.4 GWh

Bakersfield Hydrostor (USA-CA, 2026): 0.5 GW / 4 GWh

$p < 80\text{--}100$ bar

RT = Slow

DT $\approx 2\text{--}8$ h

SDR = 0.5–3 % month⁻¹

ST = months

RTE = 60–72 %

CyL ≈ 14000

UPCE = 1000–3000 \$/kW

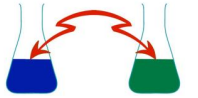
UECE = 100–1200 \$/kWh

UREC = 2–8 c\$/kWh/n

ECO-impact = middle

Hazard = low





LAES = LIQUID AIR ENERGY STORAGE

Bidirectional GOES

TRL = 7

Highview Power (UK): 0.35 MW / 2.5 MWh

Highview Power (UK, 2026): 50 MW / 300 MWh

T = -196° C

RT = Slow

DT \approx 7 h

SDR = 1.5 % month⁻¹

ST = months

RTE of 8 % (54 % ?)

CyL \approx 11000

UPCE = 7400 \$/kW

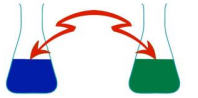
UECE = 1240 \$/kWh

UREC = 21 c\$/kWh/n

ECO-impact = middle

Hazard = middle





BES – Li-ion

Bidirectional GOES

TRL = 9

Edwards Sanborn Solar Plus Storage:

0.971 GW 3.3 GWh

RT = fast

DT \approx 1–4, 5 (8) h

SDR = 3–4 % month⁻¹

ST = month

RTE = 82–90 %

CyL \approx 4000

UPCE = 1200–2400 \$/kW

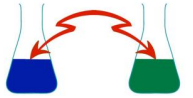
UECE = 200–500 \$/kWh

UREC = 6–20 c\$/kWh/n

ECO-impact = middle

Hazard = rather high





BES – Na-S

Bidirectional GOES

$T_w = 300^{\circ}\text{--}350^{\circ}\text{C}$

TRL = 9

Abu Dhabi Island storage: 0.108 MW 0.648 MWh

RT = fast (if in idle mode)

DT \approx 7–8 h

SDR = 4 % day⁻¹

ST = day

RTE = 82 %

CyL = 4300–7300

UPCE = 8400 \$/kW

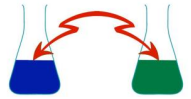
UECE = 1200 \$/kWh

UREC = 13-20 c\$/kWh/n

ECO-impact = middle

Hazard = rather high





FBES – V-V

Bidirectional GOES

TRL = 8

Rongke Power (China): 0.175 GW / 0.7 GWh

Laufenburg (CH, 2028): 0.8 GW / 1.6 GWh

RT = fast (idle mode)

DT = 4–10 h

SDR $\ll 1$ % month⁻¹ (off mode)

ST = months (off mode)

CyL ≈ 20000

UPCE = 3000–5000 \$/kW

UECE = 500–750 /kWh

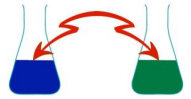
UREC = 5–6 c\$/kWh/n

ECO-impact = low

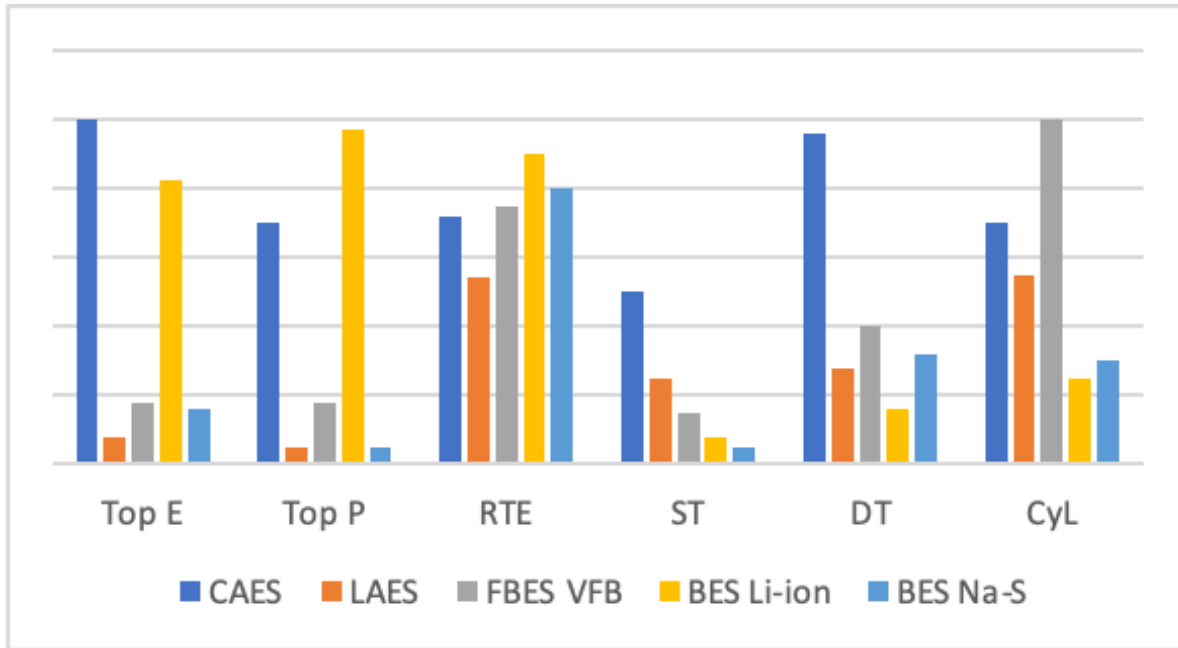
Hazard = low



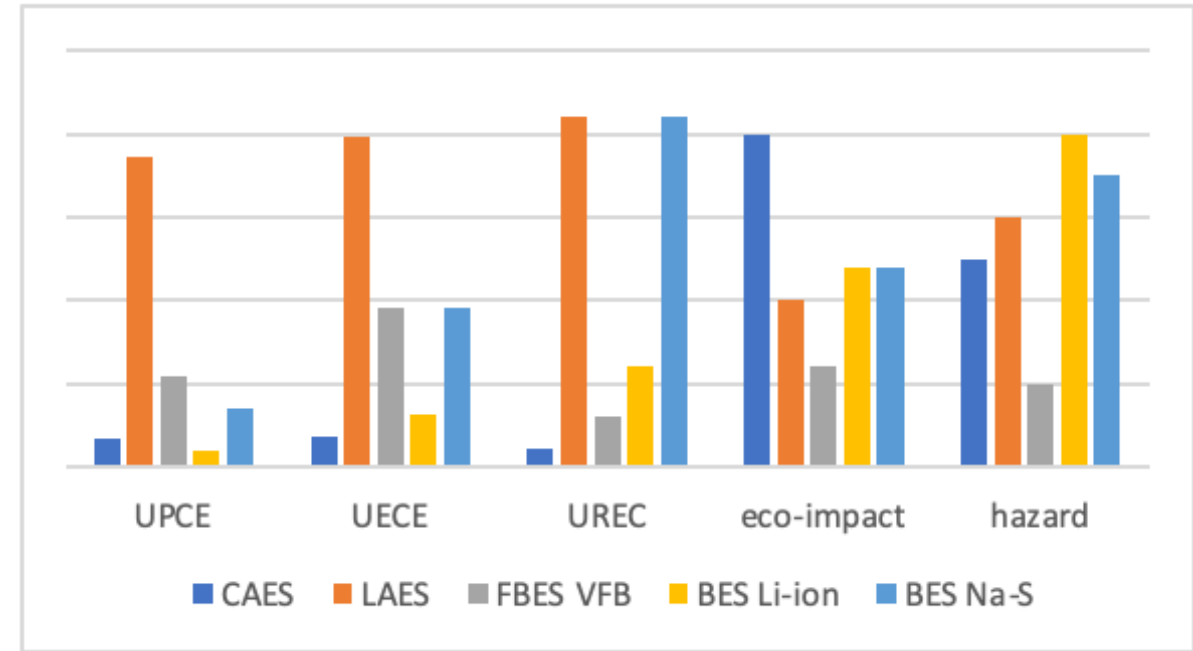
Low TRLs: other promising chemistries (e.g. Fe-Fe, Zinc-X, ...)



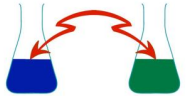
COMPARISON



KPIs of grid LDES technologies with TRL \geq 7. W = top energy, P = top power, RTE = round trip efficiency, ST = storage time, DT = discharge time, CyL = cycle life. Arbitrary units, the higher the better.



KPIs of grid LDES technologies with TRL \geq 7. UPCE = unit power capex, UECE = unit energy capex, UREC = simplified LCOS. Arbitrary units, the lower the better.



STESs UNDEMONSTRATED AT HIGH TRL

→ CRITICAL EXTRAPOLATION OF: RTE, OPEX, AND DERIVED KPIS

FBES (Fe-Fe) = Fe Flow Battery: 1981 – cheap, abundant and environment friendly iron; 2020-21 revamped by ESS (US) after gaining significant funding

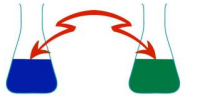
BES (MAB) = Metal-air battery energy storage

Fe-Air BES = cheap, abundant and environment friendly iron. Form Energy, US, claims very long DT (ca. 100 hours), attracted huge funding

PTES = pumped thermal energy storage – Carnot battery

heat pump (high-gain thermal flow), high temperature storage (needed in Rankine-cycle generation), thermal insulation

HES = hydrogen energy storage with electrolyzer–compression–combined-cycle Brayton gas turbines. Advanced Clean Energy Storage – Delta, US (840 MW / 90 GWhe) – fully operative on green H₂ in 2045



SO WHAT: CONCLUSIONS

Only IHES and PHES fit well for ultra LDES in terms of ST and DT
FBs are well placed among other industrial-level mild LDES technologies

Critical issues to improve FB (V) competitiveness

❖ LDES suitability

- present industrial systems DT = 1–4 (10) h
- suitability for DT > 10 h to be demonstrated (pilot systems needed)

❖ Reliability – Fault hazard

- 3 major leakage cases reported in US
- 3 major leakage cases (confidential) known in EU
- ... other unreported cases worldwide?

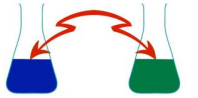
leakage issues are emerging as important factors capable of compromising FB safety reputation

❖ Fire hazard

- Unoperated mixed-acid VFB (2.5 M) at Sandia: leaked out of secondary containment*
- $\text{Cl}_2 + \text{H}_2$ evolution \rightarrow explosive mix \rightarrow UV + high T triggered fire

need to monitor gas evolution for safe operation

* R. Wittman, (Some) Lessons from Vanadium Flow Batteries for Non-Vanadium Flow Batteries, 247 ECS Meeting, Montreal, 19-23 May, 2025.



SO WHAT: CONCLUSIONS

FBs – pure (V) – Critical issues

❖ Safety, efficiency and cost

- All affect the competitiveness and profitability of storage systems
- “... applies the metrics of safety, low cost, and high efficiency, in this order*:
- It is absolutely essential that explosive release of *the* stored energy be physically impossible.
- Once this safety criterion is met, capital and maintenance costs must be brutally minimized, even at the price of a small hit in round-trip efficiency
- because storage of electricity is fundamentally about value, not about conserving energy.”

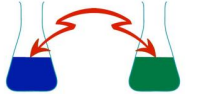
* R. B. Laughlin, Pumped thermal grid storage with heat exchange, J. Ren Sust Energy 9, 044103 (2017)
(1998 Nobel Laureate in Physics)



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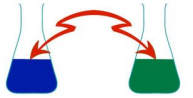


THANKS FOR YOUR ATTENTION

massimo.guarnieri@unipd.it

<https://research.dii.unipd.it/eescolab/>





OTHERS ESTs

DEMONSTRATED AT TRL ≥ 7

FES = flywheel energy storage (FES)

600 MW 100 MWh flywheel energy plant by Stoentech at Munich, Germany, designed for fast power quality service, far from LDES.

RT = fast

DT ≈ 10 MIN

SDR = 5–20% hour⁻¹

ST ≈ 10 min

Similar KPIs

SMES = superconducting magnet energy storage

SCES = supercapacitor energy storage

Short DT

GES = gravitational energy storage (heavy solid masses, limited energy)

