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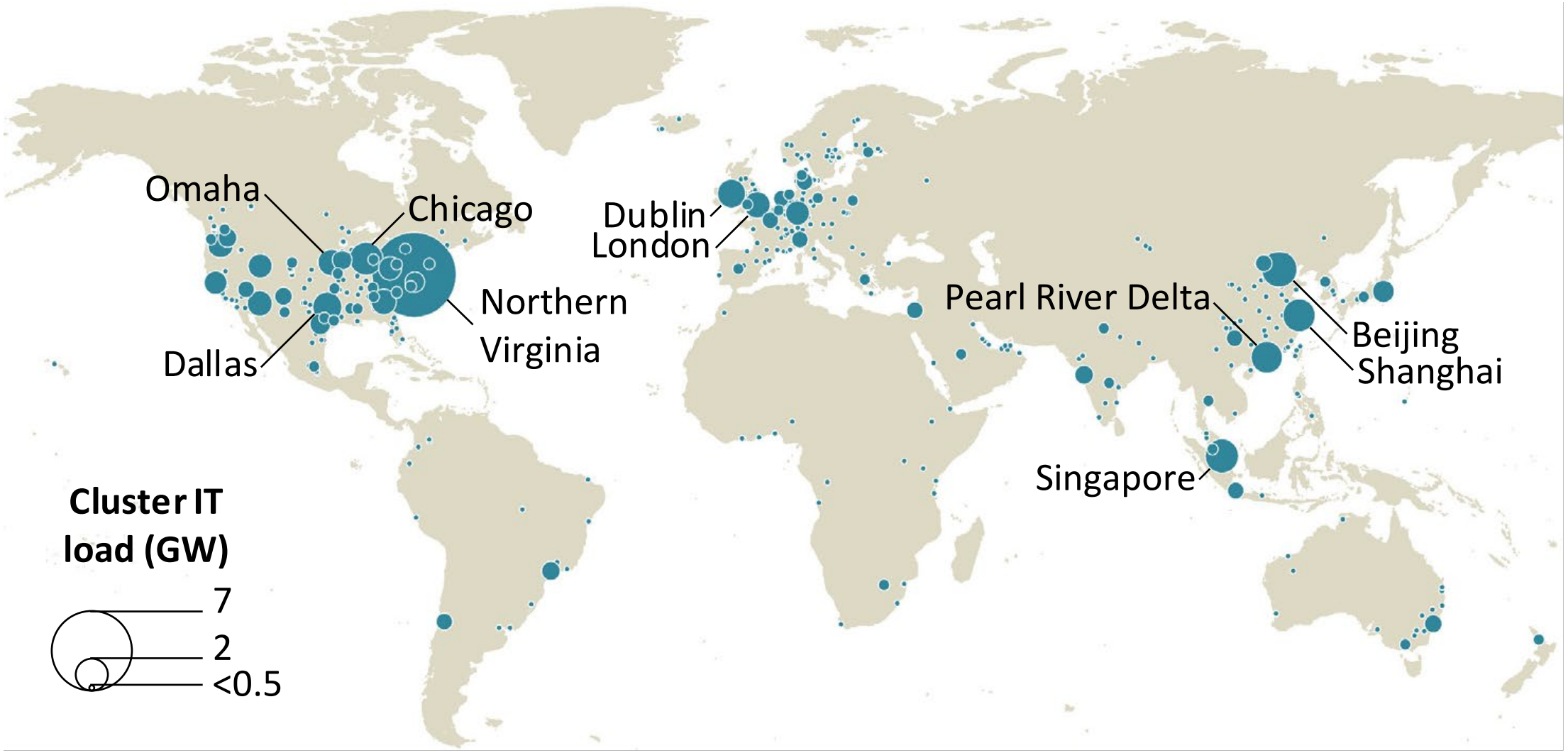
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Fast Forward Fusion

Prof. Dr. Sarbajit Banerjee
Full Professor of Chemistry, D-CHAB
Laboratory Head, Laboratory for Battery Science, PSI sbanerje@ethz.ch

The Elephant in the Room – AI/Data Center Growth



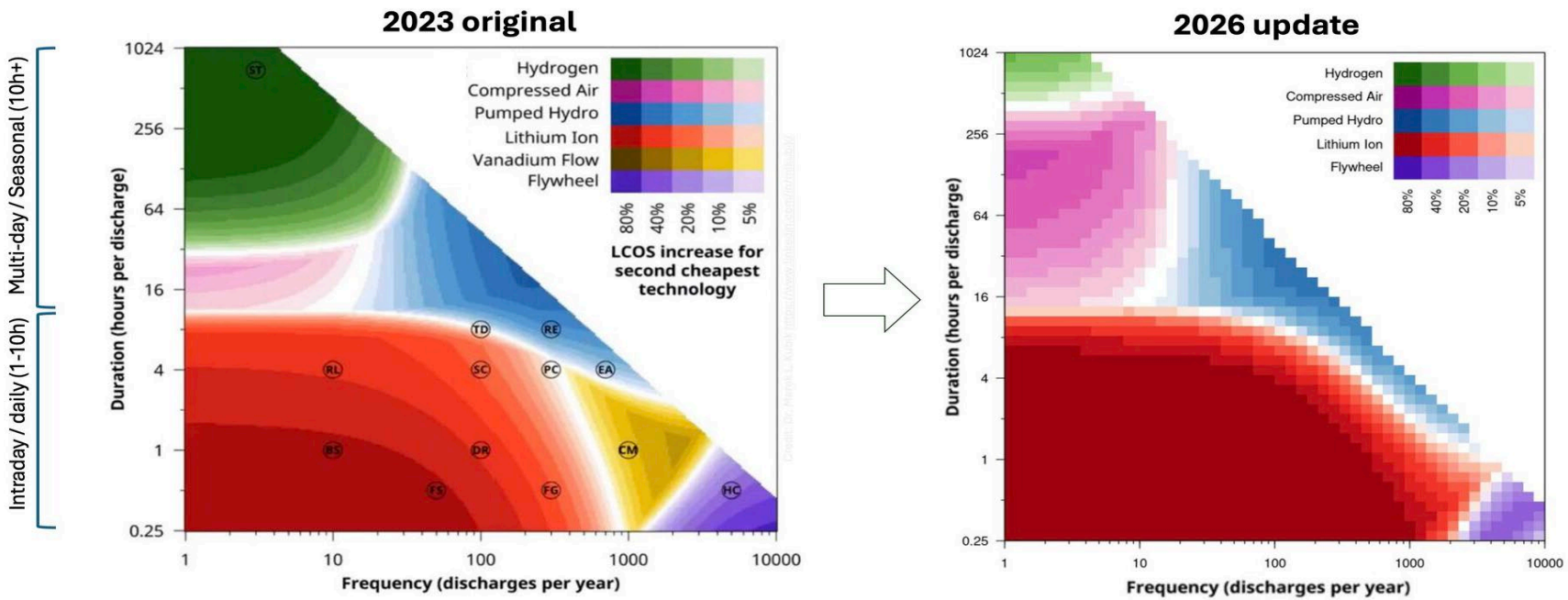
OMDIA (2025), Data Center Building and Investment Intelligence Service, https://omdia.tech.informa.com/advance-your-business/cloud-and-data-center/datacenter-building-and-investment-intelligence-service

Energy Solutions in a Changing World

PSI Center for Energy and Environmental Sciences

Lowest-LCOS storage by duration & cycling (2030)

BESS dominates for <10h | CAES and PHS wins multi-day >10h



Credit: Dr. Marek L. Kubik https://www.linkedin.com/in/mlkubik

Sources : Dr. Oliver Schmidt Linkedin analysis (2026 update) and original in Schmidt & Staffell 2023 Monitizing Energy Storage.

Plots were updated for Lithium Ion cost data using $110/kWh for 2030, perfromed using analysis with http://www.energystorage.ninja







Supply Chains Matter...

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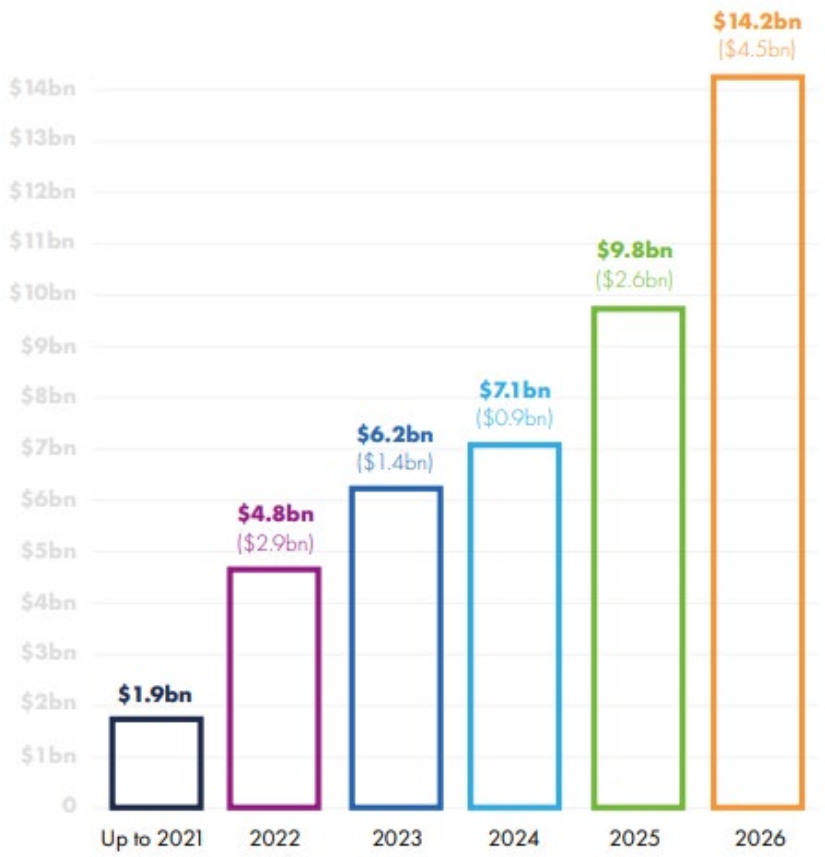
	Value Capture Index	Effective Substitution Time		Substitution Stress Ratio	Supply Chain Vulnerability Index
China → Russian oil	~€35.9/MWh-primary*	same 1–2 SSR scenario initially	same normalized oil-buffer scenario initially	~1–2	36-72
Europe → Russian nuclear	~€20.2/MWh-electric	multi-year	fuel inventories + forward procurement	~2 central	~40
Europe → Chinese LFP BESS	€9.14/MWh discharged	2.5–6 y; 4 y central	0.5–1.5 y; 1 y central	4.0	36.6
Europe → Chinese NMC BESS	€17.51/MWh discharged	1.5–4 y; 2.5 y central	0.5–1.5 y; 1 y central	2.5	43.8



For energy security, technological sovereignty, and for manufacturing competitiveness

FUSION IS A BIG BUSINESS…

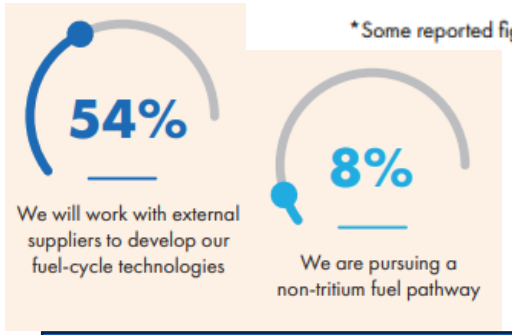
- Total fusion funding by year



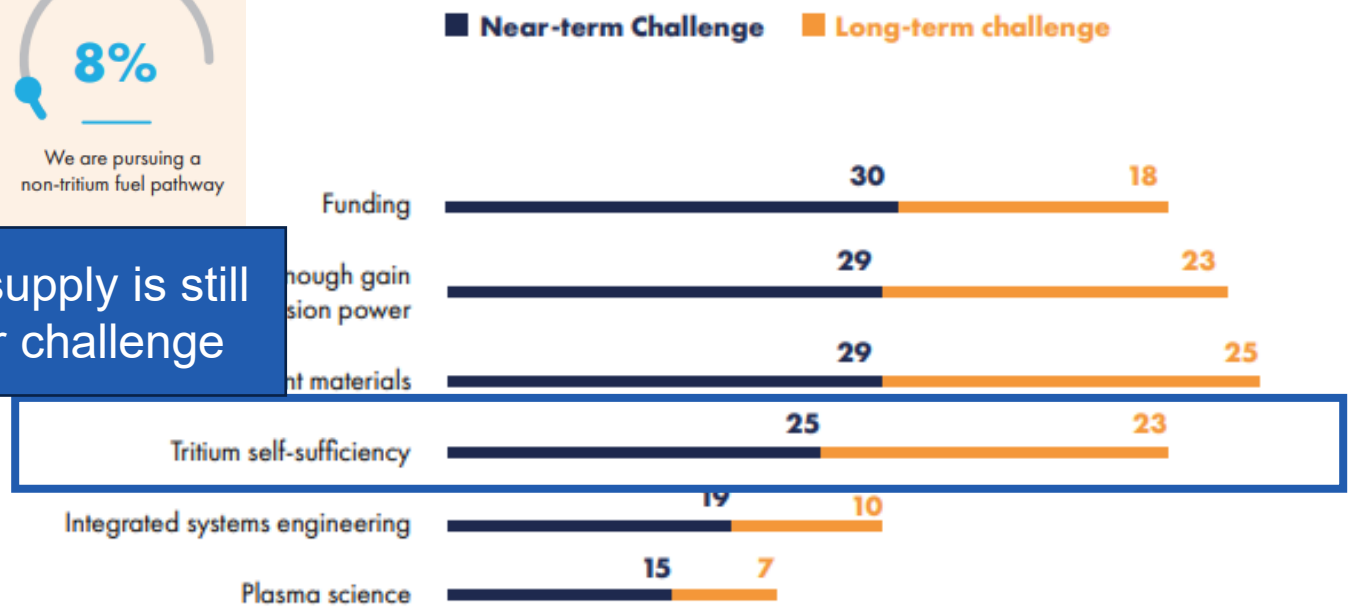
- Fusion funding in 2026 to date



Private companies are investing heavily in fusion



Tritium supply is still a major challenge

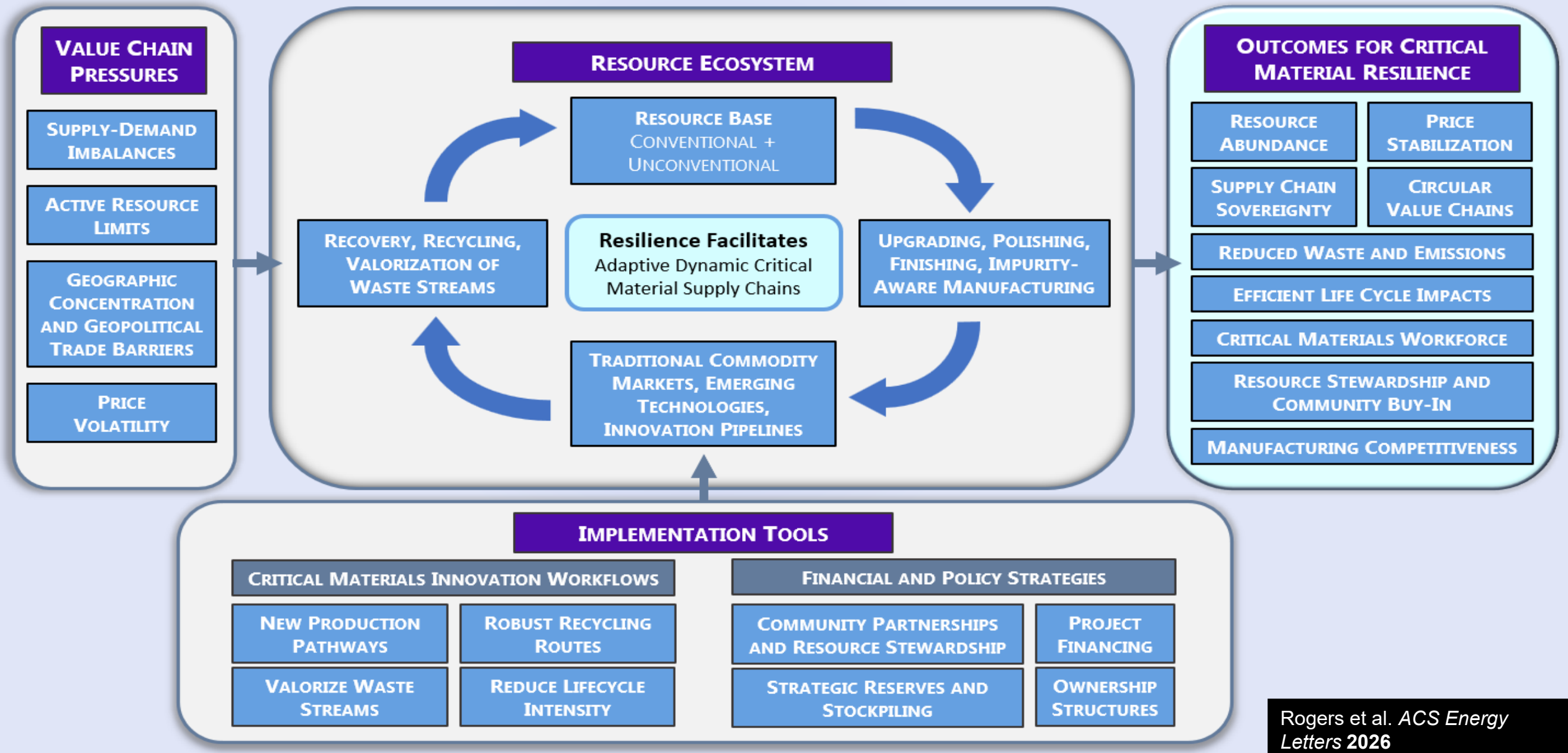


we must build supply chains now…

Fusion Industry Association. *The Fusion Industry Supply Chain 2026*. Fusion Industry Association, **2026**. (Accessed September 5th, 2026)
Fusion Industry Association. *The Global Fusion Industry Report 2026*. Fusion Industry Association, **2026**. (Accessed September 5th, 2026)

A Blueprint for Supply Chain Resilience

PSI Center for Energy and Environmental Sciences



Rogers et al. *ACS Energy Letters* **2026**

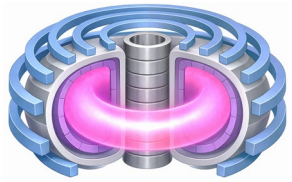
Fission and Fusion: Critical Energy Materials

ETH zürich

Principal Energy Generation Pathways

Fusion Energy

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He}\ (3.5\ \mathrm{MeV}) + ^{1}_{0}n\ (14.1\ \mathrm{MeV})$$



Principal Lithium Application

Tritium Breeding

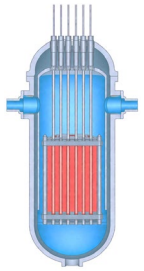
$$^{6}_{3}\mathrm{Li} + ^{1}_{0}n \rightarrow ^{4}_{2}\mathrm{He}\ (2.7\ \mathrm{MeV}) + ^{3}_{1}\mathrm{H}\ (2.1\ \mathrm{MeV})$$

Pressurized Water Reactors PWR

$$^{235}_{92}\mathrm{U} + ^{1}_{0}n \rightarrow ^{94}_{38}\mathrm{Sr} + ^{140}_{54}\mathrm{Xe} + 2\ ^{1}_{0}n + \sim 200\ \mathrm{MeV}$$

$$^{235}_{92}\mathrm{U} + ^{1}_{0}n \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\ ^{1}_{0}n + \sim 200\ \mathrm{MeV}$$

$$^{235}_{92}\mathrm{U} + ^{1}_{0}n \rightarrow ^{144}_{56}\mathrm{Ba} + ^{90}_{36}\mathrm{Kr} + 2\ ^{1}_{0}n + \sim 200\ \mathrm{MeV}$$



pH Control in Coolant

$$^{7}_{3}\mathrm{LiOH} + \mathrm{H_3BO_3} \rightarrow \mathrm{LiBO_2} + 2\mathrm{H_2O}$$

Molten Salt Reactors MSR

$$^{233}_{92}\mathrm{U} + ^{1}_{0}n \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\ ^{1}_{0}n + \sim 200\ \mathrm{MeV}$$

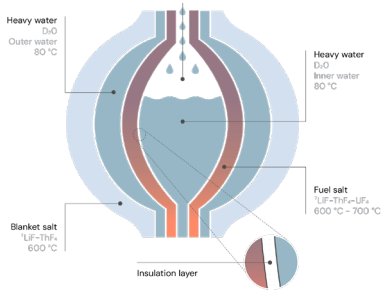


Image Source: Copenhagen Atomics

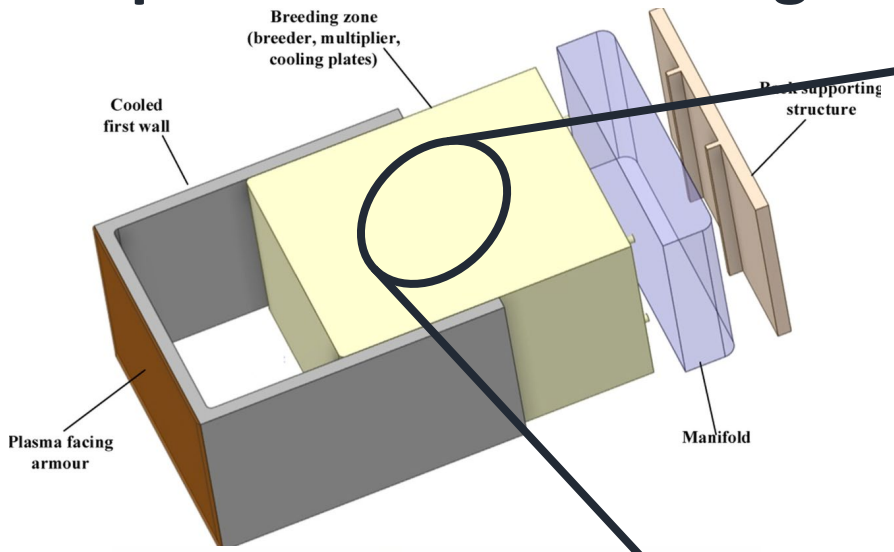
Salt Eutectic Coolant/Fuel Solvent

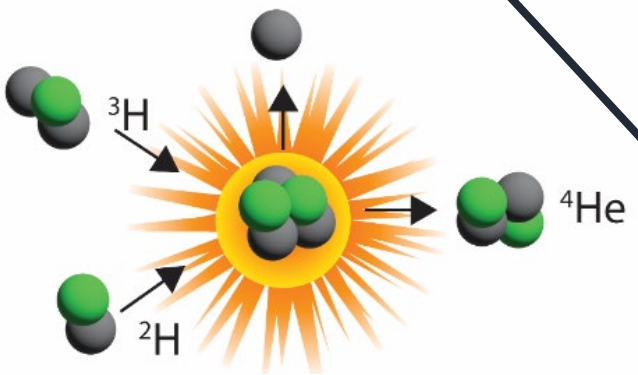
$$2\ ^{7}\mathrm{LiF} \bullet \mathrm{BeF_2}$$

BREEDING BLANKETS ARE AT THE HEART OF FUSION

PSI Center for Energy and Environmental Sciences

Components of a breeding blanket





$^3H + {}^2H \longrightarrow {}^4He + {}^1n + 17.6\ MeV$

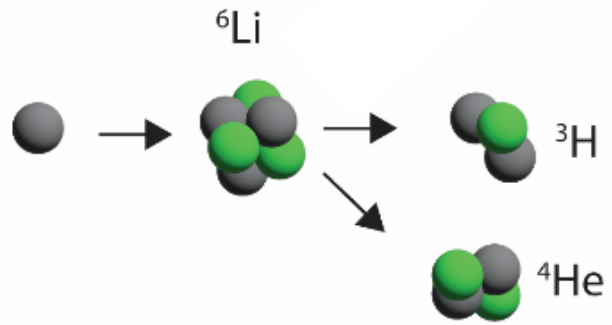
1 neutron is produced when D-T fusion occurs

Components of the breeding material

Neutron

Proton

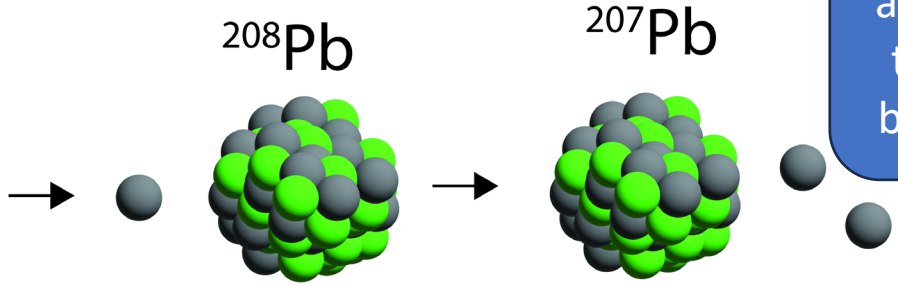
^{6}Li generates tritium



^6Li interacts with a neutron to produce ^3H

$^6Li + {}^1n \longrightarrow {}^4He + {}^3H + 4.8\ MeV$

Neutron Multiplier



$^{208}Pb + {}^1n \longrightarrow 2{}^1n + {}^{207}Pb$

Neutron multipliers are embedded in BB to enhance tritium breeding ratio (TBR)

Li, W; Wang, Q; Li, W; Zhang, Z; Cheng, J; Wang, L; Liu, Q; Deng, X; Song, X; Liu, *Superconductivity* **2026**, *19*, 100279. DOI: 10.1016/j.supcon.2026.100279

Some Breeder Concepts

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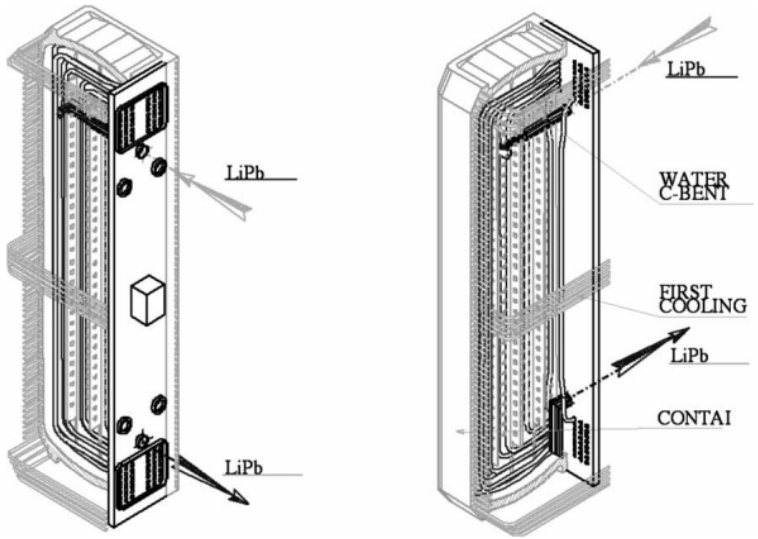
Liquid breeder material

Lithium-6 enrichment: 90%

Lead-lithium eutectic (15.7 at.% Li)

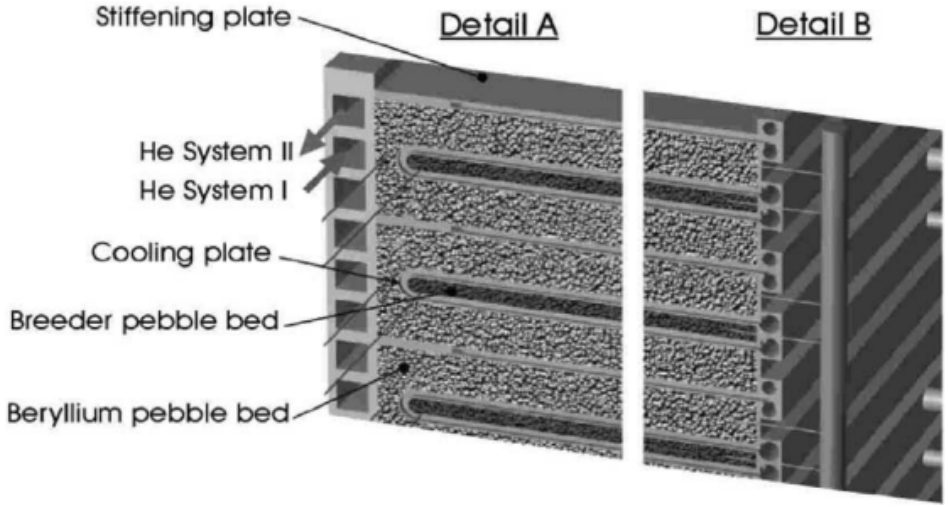
Leading concepts:

- Water Cooled Lithium Lead (WCLL)



Solid breeder material

- Lithium-6 enrichment: 30-60%
- Lithium ceramic is used
  - Li_4SiO_4 or Li_2TiO_3
  - Be is used as neutron multiplier
- Leading concepts:
  - Helium Cooled Pebble Bed (HCPB)



Both concepts require ^{6}Li enrichment…stay tuned for PSI Breeder Concept

Andreani, R.; M. Gasparotto. *Fusion Eng. Des.* **2002**, 61-62, 27-36.

Li, W; Wang, Q; Li, W; Zhang, Z; Cheng, J; Wang, L; Liu, Q; Deng, X; Song, X; Liu, *Superconductivity* **2026**, *19*, 100279. DOI: 10.1016/j.supcon.2026.100279

Methods for Li isotope separation

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COLEX process

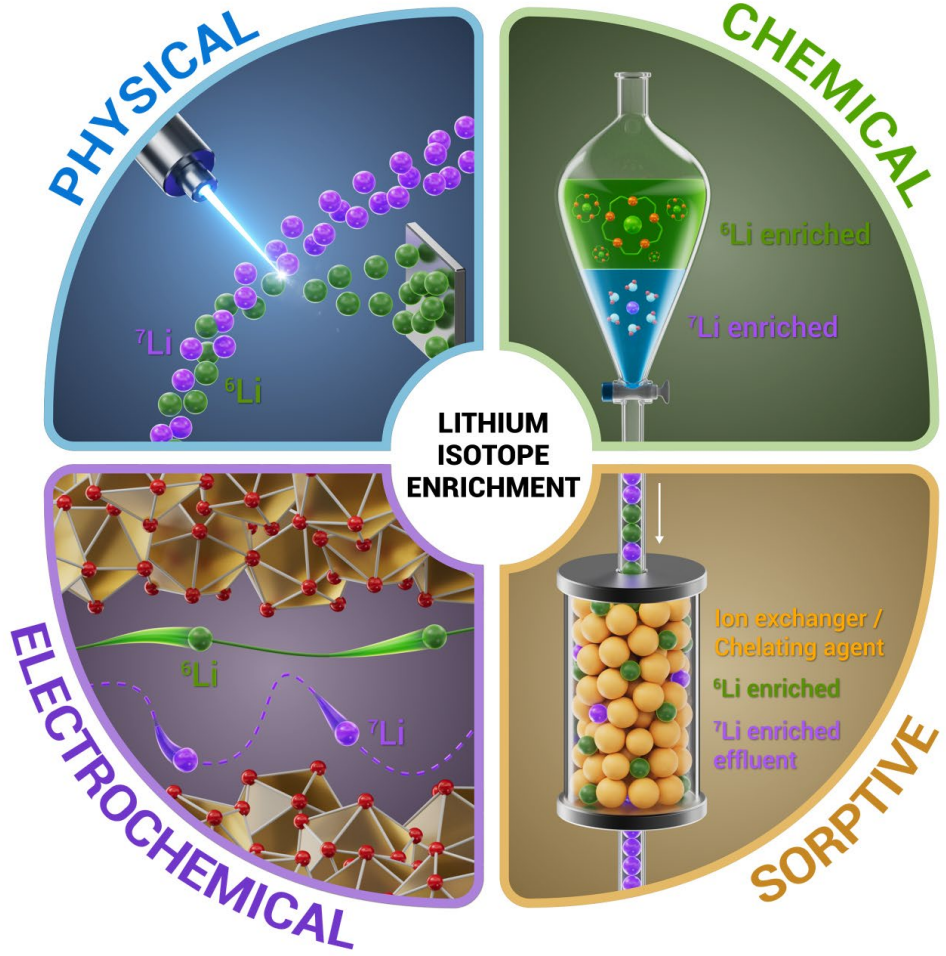


LiOH is cross flowed against mercury

^{6}Li creates amalgam with mercury ^{7}Li stays in LiOH

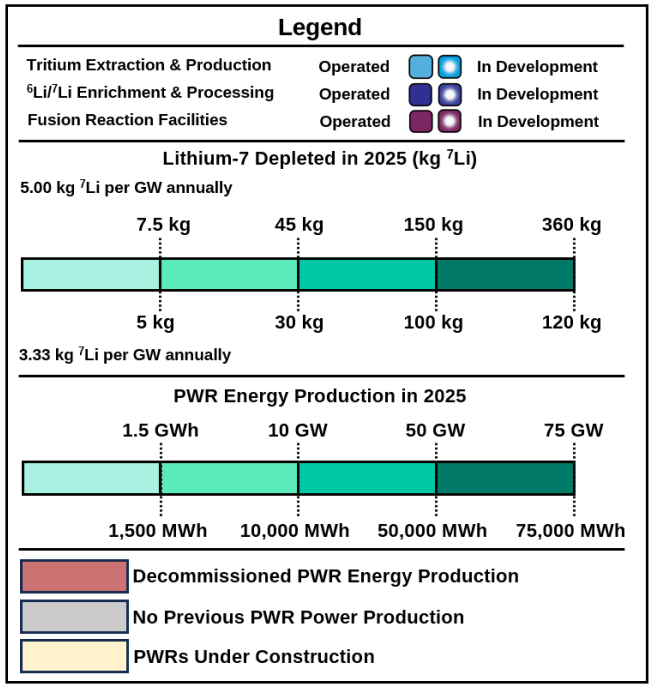
COLEX was phased out in the 1960's in the US due to local waterways being contaminated in Mercury

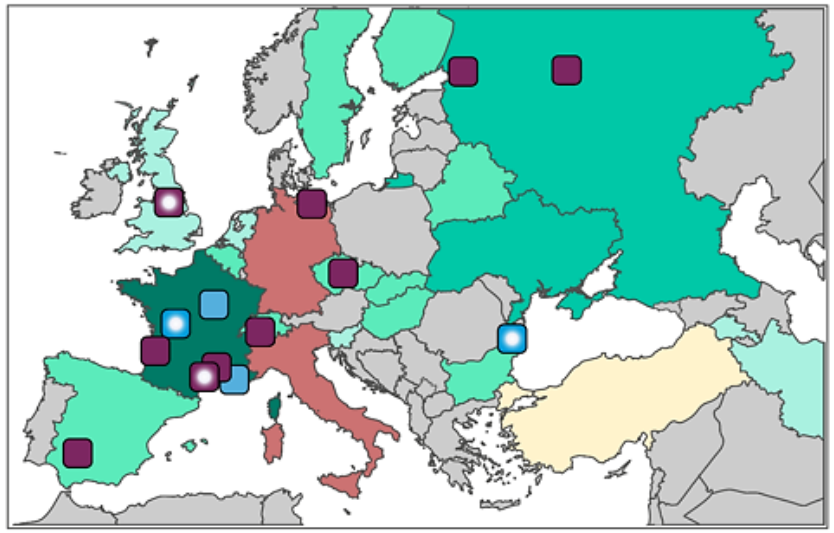
Modern Li Enrichment Techniques

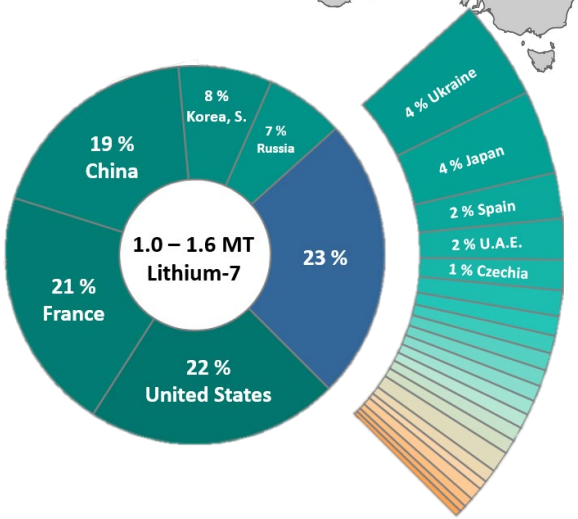


Electrochemical enrichment techniques offer a promising step forward

Mapping Supply Chains







Piecing Together the Tritium Supply Chain

ETH zürich

Fusion Energy Requires ^{6}Li to Breed Tritium

Tritium Breeding: $^{6}Li + n \rightarrow {}^{4}He + {}^{3}H + 4.78$ MeV

Energy Production: $^{3}H + {}^{2}H \rightarrow {}^{4}He + n + 17.6$ MeV

Fusion Devices – ^{6}Li Consumption

Facility	Supervising Organization	Reaction	Technology	Stage	Country	Locality	Role
LM26	General Fusion	D-D demonstrated	Magnetized Target Fusion	Operated	Canada	Richmond, BC	Demo
EAST	ASIPP / Hefei Institutes of Physical Science, CAS	D-D demonstrated	Tokamak	Operated	China	Hefei, Anhui	Research
HL-2A	Southwestern Institute of Physics (SWIP)	D-D demonstrated	Tokamak	Operated	China	Chengdu, Sichuan	Research
HL-3	Southwestern Institute of Physics (SWIP)	Unspecified	Tokamak	Operated	China	Chengdu, Sichuan	Research
SG-II-U	Shanghai Institute of Optics and Fine Mechanics, Chinese	D-D and D-T	Laser intertial confinement	Operated	China	Shanghai	Research
HH70	Energy Singularity Fusion Power Technology (Shanghai)	Unspecified	Superconducting Tokemak	Operated	China	Shanghai	Research
LMJ Laser Megajoule	CEA / Direction des applications militaires / CESTA	D-T	Laser Inertial Confinement	Operated	France	Le Barp, Nouvelle-	Research
WEST	Commissariat à l'énergie Atomique et aux énergies	D-D demonstrated	Tokamak	Operated	France	Saint-Paul-lès-	Research
ASDEX Upgrade	Max Planck Institute for Plasma Physics	D-D	Tokamak	Operated	Germany	Garching	Research
Wendelstein 7-X	Max Planck Institute for Plasma Physics	D-D planned	Stellarator	Operated	Germany	Greifswald	Research
SST-1	Institute for Plasma Research, Indian Department of	Unspecified	Superconducting Tokemak	Operated	India	Gandhinagar,	Research
ADITYA-U	Institute for Plasma Research, Indian Department of	D-D	Tokamak	Operated	India	Gandhinagar,	Research
FNG	Frascati Research Center (ENEA)	Gandhinagar India	Accelerator beam-target fusion	Operated	Italy	Frascati	Research
GEKKO XII/LFEX	The University of Osaka, Institute of Laser Science	D-D demonstrated	Laser Inertial Confinement	Operated	Japan	Suita, Osaka	Research
PF-1000U	Institute of Plasma Physics and Laser Microfusion (IPPLM)	D-D	Dense plasma focus	Operated	Poland	Warsaw	Research
PF-24	Institute of Nuclear Physics PAN	D-D demonstrated, D-T	Dense plasma focus	Operated	Poland	Kraków	Research
Globus-M2	Ioffe Institute	D-D	Spherical tokamak	Operated	Russia	St. Petersburg	Research
T-15MD	NRC Kurchatov Institute	Unspecified	Tokamak	Operated	Russia	Moscow	Research
TUMAN-3M	Ioffe Institute	D-D	Tokamak	Operated	Russia	St. Petersburg	Research
Gas Dynamic Trap	Budker Institute of Nuclear Physics, Siberian Branch,	D-D Demonstrated	Magnetic mirror confinement/gas dynamic	Operated	Russia	Novosibirsk	Research
KSTAR	Korea Institute of Fusion Energy (KFE)	D-D demonstrated	Tokamak	Operated	S. Korea	Daejeon	Research
TCV	EPFL / Swiss Plasma Center	D-D demonstrated	Tokamak	Operated	Switzerland	Lausanne	Research
ST40	Tokamak Energy	D-D demonstrated	Spherical tokamak	Operated	UK	Milton Park,	Research
MAST Upgrade	United Kingdom Atomic Energy Authority	D-D demonstrated	Spherical tokamak	Operated	UK	Culham, Oxfordshire	Research
3HeCTRE	University of Wisconsin–Madison	D-D and D-He3	Inertial electrostatic confinement	Operated	USA	Madison, WI	Research
FuZE / FuZE-Q	University of Washington / Zap Energy	D-D	Sheared-flow-stabilized Z pinch	Operated	USA	Everett, WA	Research
HBT-EP	Columbia University, Fusion Research Center	Unspecified	Tokamak	Operated	USA	New York, NY	Research
HELIOS (IEC-2)	University of Wisconsin–Madison	D-D and He3-He3	Inertial electrostatic confinement	Operated	USA	Madison, WI	Research
HFNG	University of California, Berkeley	D-D	Accelerator beam-target fusion	Operated	USA	Berkeley, CA	Research
HOMER (IEC-1)	University of Wisconsin–Madison	D-D and D-He3	Inertial electrostatic confinement	Operated	USA	Madison, WI	Research
NIF	Lawrence Livermore National Laboratory	D-D, D-T, T-T	Laser Inertial Confinement	Operated	USA	Livermore, CA	Research
NSTX-U	Princeton Plasma Physics Laboratory	D-D	Spherical tokamak	Operated	USA	Plainsboro, NJ	Research
OMEGA (60-beam)	University of Rochester / LLE	D-T and D-D	Laser inertial confinement	Operated	USA	Rochester, NY	Research
Polaris	Helion Energy	D-T and D-D	Pulsed Field-Reversed Configuration	Operated	USA	Everett, WA	Demo
WHAM	University of Wisconsin-Madison / Realta Fusion	D-D planned	Magnetic Mirror Confinement	Operated	USA	Stoughton, WI	Research
Z machine (MagLIF	Sandia National Laboratories	D-D	Pulsed power / magnetized liner inertial	Operated	USA	Albuquerque, NM	Research
FLARE	SHINE Technologies	D-T demonstrated	Accelerator beam-gas-target fusion	Operated	USA	Janesville, WI	Research
DIII-D	General Atomics	D-D demonstrated	Tokamak	Operated	USA	San Diego, CA	Research
BEST	ASIPP / Hefei Institutes of Physical Science, CAS	D-T planned	Tokamak	Under Construction	China	Hefei, Anhui	Research
COMPASS-U	Institute of Plasma Physics, Czech Academy of Sciences	D-D planned	Tokamak	Under Construction	Czechia	Prague	Research
ITER Cadarache	ITER Organization	D-T planned	Tokamak	Under Construction	France	Saint-Paul-lès-	Research
JT-60SA	QST / Fusion for Energy (Japan-Europe Broader Approach)	D-D planned	Tokamak	Under Construction	Japan	Naka	Research
UKAEA STEP Prototype	UK Fusion Energy Ltd (UKAEA Group)	D-T planned	Spherical tokamak	Under Construction	UK	Nottinghamshire,	Demo
SPARC	Commonwealth Fusion Systems	D-T planned	Tokamak	Under Construction	USA	Devens, MA	Demo
Orion	Helion Energy	D-He3 planned	Pulsed Field-Reversed Configuration	Under Construction	USA	Malaga, WA	Electricity
CFETR	Institute of Plasma Physics, Chinese Academy of Sciences	D-T planned	Tokamak	Announced	China	Hefei, Anhui	Demo
ARC Power Plant	Commonwealth Fusion Systems; Dominion Energy Virginia	D-T planned	Tokamak	Announced	USA	Chesterfield County,	Electricity

Fission Energy Requires ^{7}Li

$^{7}Li + n \rightarrow {}^{4}He + {}^{3}H + n' - 2.47$ MeV

^{6}Li and ^{7}Li Enrichment

Facility	Reaction	Stage	Country	Locality
Shanghai Institute of Applied Physics, Affiliate	Hg-Amalgam Exchange	Operating	China	Shanghai
Hungnam Chemical Complex	Hg-Amalgam Exchange	Operating	North Korea	Hamhung
Novosibirsk Nuclear Chemical Plant	Electrolysis, Hg	Operating	Russia	Novosibirsk
Molten Salt Solutions	Chromatography	Developing	USA	Santa Fe, NM
Precision Periodic	Displacement Chromatography	Developing	USA	Orlando, FL
Nusano	Electromagnetic	Developing	USA	West Valley City, UT
EnergyX, NUKE-it	Membranes	Developing	USA	Austin, TX
Hexium	Atomic Vapor Laser	Developing	USA	Austin, TX
ASP Isotopes/Quantum Leap Energy	Laser	Announced	UK	England
Y-12 National Security Complex	Hg-Amalgam Exchange	Terminated	USA	Oak Ridge, TN
AEC/Armscor	Cu Atomic Vapor Laser	Terminated	South Africa	Pelindaba

Tritium ^{3}H Production

Facility	Processes	Stage	Country	Locality
Embalse	Generation via heavy-water by-product	Operating	Argentina	Embalse, Cordoba
Darlington Tritium Removal Facility	Recovery & Purification	Operating	Canada	Bowmanville, ON
Valduc	Recovery, Purification & Recycling	Operating	France	Salives
Karlsruhe Tritium Laboratory, KIT	Research Processing/Fusion-Fuel Cycles	Operating	Germany	Karlsruhe
QST Tritium Process Laboratory	Research Processing/Fusion-Fuel Cycles	Operating	Japan	Naka, Ibaraki
Mayak Production Association	Generation + Recovery & Purification	Operating	Russia	Ozyorsk
Wolsong Tritium Removal Facility	Recovery & Purification	Operating	South Korea	Gyeongju
Watts Bar Nuclear Plant	Generation via lithium-target irradiation	Operating	USA	Spring City, TN
Savannah River Site	Recovery & Purification	Operating	USA	Aiken, SC
Qinshan Nuclear Power Plant	Generation via heavy-water by-product	Developing	China	Qinshan, Zhejiang Province
Civaux Nuclear Site	Generation via lithium-target irradiation	Developing	France	Civaux
ITER Tritium Plant/Fuel-Cycle Facilities	Research Processing/Fusion-Fuel Cycles	Developing	France	Saint-Paul-lès-Durance
Cernavoda Tritium Removal Facility	Generation + Recovery & Purification	Developing	Romania	Cernavoda
UKAEA–Eni H3AT Tritium Loop Facility	Research Processing/Fusion-Fuel Cycles	Developing	UK	Culham, Oxfordshire
Marcoule Nuclear Site	Historical Generation + Recovery & Purification	Terminated	France	Chusclan
Hanford Site	Historical Generation + Recovery & Purification	Terminated	USA	Benton County, WA
Chapelcross Nuclear Site	Historical Generation + Recovery & Purification	Terminated	UK	Annan, Scotland
AEB Building 5100 pilot programme	Generation	Terminated	South Africa	Pelindaba

MINING BRINES FOR LITHIUM

Texas Permian Basin

- Leading oil and gas producing region in America
  - Daily production of 4.5 million barrels of oil
- Fracking creates produced water
  - Excess of **3 billion L** per day
    - Li^+ concentrations between 50-150 ppm.

Please cite this article in press as: Gobbato et al., Mining brine to source lithium for the energy transition, Chem Circularity (2026), https://doi.org/10.1016/j.checir.2026.100007

Chem Circularity

CellPress

Voices

Mining brine to source lithium for the energy transition

Growing gaps between lithium supply and demand risk slowing the energy transition. Brine resources in the Lithium Triangle are expected to be critical, yet significant scientific, environmental, and societal challenges remain. This Voices article reflects on insights from the recent Direct Lithium Extraction Symposium at KIT by highlighting technological advances, unresolved obstacles, and pathways toward potentially more circular and reliable lithium production.

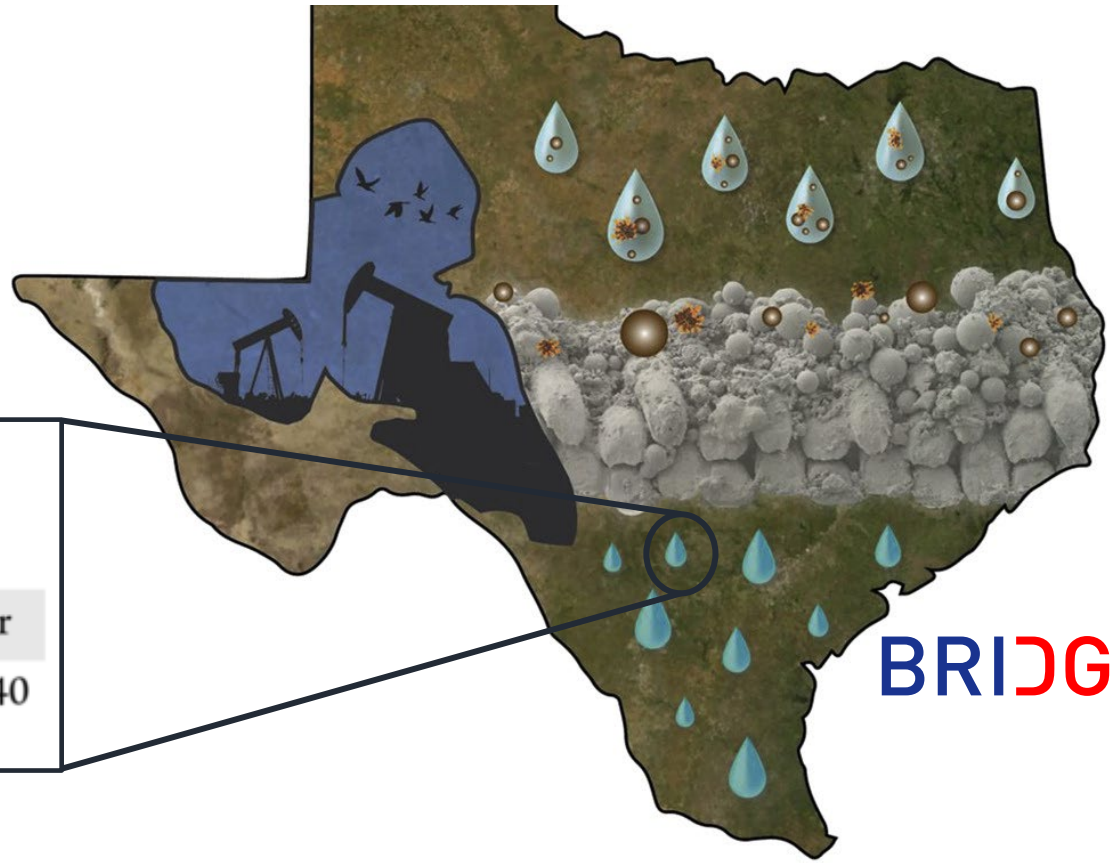


Table 2. ICP–MS Results of the Ionic Composition of Residual Salt upon Evaporation of FPW[a]

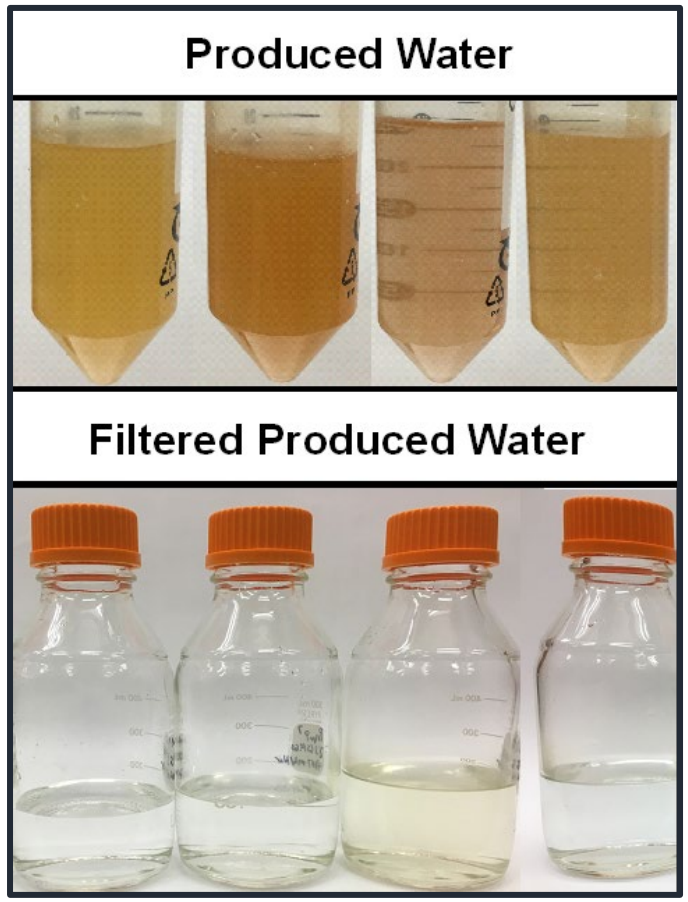
	Li	Na	K	Mg	Ca	Sr
salt composition (at. %)	0.35	94.03	0.95	1.02	3.25	0.40

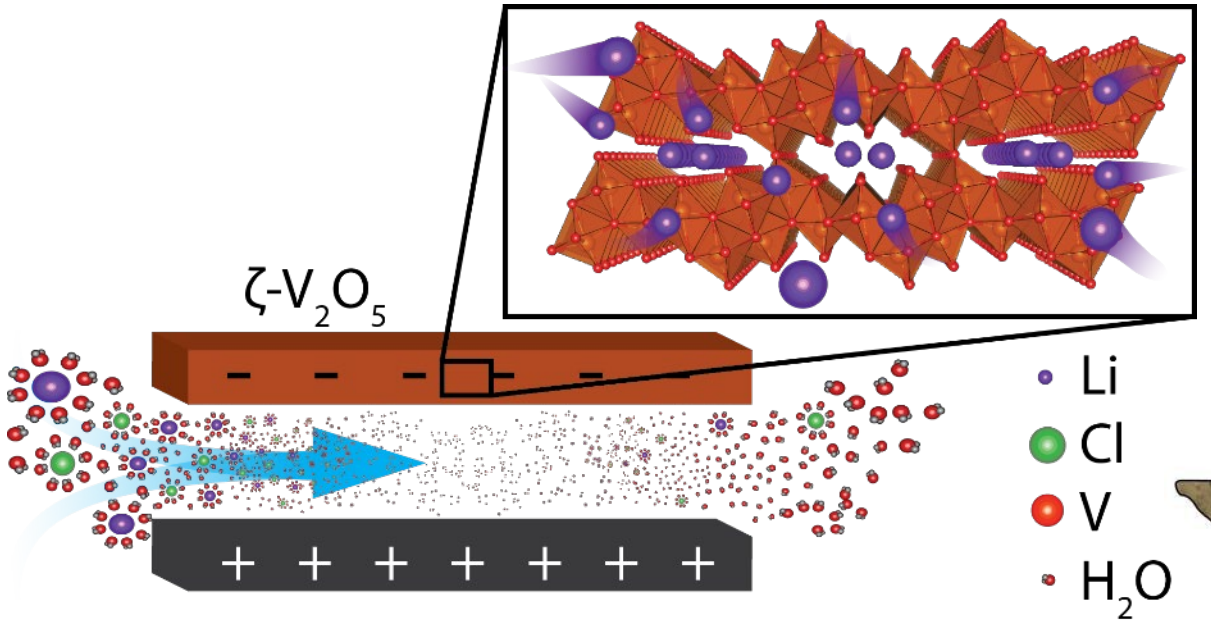
BRIDGE

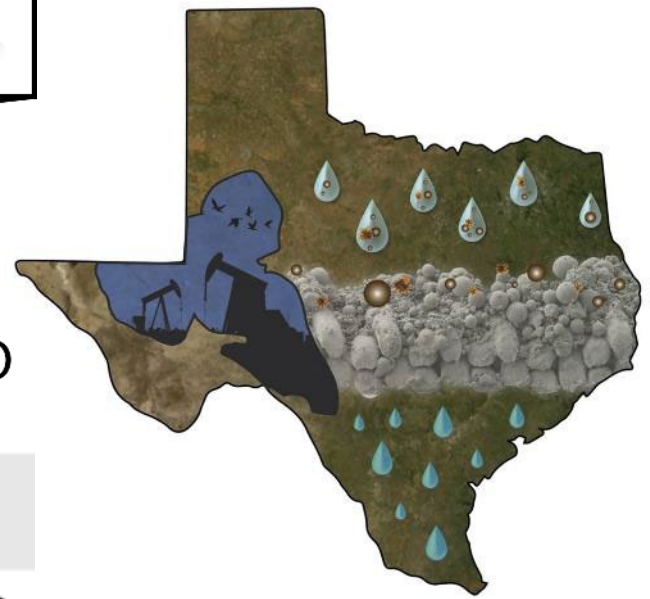
Rivera-Gonzalez, N.; Bajpayee, A.; Nielsen, J.; Zakira, U.; Zaheer, W.; Handy, J.; Sill, T.; Birgisson, B.; Bhatia, M.; Banerjee, S. *iScience* **2022**, *25* (10), 105063. DOI: 10.1016/j.isci.2022.105063

Cool, N. I.; James, R.; Schofield, P.; Handy, J. V.; Bhatia, M.; Banerjee, S. *ACS Appl. Mater. Interfaces* **2023**, *15*, 1554–1562. DOI: 10.1021/acsami.2c17800.

Hybrid Capacitive Deionization: a battery in reverse







	Li	Na
salt composition (at. %)	0.35	94.03
sequestered ions (at. %)	7.29	24.27

Selective Li-ion extraction from unconventional sources

Cool, N. I.; James, R.; Schofield, P.; Handy, J. V.; Bhatia, M.; Banerjee, S. *ACS Appl. Mater. Interfaces* **2023**, *15*, 1554–1562. DOI: 10.1021/acsami.2c17800.

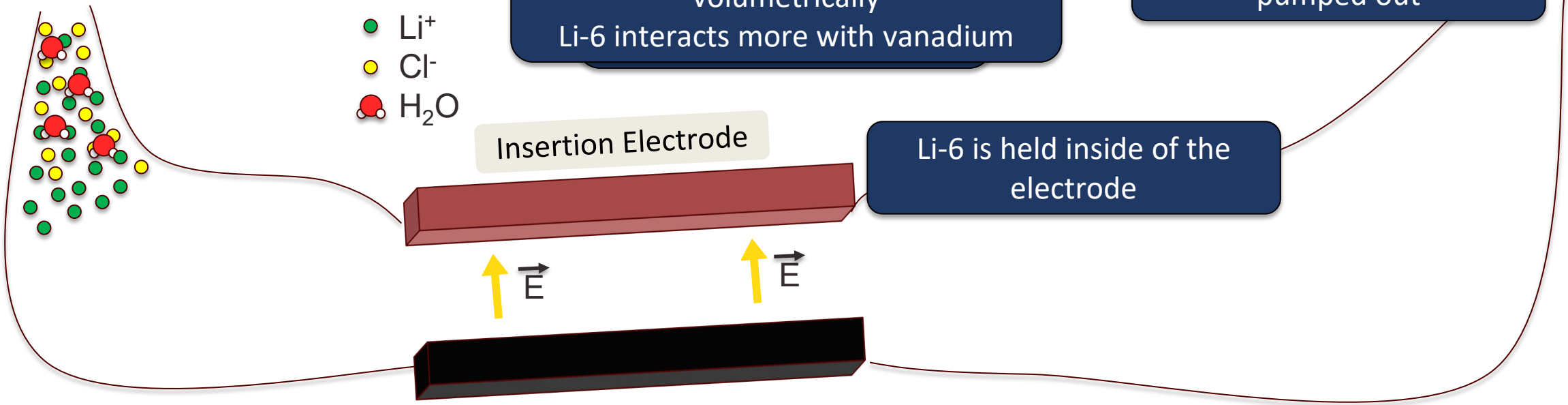
Hybrid Capacitive Deionization: a battery in reverse

ETH zürich

Deionized water is flowed through the system

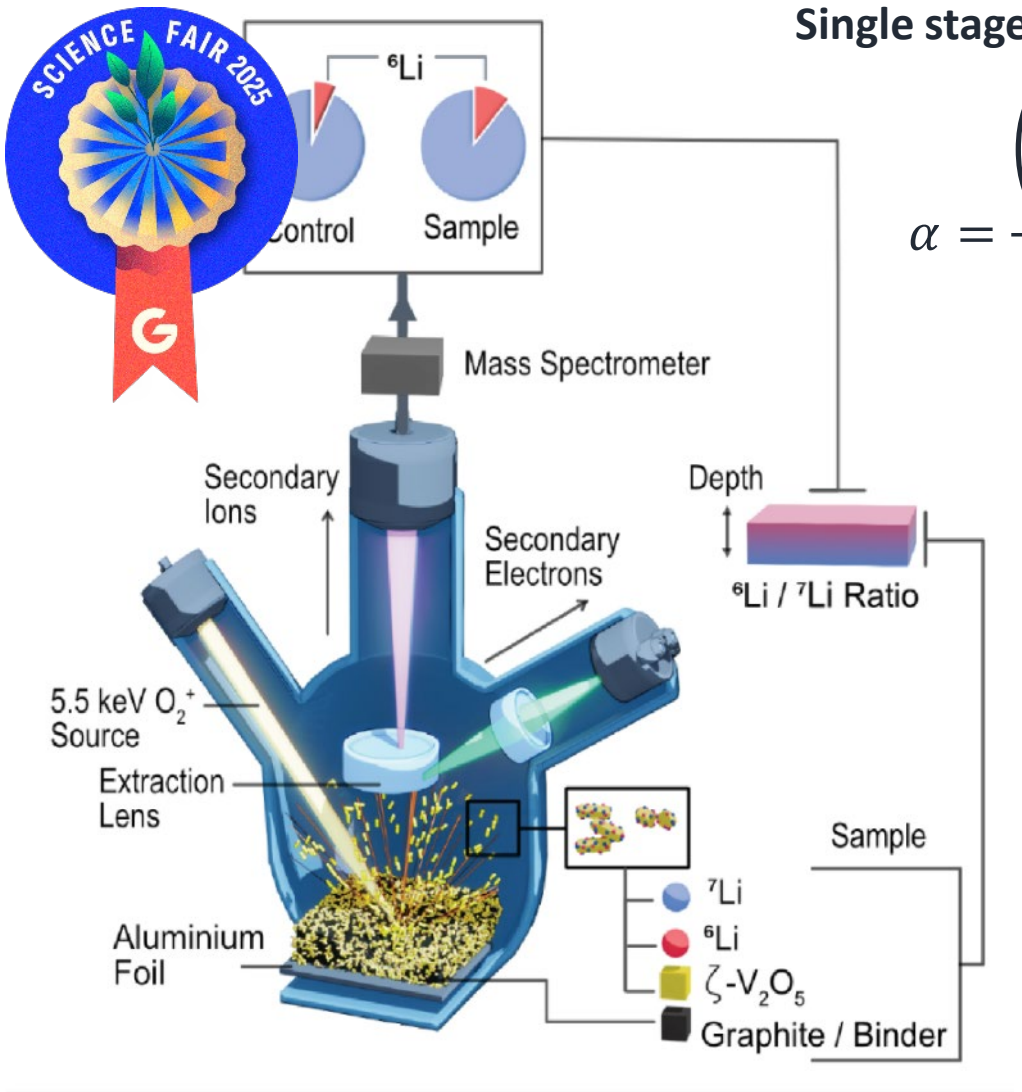
Lithium Ions are stored surficially and volumetrically
Li-6 interacts more with vanadium

Li-7 enriched effluent is pumped out



Li-6 is held inside of the electrode

ISOTOPIC ENRICHMENT

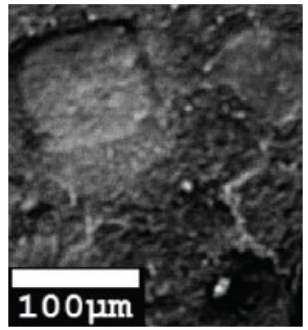


Single stage enrichment factor (α)

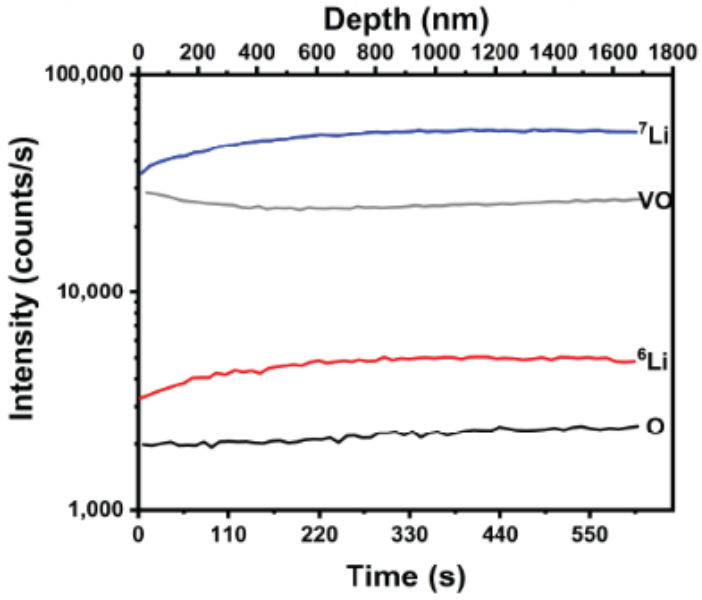
$$\alpha = \frac{\left({}^{6}\mathrm{Li}/{}^{7}\mathrm{Li}\right)_{enriched}}{\left({}^{6}\mathrm{Li}/{}^{7}\mathrm{Li}\right)_{initial}}$$

ζ-V_2O_5 at 20 °C:
α = 1.06

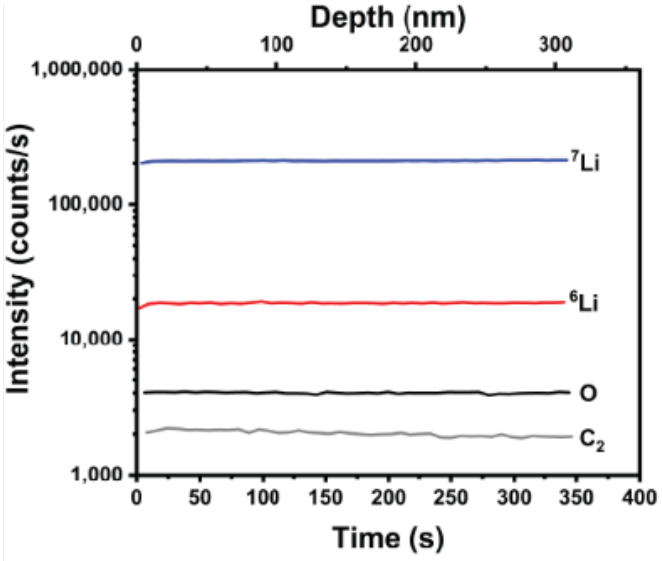
COLEX at 0 °C:
α = 1.04



ζ-V_2O_5 electrode



$Li_{1.4}Al_{0.4}Ti_{1.6}(PO_4)_3$ standard



Carillo, L.; Ezazi, A.A.; Perez-Beltran, S.; Larriuz, C.A.; **Kohl, H.E.**; Ayala, J.A.; Maji, A.; Verkhoturov, S.; Al-Hashimi, M.; Bazzi, H.S.; Weiland, C.; Jaye, C.; Fischer, D.A.; Zuin, L; Wang, J.; Banerjee, S. *Chem* **2025**, *11*. DOI: 10.1016/j.chempr.2025.102486

High-purity isotopically enriched lithium

PSI Center for Energy and Environmental Sciences

c&en CHEMICAL & ENGINEERING NEWS

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NUCLEAR POWER

Nuclear fusion fuel without toxic mercury

Electrochemical process isolates lithium-6, critical for scaling fusion energy

by **Prachi Patel**

March 20, 2025

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NEWS

Mercury-free electrochemical lithium isotope separation could fuel a fusion future

BY KIRA WELTER | 1 APRIL 2025

Bioengineer.org

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Researchers Discover Alternative to Nuclear Fusion Fuel Amid US Toxicity Ban

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SCI AM

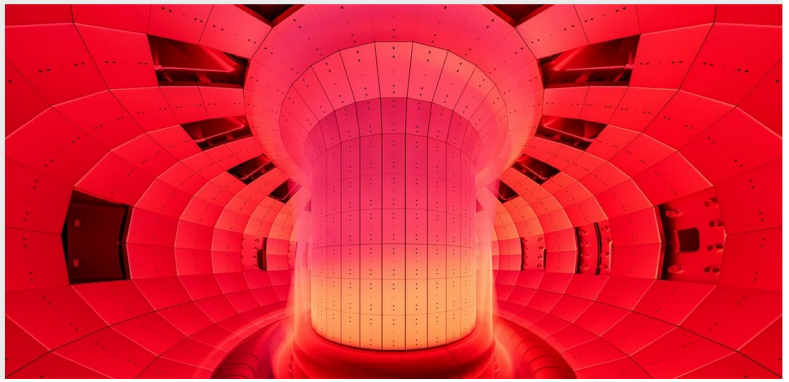
$1 for 90 days

MARCH 25, 2025 | 4 MIN READ

How Researchers Found a Greener Way to Make Fuel for Nuclear Fusion—By Accident

Researchers have found an environmentally safer way to extract the lithium 6 needed to create fuel for nuclear fusion reactors. The new approach doesn't require toxic mercury, as conventional methods do

BY JACEK KRYWKO EDITED BY ANDREA THOMPSON



PHYSICS & CHEMISTRY

Researchers in Texas Figure Out a Non-Toxic Method of Making Fuel for Nuclear Fusion

Enriched Lithium is a critical ingredient in fusion reactors. Making it is a toxic nightmare, but scientists may have found a way to do it without poisoning the world.

Interesting Engineering + Follow 49.8K Followers

Nuclear fusion fuel: US scientists find mercury-free way to source lithium-6 from batteries

Story by Ameya Paleja • 2w • 3 min read

New Scientist

Flash sale

Chemistry

Nuclear fusion fuel could be made greener with new chemical process

Lithium-6 is a crucial material for nuclear fusion reactors, but isolating it is challenging – now researchers have found a way to do this without using toxic mercury

By James Woodford

20 March 2025

SciTechDaily

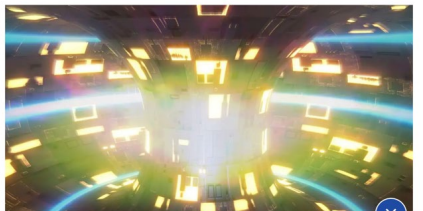
Biology Chemistry Earth Health Physics

Home » Chemistry » Scientists Were Cleaning Dirty Water – Then They Accidentally Solved a Fusion Energy Problem

CHEMISTRY

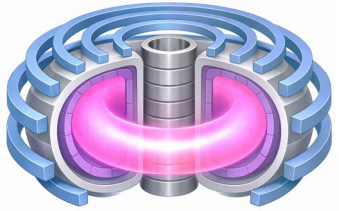
Scientists Were Cleaning Dirty Water – Then They Accidentally Solved a Fusion Energy Problem

BY CELL PRESS – MARCH 22, 2025 3 COMMENTS 5 MINS READ



Scaling to Production

PSI Center for Energy and Environmental Sciences



^{6}Li is then enriched for fusion applications

Geothermal Brines

Oilfield Produced Water

South American Salars

Fusion Grade ^{6}Li Production Chain

Process Repeated from Fresh Precursor Solution

0.9 GWh per 1 MT 90% enriched ^{6}Li

Li Precursor Solution → HCDI Electrode (7.9% ^{6}Li, 92.1% ^{7}Li) → HCDI Electrode (90% ^{6}Li, 10% ^{7}Li) → ^{6}Li Enriched Flowstream → Precipitation → Fusion Grade ^{6}Li (90% ^{6}Li, 10% ^{7}Li)

7.5% ^{6}Li, 92.5% ^{7}Li

1st Cycle

85th Cycle

^{7}Li Enriched Effluent (7.2% ^{6}Li, 92.8% ^{7}Li) → ^{7}Li Enriched Effluent (0.07% ^{6}Li, 99.93% ^{7}Li)

Process Repeated with Fresh Enriched Effluent

HCDI Electrode (0.10% ^{6}Li, 99.90% ^{7}Li) → HCDI Electrode (0.51% ^{6}Li, 99.49% ^{7}Li)

92nd Cycle

121st Cycle

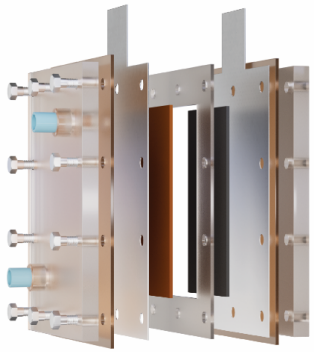
Fission Grade ^{7}Li Production Chain

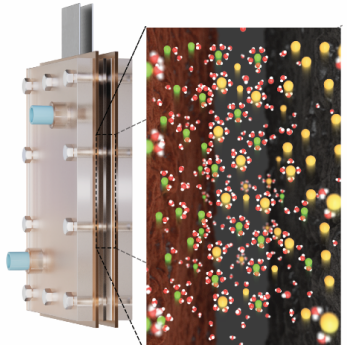
0.16 GWh per 1 MT 99.99% enriched ^{7}Li

^{7}Li Enriched Effluent (0.05% ^{6}Li, 99.95% ^{7}Li) → ^{7}Li Enriched Effluent (0.01% ^{6}Li, 99.99% ^{7}Li) → Precipitation → Fission Grade High Purity ^{7}Li (0.01% ^{6}Li, 99.99% ^{7}Li)

Precipitation → Fission Grade ^{7}Li (0.05% ^{6}Li, 99.95% ^{7}Li)

0.03 GWh per 1 MT 99.95% enriched ^{7}Li

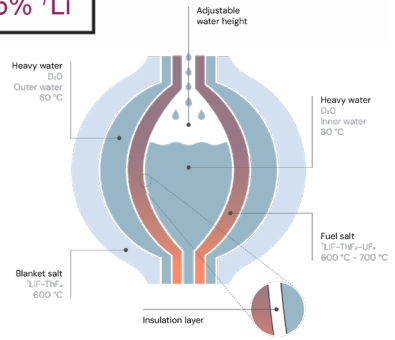




ζ-V_2O_5 selectively extracts Li^+ from complex saline solutions



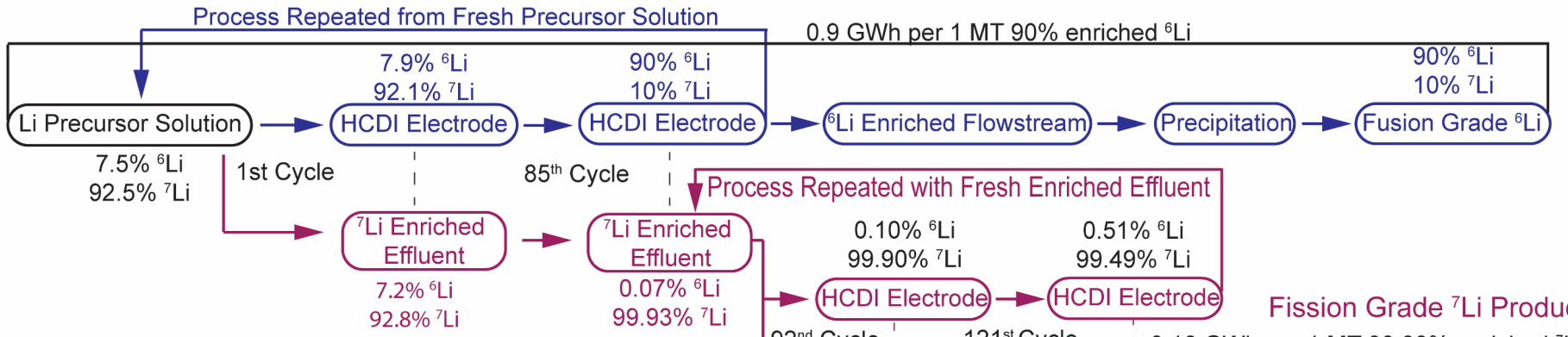
^{7}Li enriched effluent is further processed for fission applications



Scaling to Production

PSI Center for Energy and Environmental Sciences

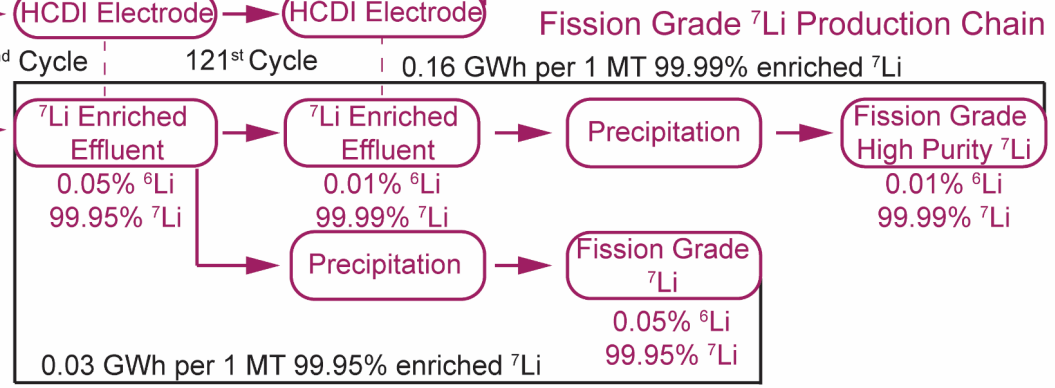
Fusion Grade ^{6}Li Production Chain



1GW Fusion Reactor

- ^{6}Li Demand **22.4 MT**
- Energy Demand **22.24 GWh**
- Vanadium Demand **8.0 MT**

Fission Grade ^{7}Li Production Chain

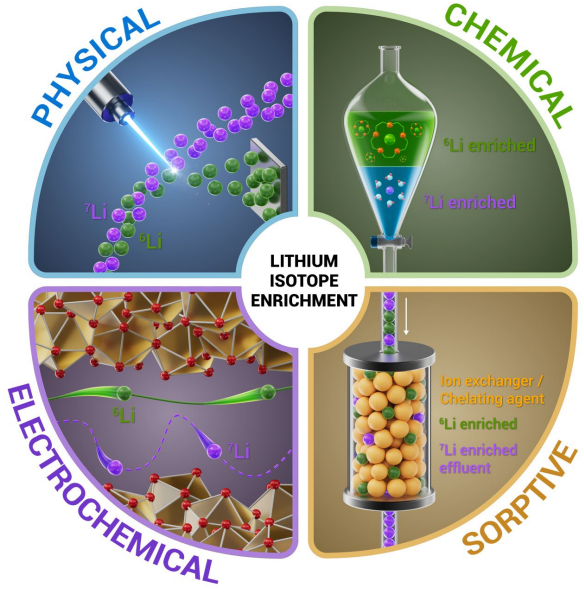


^{7}Li Market for Fission

- ^{7}Li Demand **1.6 MT**
- Energy Demand **0.04 GWh**
- Vanadium Demand **0.8 MT**

*all ^{6}Li numbers assume DCLL reactor type

*all ^{7}Li numbers assume 99.95% purity





Harris Kohl
Doctoral Student

Fusion

85 cycles for 90% ^{6}Li

Fission

92 cycles for 99.95% ^{7}Li

121 cycles for 99.99% ^{7}Li

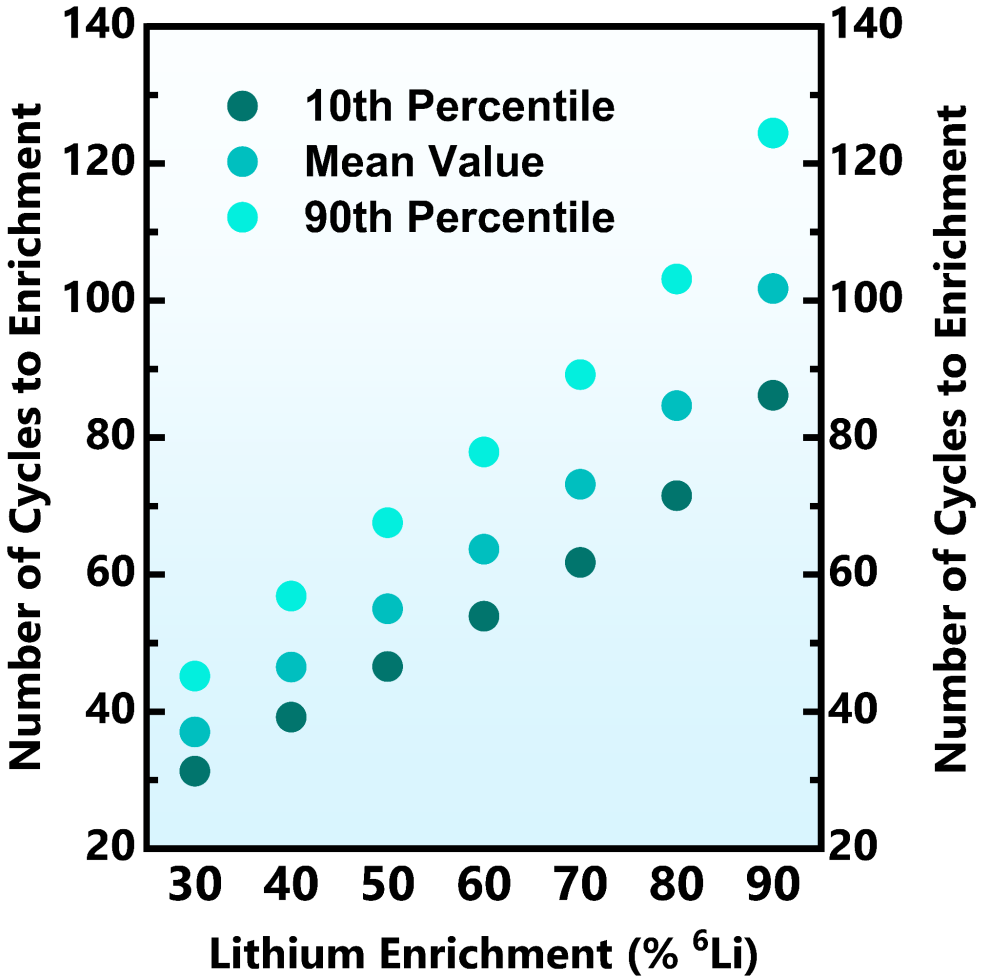
Cycling ζ-V_2O_5 to Lithium Enrichment

ETH zürich

$$\text{Number of Cycles to Enrichment} = \frac{\ln(\frac{R_t}{R_0})}{\ln(\alpha)}$$

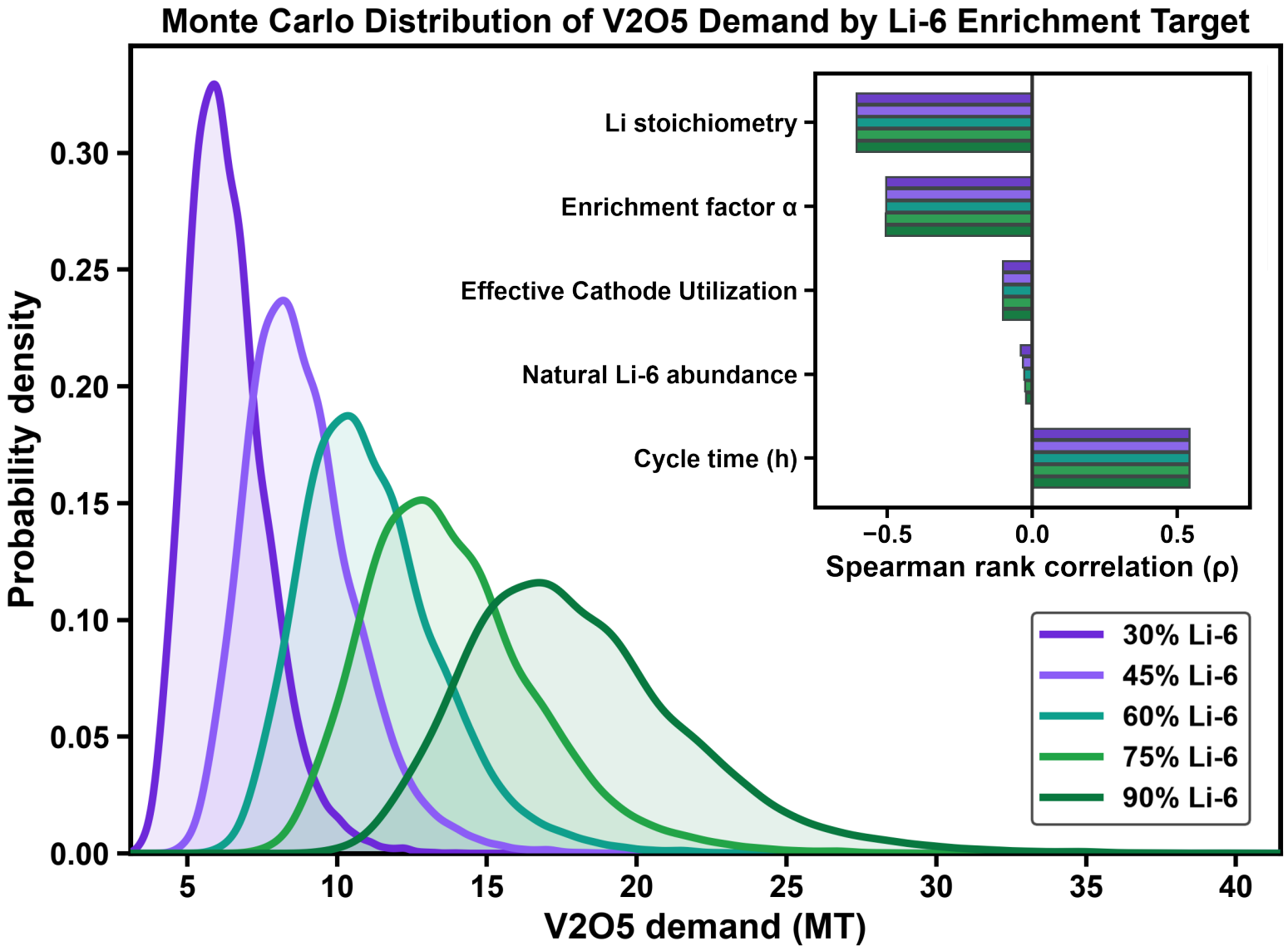
Variable Parameter	Dist.	min	mode	max
Natural Abundance of ^{6}Li	triang.	0.0740	0.0759	0.0770
α Enrichment Factor (concen.6/7 solution/ concen.6/7 electrode) Single Stage Fractionation [Li-6 substitutions per cycle]	triang.	1.03	1.057	1.06

10,000 Monte Carlo Simulations for each target enrichment.



V_2O_5 Demands for ^{6}Li Enrichment

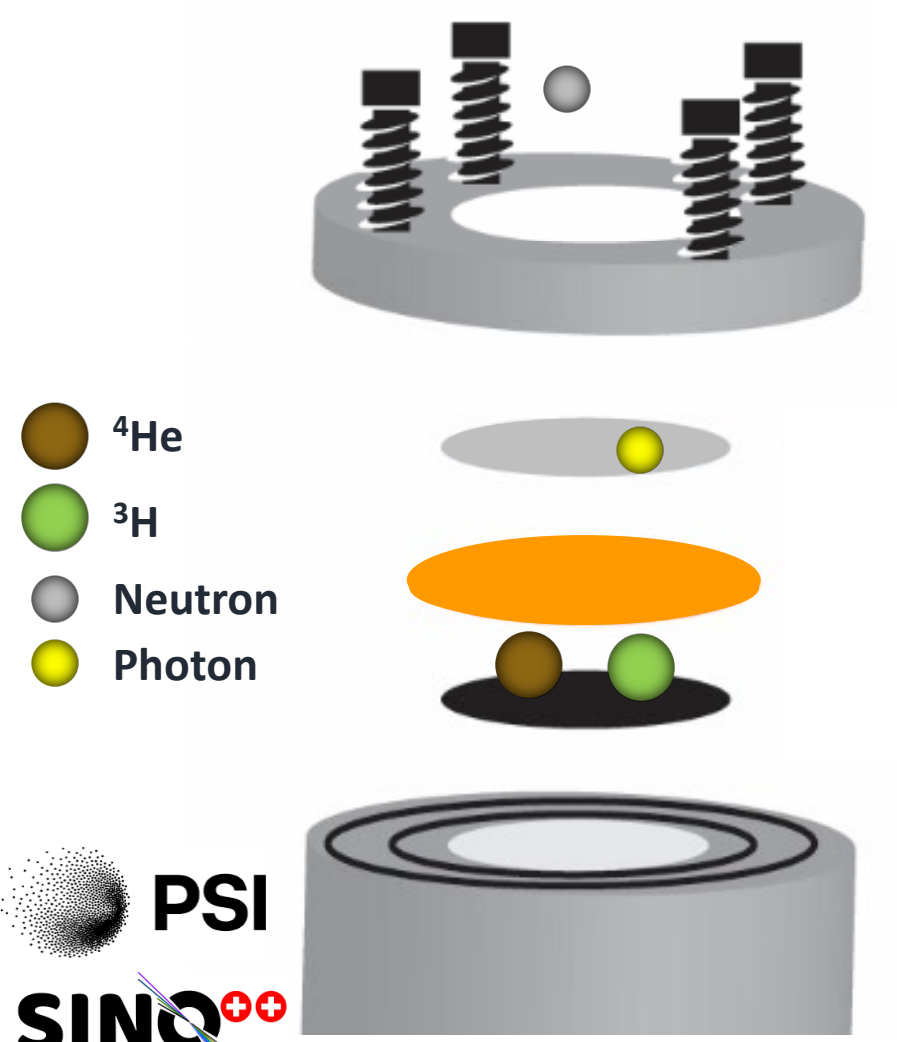
ETH zürich



90% Enrichment	Value
N simulations	10000
Mean V2O5 demand (MT)	18.132
Std. dev. V2O5 demand (MT)	3.5308
Minimum (MT)	10.495
P5 (MT)	13.267
P25 (MT)	15.604
Median / P50 (MT)	17.658
P75 (MT)	20.143
P95 (MT)	24.607
Maximum (MT)	39.982

Neutron Bombardment & Imaging

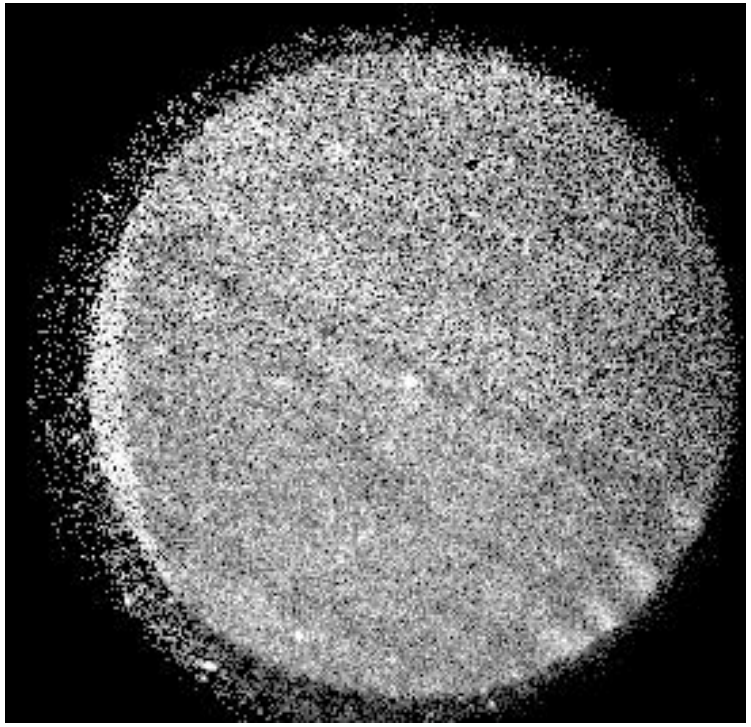
PSI Center for Energy and Environmental Sciences

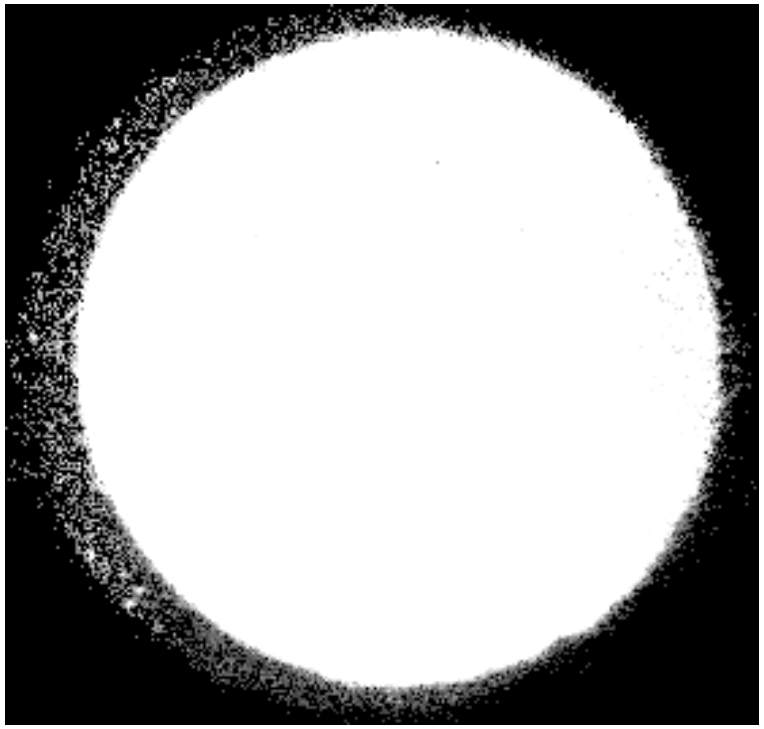


Topochemical lithiation of ζ-V_2O_5:

$$x\mathrm{LiI} + \zeta\text{–}\mathrm{V_2O_5} \xrightarrow[45\ ^\circ\mathrm{C}]{\mathrm{CH_3CN}} \beta\text{–}\mathrm{Li}_x\mathrm{V_2O_5} + \frac{1}{2}x\mathrm{I_2}$$

Natural Abundance Li **^{6}Li Electrode**

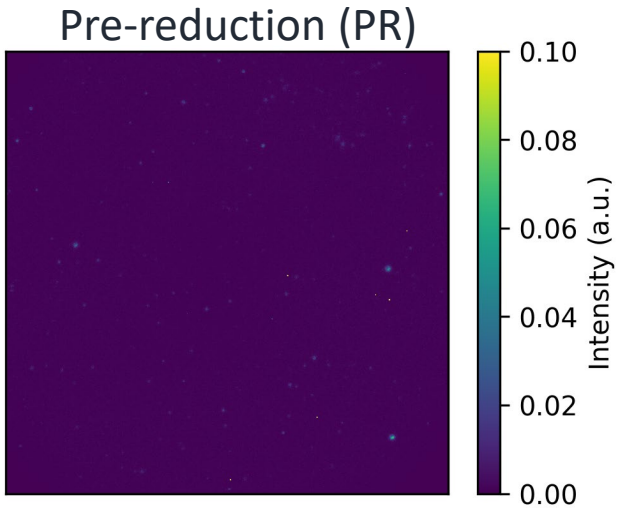




1) Measures ^{6}Li enrichment as a function of image intensity
2) V_2O_5 electrodes used to generate ^{3}H

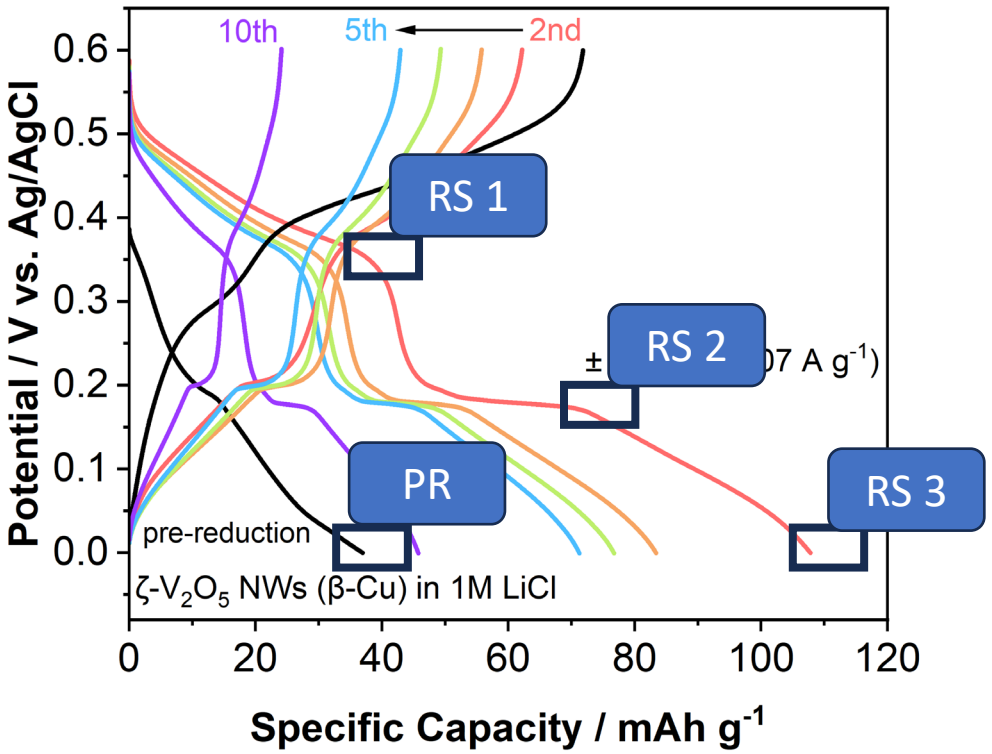
Tritium Production + Breeder Concepts

PSI Center for Energy and Environmental Sciences



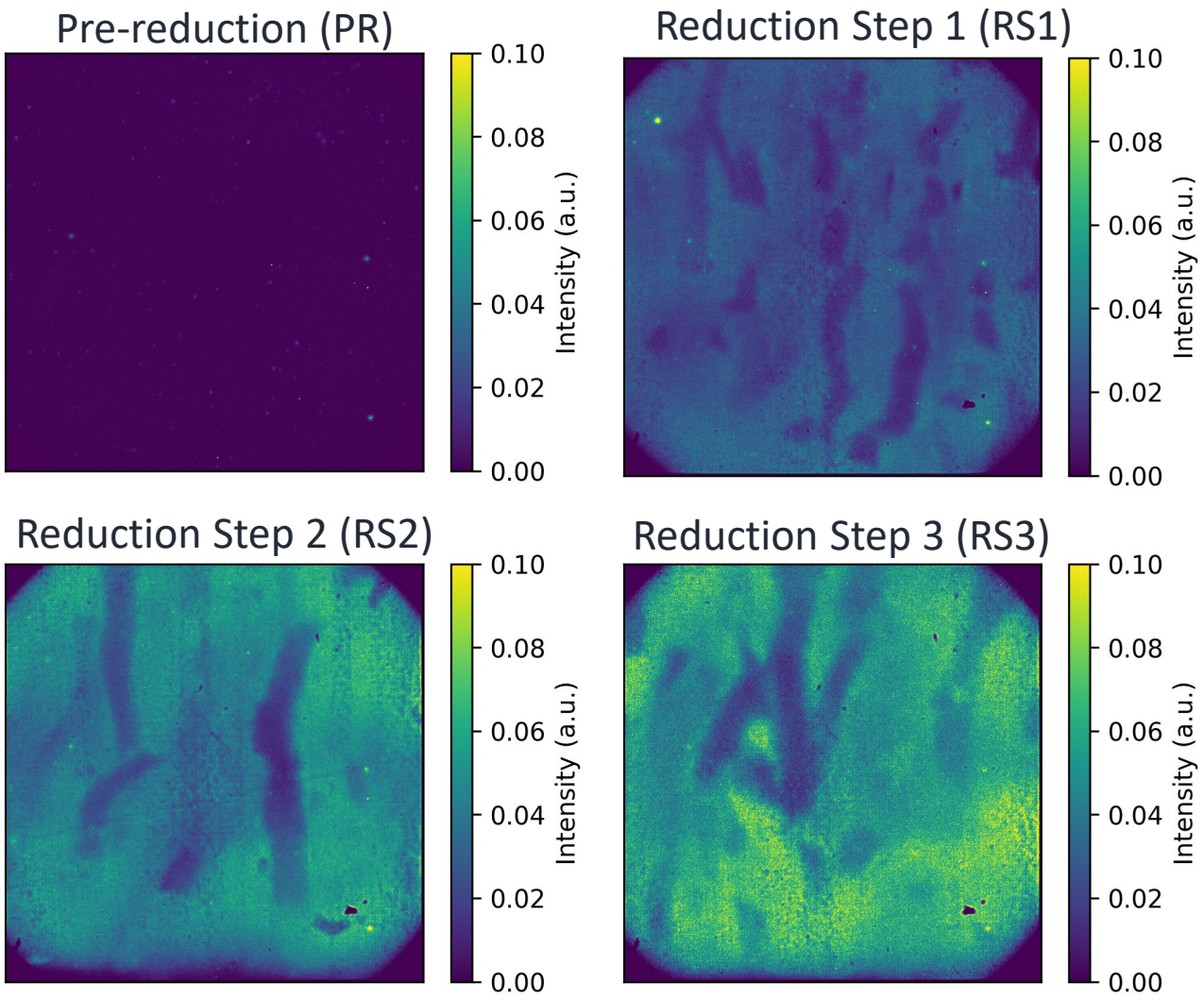
Question:
Does ^{6}Li insertion occur at a specific voltage window

ζ-V_2O_5



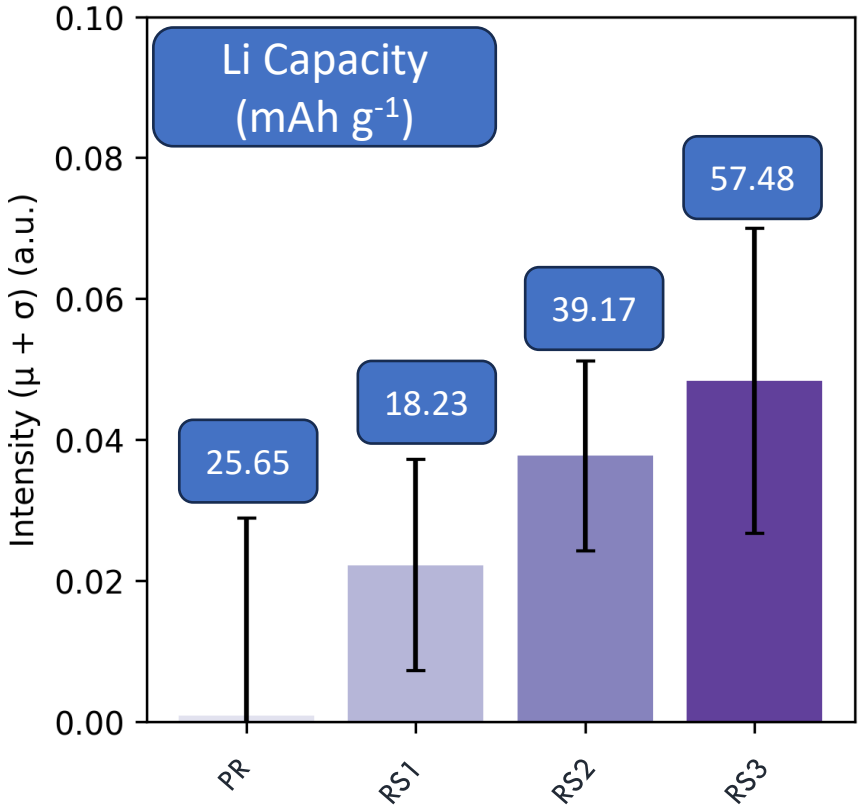
Tritium Production + Breeder Concepts

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Limiting voltage window to 0.6–0.15 V vs Ag/AgCl would decrease energy expenditure and possibly increase α

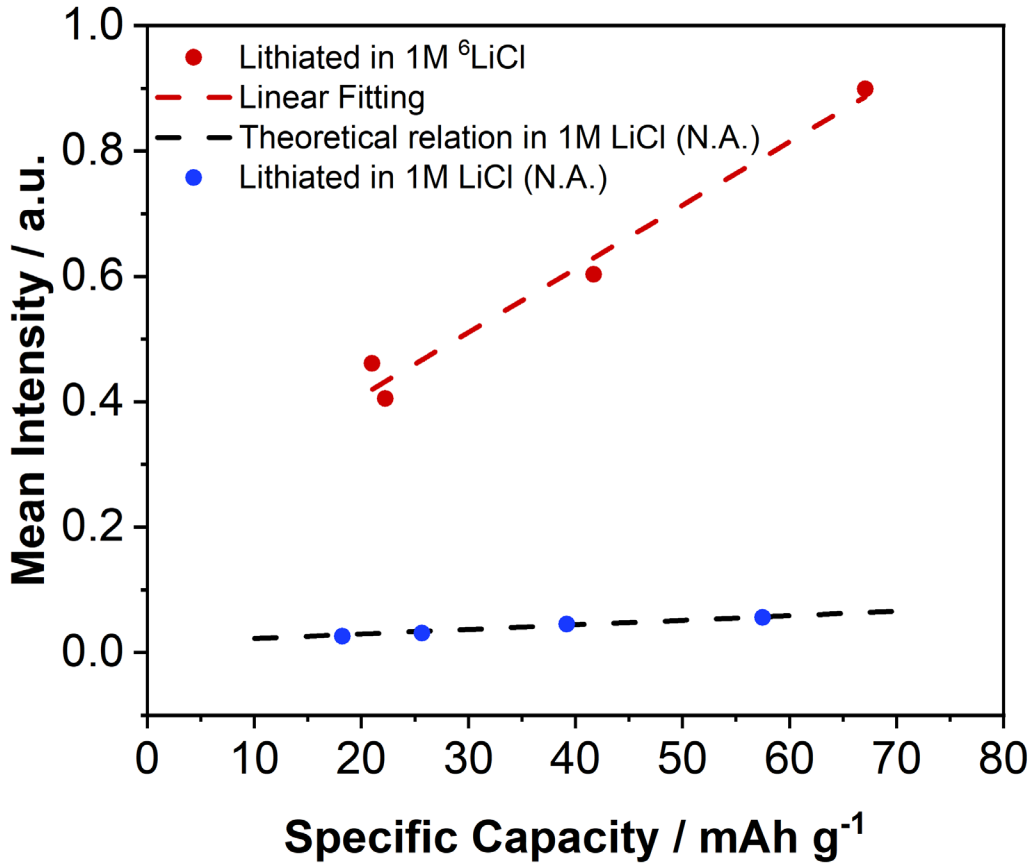
Question:
Does ^{6}Li insertion occur at a specific voltage window



Pre-reduction seems to uptake mostly ^{7}Li

RS1 and RS2 insert more ^{6}Li than RS3 and PR

Breeder Concepts

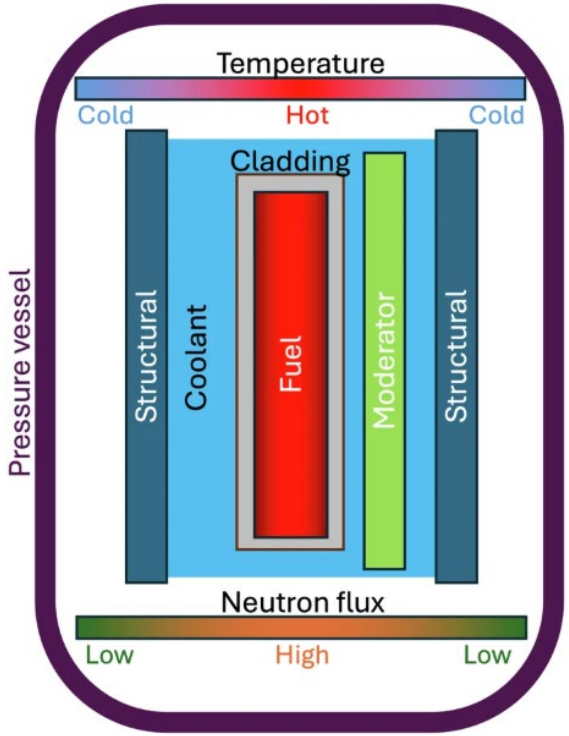


- NCI response is linear.
- Same mass loading across multiple electrodes.
- No side reactions.
- ^{6}LiCl : 95% ^{6}Li.
- N.A. LiCl : 7.59% ^{6}Li.

The Perennial "First Wall Problem"

How do you design a material that can withstand the conditions of the plasma of fusion reactions?

Fusion Energy Production: $^{3}H + {}^{2}H \rightarrow {}^{4}He + n + 17.6$ MeV



Stable Nucleons: 14.1 MeV Neutron Bombardment

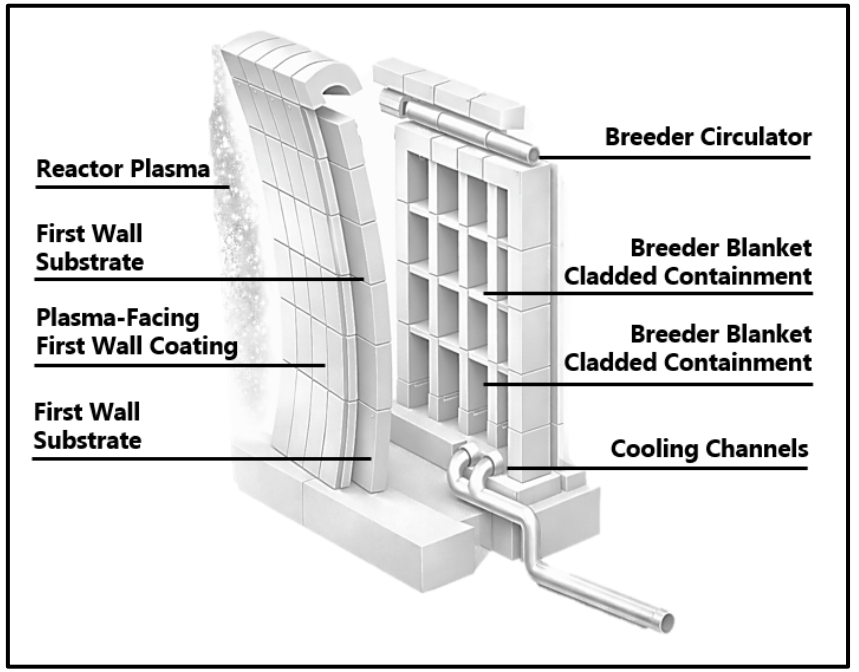
Chemically Inert: Sputtered C, W, Be, O

Electronic Stability: X-Rays, γ-Rays

Heat Resistance: Heat Fluxes 1–10 MW/m²

Ionized Particle Radiation: D^{+}, T^{+}, He^{2+}, He^{+}

Magnetic Transparency: 3 – 13 T



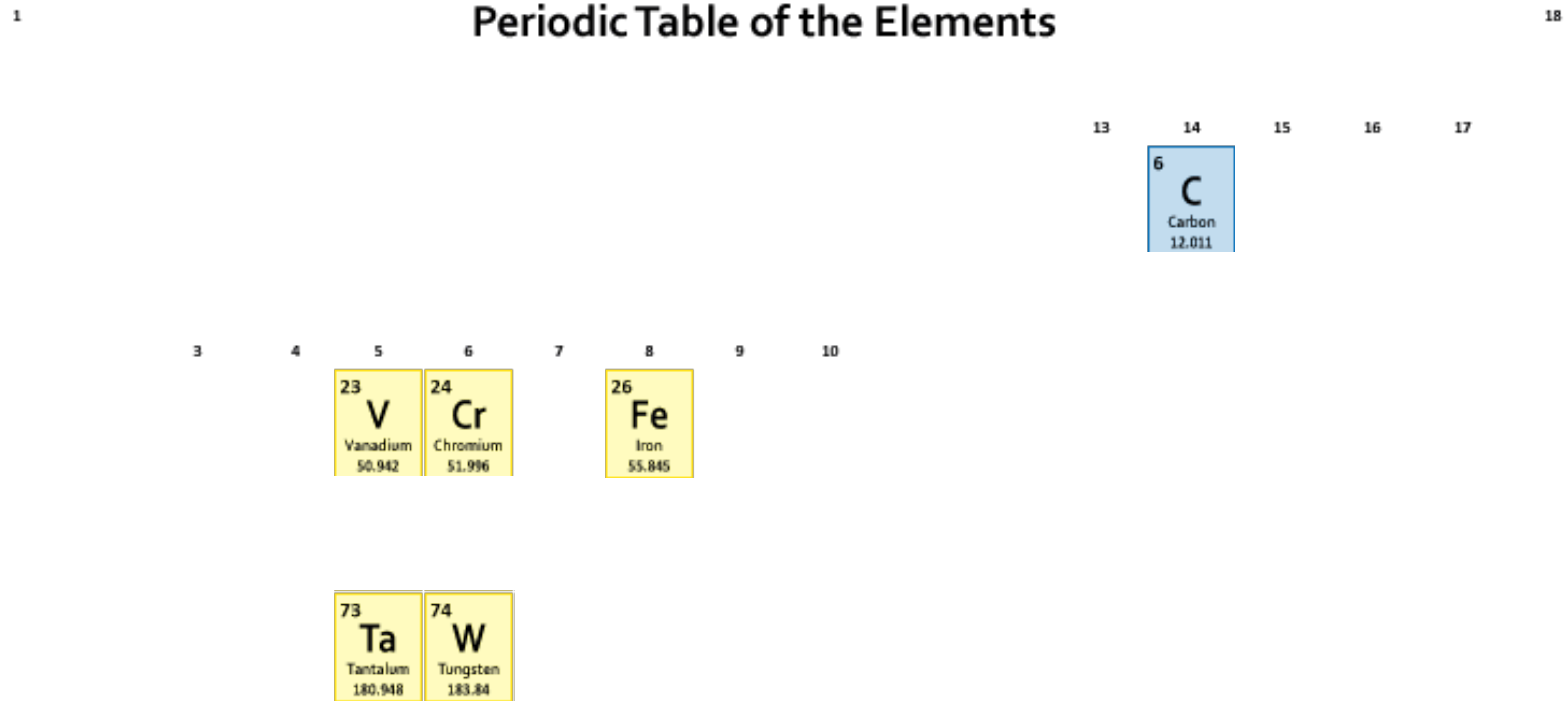
Reduced-activation ferritic–martensitic (RAFM) steels V-4Ti-4Cr alloys **EUROFER97**, **F82H**, and **CLAM steel**

Tonks, M.R.; Andersson, D.A.; Aitkaliyeva, A. Computational Design of Materials for Nuclear Reactors. *npj Comput. Mater.* **2026**, *12,* 106. https://doi.org/10.1038/s41524-026-01980-8

A Refined Palette of Fusion First Wall Materials

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- No gases or liquids
- No radioactive elements
- No high-activation elements
- No large neutron cross-sections
- No Low Melting Points
- No radiative cooling/quenchers
- No He embrittlement
- Withstand large mechanical loads
- Low sputtering yields
- Robust to thermal gradients



Reduced-activation ferritic–martensitic (RAFM) steels

V-4Ti-4Cr alloys, **EUROFER97**, **F82H**, and **CLAM steel**

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetal | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

VANADIUM IN THE FIRST WALL

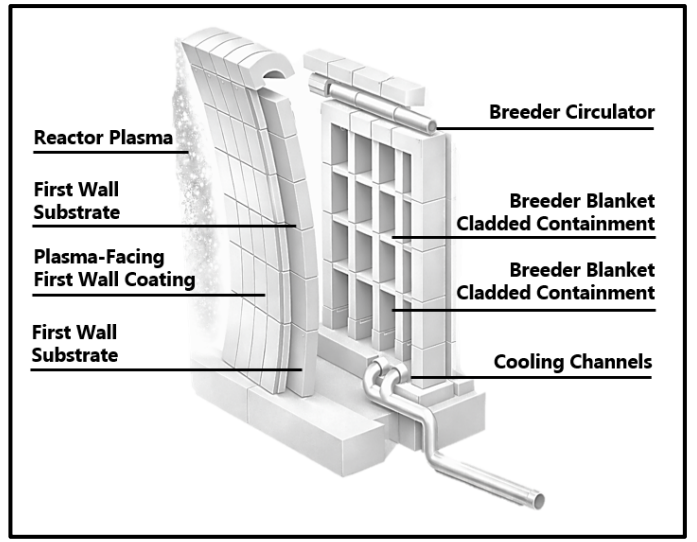
V-4Ti-4Cr alloy (92 wt.% V) is considered an excellent candidate for first wall construction because it doesn't undergo deleterious transmutations from free neutrons in nuclear reactors.

First Wall Blanket Substrate Shell

0.0022 kg V	7,550 kg RAFM steel	(0.03 m • 1,200 m^2) RAFM steel	=	6 kg V
100 kg RAFM steel	1 m^3 RAFM steel	1.5 GW fusion reactor		

First Wall Blanket Cooling Modules: Channels & Breeder Cladding Parameters

0.92 kg V	1,000 kg V-4Cr-4Ti alloy	736 cooling modules	=	677,120 kg V
1 kg V-4Cr-4Ti alloy	1 cooling module	1.5 GW fusion reactor		



For a 1 GW Fusion Reactor

Total Initial Construction = 677 metric tons of Vanadium

Lindau, R.; Möslang, A.; Rieth, M.; Klimiankou, et al. Present development status of EUROFER and ODS-EUROFER for application in blanket concepts. *Fusion Eng. Des.* **2005,** *75-79*, 989–996. https://doi.org/10.1016/j.fusengdes.2005.06.186

EUROfusion Materials Handbook / EUROFER97 material specification (European Fusion Development Agreement).

Chun, Y. B.; Lee, D. W.; Cho, S.; Rhee, C. K. Physical, Thermal, Magnetic, and Mechanical Properties of ARAA. *Transactions of the Korean Nuclear Society Autumn Meeting*, Gyeongju, Korea, October 29-30, **2015** https://nstx.pppl.gov/nstxhome/DragNDrop/Scientific_Conferences/SOFE/2013/NSTX-U_engineering/Kessel_KDEMO_SOFE2013_papers-2.pdf

Kim, G.-W.; Lee, J.-H.; Cho, H.-K.; Park, G.-C.; Im, K. Development of Thermal-Hydraulic Analysis Methodology for Multiple Modules of Water-Cooled Breeder Blanket in Fusion DEMO Reactor. *Fusion Eng. Des.* **2016**, *103*, 98–109. DOI: 10.1016/j.fusengdes.2015.12.042. https://www.sciencedirect.com/science/article/abs/pii/S0920379615304257

Living Supply Chain Databases

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Production Database

Property Name	Company
Maracas Menchen Mine	Largo Inc

Production Type	Stage
Co-production	Operational

Location	Country	Region	EU-27
Maracas, Bahia	Brazil	Latin America	No

Vanadium-host Resource	Product Output
Vanadium titanomagnetite	Vanadium oxide flake, Vanadium oxide powder

Total Resources (Mt ore)	Measured and Indicated Resources (Mt ore)	Inferred Resources (Mt Ore)
60.36	45.17	15.19

Ore Grade (% V_2O_5)	High-Purity V (>99.5 %)	Production per Annum (tpa V_2O_5)
0.79	Yes	11,000.00



VFB Database

Project	Developer
Minami Hayakita Substation Hokkaido Electric Power – Wind Stabilization	Sumitomo

Locality	Country	Region
Abira-Chou, Hokkaido, Japan	Japan	Asia Pacific

Status	Power (kW)	Duration (hr)	Capacity (kWh)
Operational	15,000	4.0	60,000

Processing Database

Project Name	Company
Panzhihua Group Vanadium and Titanium Resources and Rongke Power Joint Venture	Panzhihua Group/Dalian Rongke Power

Locality	Country	Region	EU-27
Panzhihua, Sichuan Province	China	Asia Pacific	No

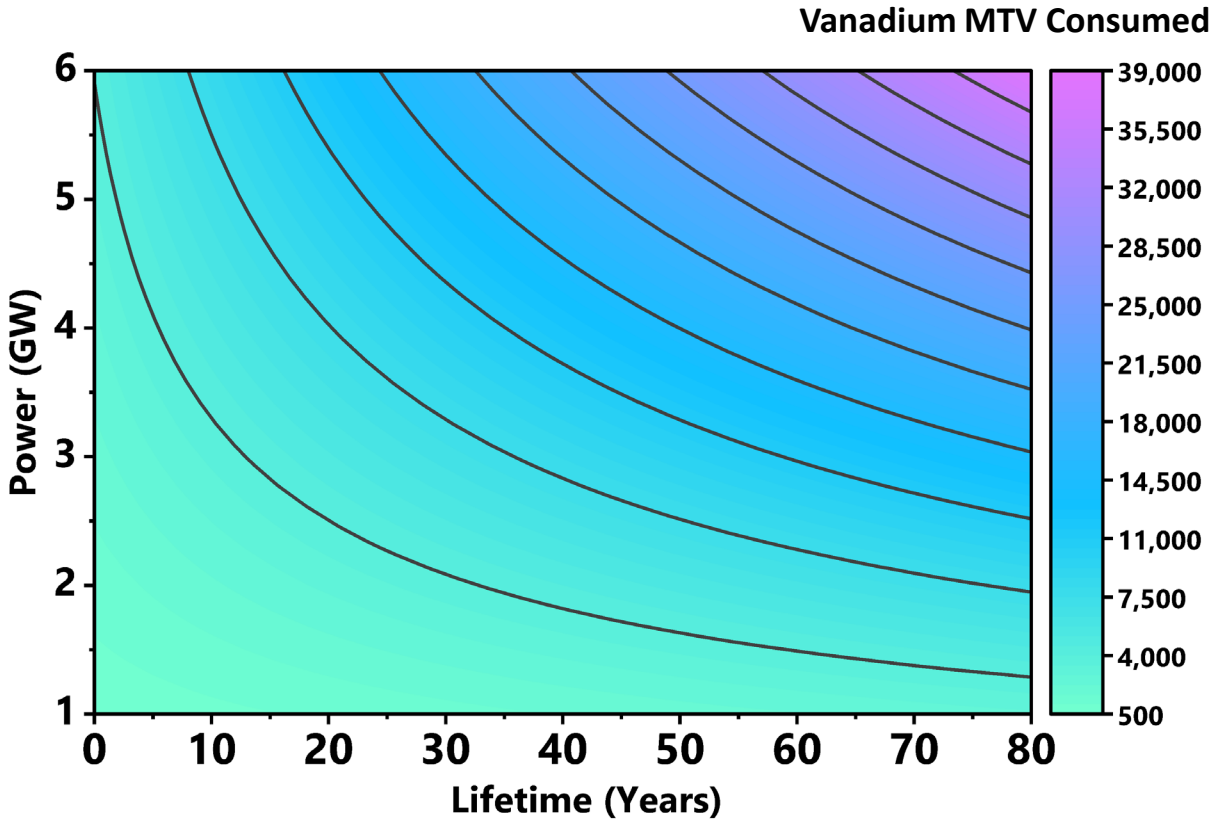
Operation Status	Resource Input	Product Output	Production per Annum, Electrolyte (m^3)
Operational	Vanadium oxide	Electrolyte	2.00

Rogers, B.; Banerjee, S. Mine the Gap: Sourcing Vanadium for the Energy Transition *Joule* **2025** *9,* (11) 1-14.

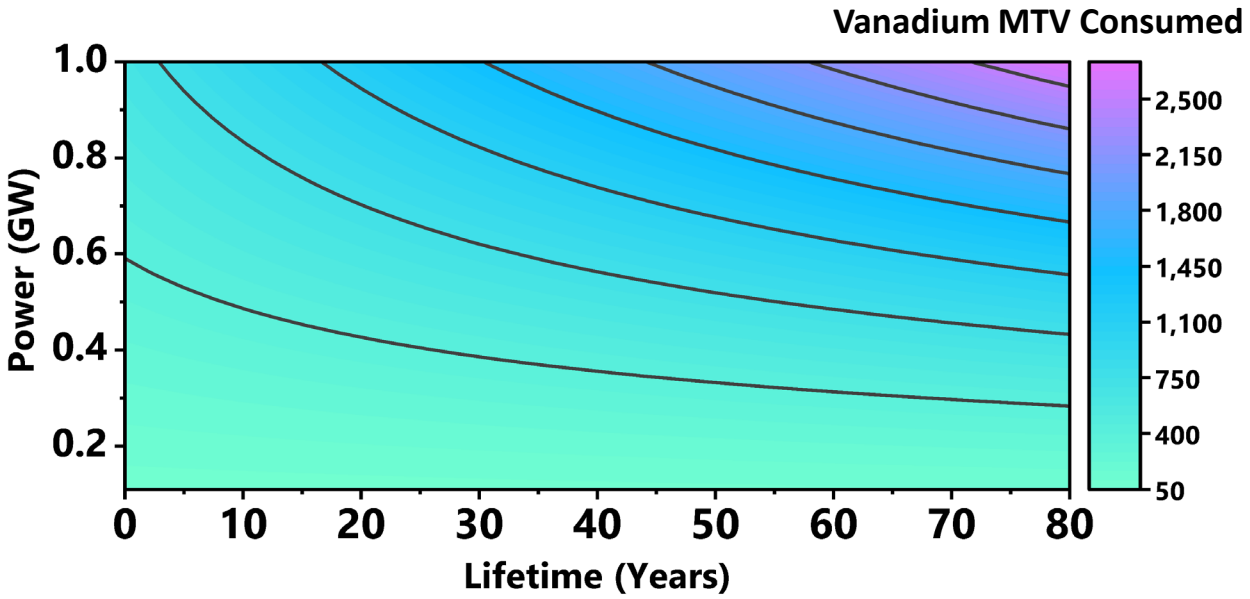
Vanadium Depletion in Fusion Reactors

ETH zürich

- Vanadium consumption for the lifetime of a nuclear fusion reactor are calculated as a function of the rate of transmutation of V to Cr, thermal degradation, and resulting **replacement rate** for components from initial construction

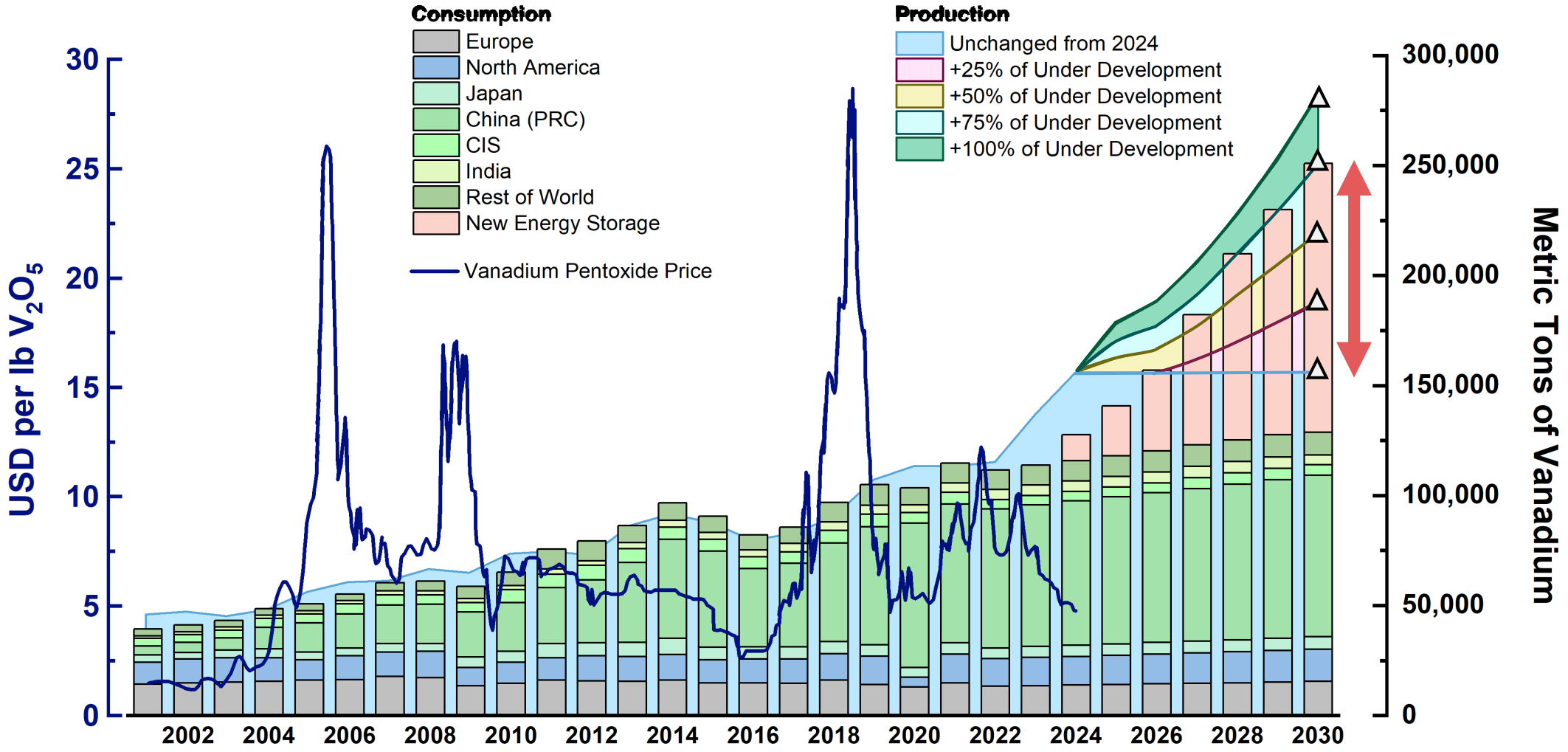


$$z = \ln(y+1)\ 226\ xy + 677\ y$$



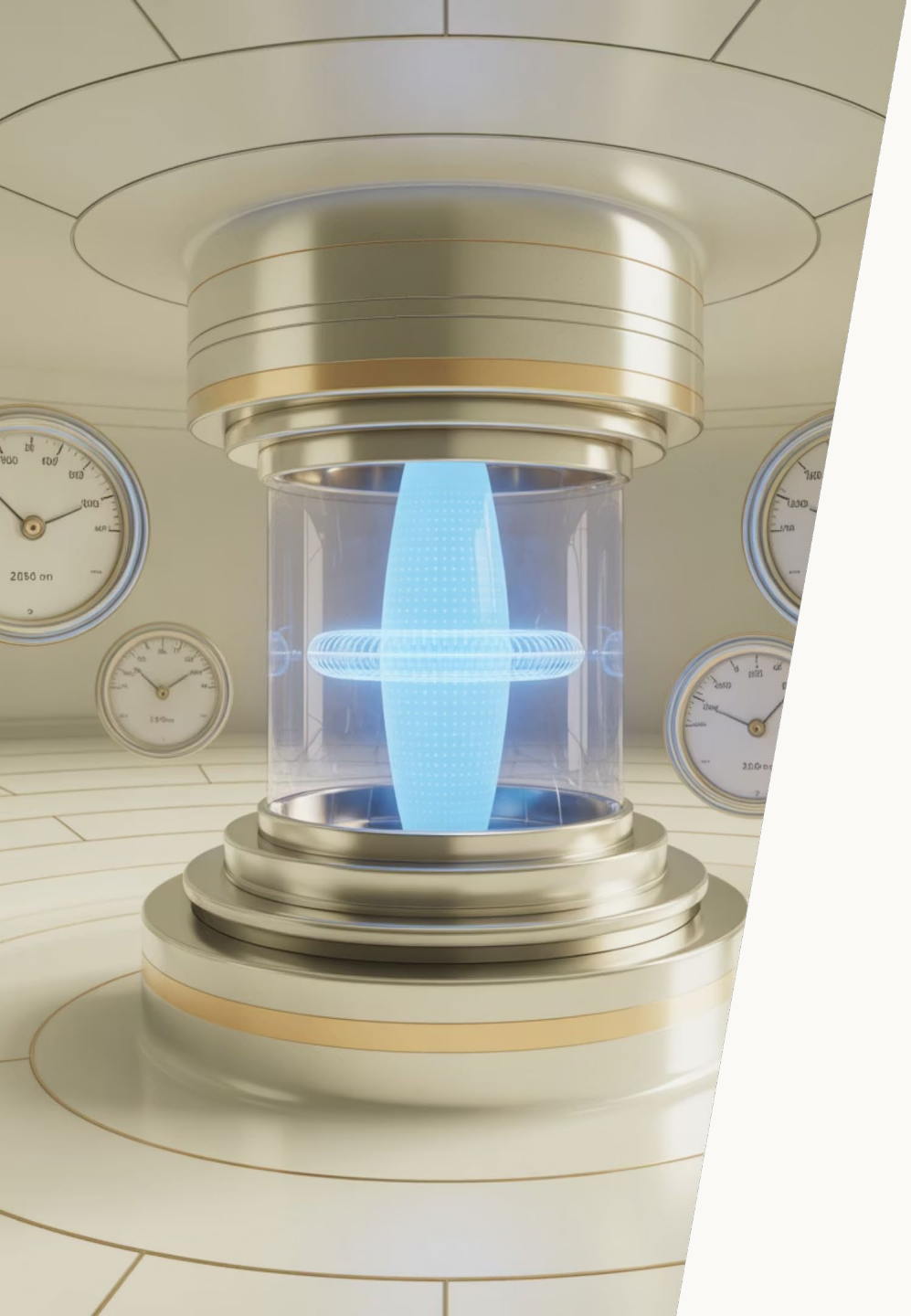
Gaps in supply: resource mismatch

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Energy storage demand is projected to make up 50% of global vanadium consumption in the next 5 years

Rogers, B.; Banerjee, S. Mine the Gap: Sourcing Vanadium for the Energy Transition **2025;** DOI: 10.1016/j.joule.2025.102139



Fusion Fuel Cycle Management Cluster

An Initiative by Daniel Jakob/ Robin Senn, APRIL 2026

How to catalyze the Swiss fusion ecosystem?

How to mobilize SINQ++?

Building a Materials Hub and an overarching Hub and Spoke Model

Field of action & resulting products

Main Fusion Fuel Cycle Management Topics

Gas Management

- Tritium Breeding
  - Breeding blankets (tiles, others)
- Gas Purification
  - Optimized, industrial Li-separation process
- Gas Storage
  - Industrial process of isotope separation
  - High capacity, long-live getter beds

Process & Analytics

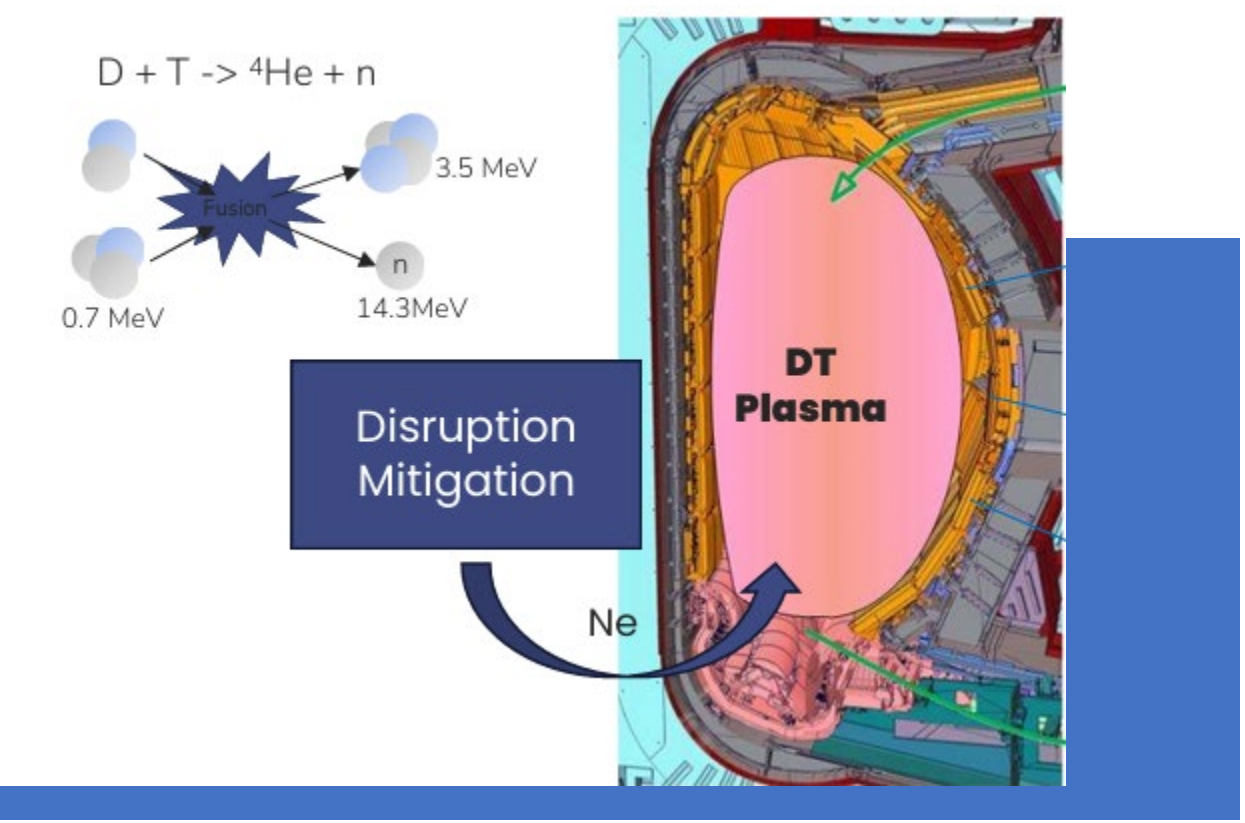
- High Pressure In-Line Analytics
  - Industrial grade, combined instruments
- Gas & Vacuum Pumps
  - Long-live tritium compatible high vacuum pump

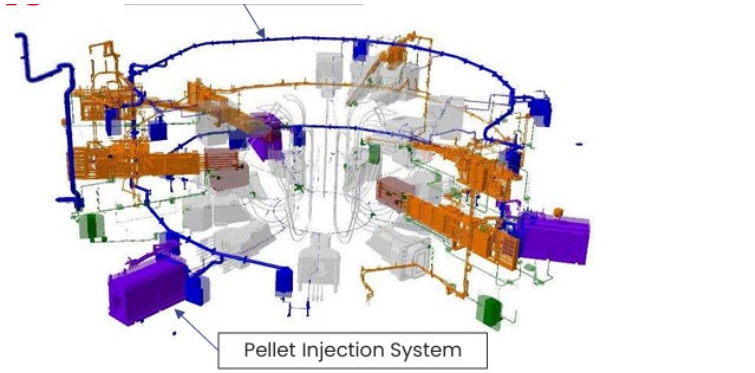
Safety

- De-Tritiation Systems
  - Industrial process
- Anti Permeation Barriers
  - Coating materials and processes

3HLiBe Swiss Blanket Research Lab

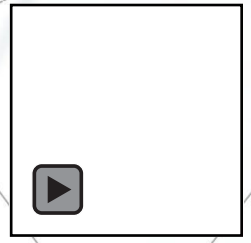
Fusion needs for Fuel Cycles





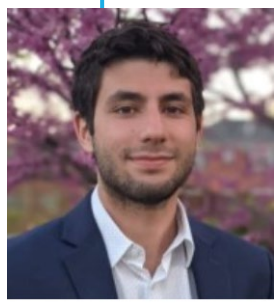
The growing need for lithium isotope separation for fusion breeder blankets and advanced fission systems is limited by the lack of non-destructive methods that can directly observe isotope enrichment and lithium transport inside realistic devices. SINQ++ should deliver more sensitive, quantitative, and operando neutron imaging for low lithium concentrations, realistic flow-cell and breeder-relevant sample environments, and faster 3D/4D analysis, thereby enabling the mechanistic understanding and process innovation required for future nuclear-energy supply chains

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This is a choice we make. We choose to do it in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too...

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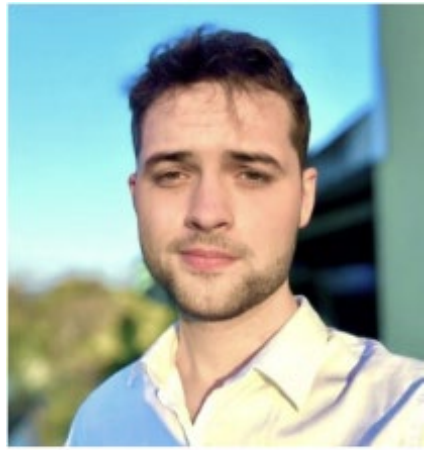
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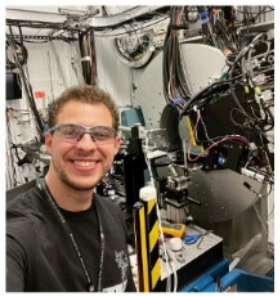
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