Balanced Energy Systems

The future of energy storage: batteries and chemical carriers

Prof. Dr. Sadegh Seddighi

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Why Energy Storage Matters Now

- Electrification of industry, mobility, and heating
- Rapid growth of solar and wind
- Grid congestion and volatility increasing
- Storage is becoming a system necessity, not an option

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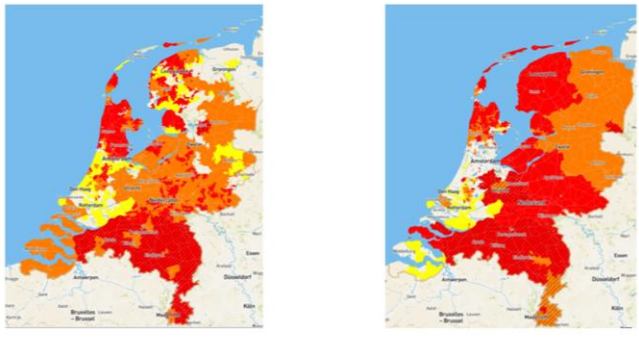
The Dutch Energy System Challenge

- Severe grid congestion across NL
- €8B/year estimated cost of congestion
- Workforce shortages (technicians, engineers)
- Urgency for flexibility solutions

Grid congestion map: load connection (left) and generation connection (right)



Source: https://capaciteitskaart.netbeheernederland.nl/

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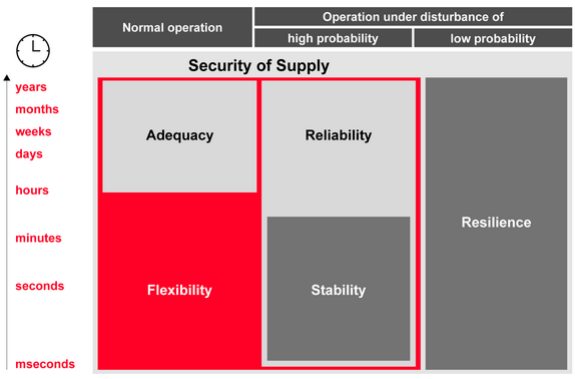
From Energy Production to System Stability

- Past focus: adding renewables
- Future focus: system stability & flexibility
- Storage, demand response, digital control



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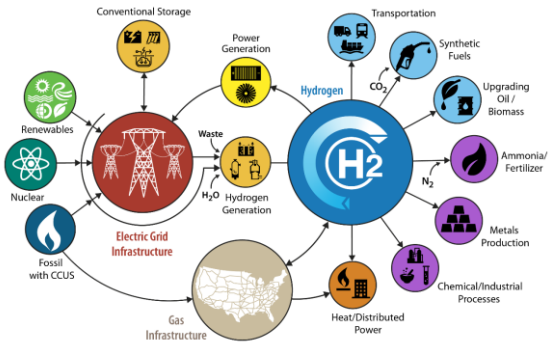
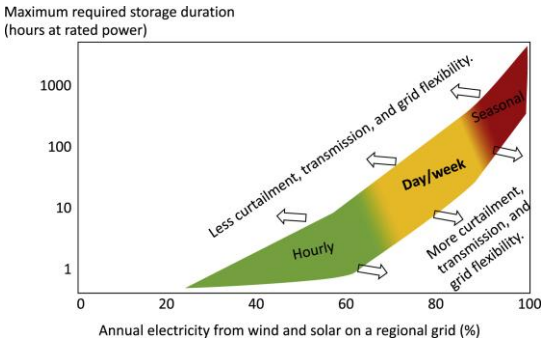
Storage Across Time Scales

- Seconds–hours: batteries, supercapacitors
- Hours–days: batteries, pumped hydro
- Weeks–months: hydrogen, e-fuels, thermal
- Seasonal: chemical carriers



Ref: DOE Report



Ref: Albertus et al, Joule, 2020

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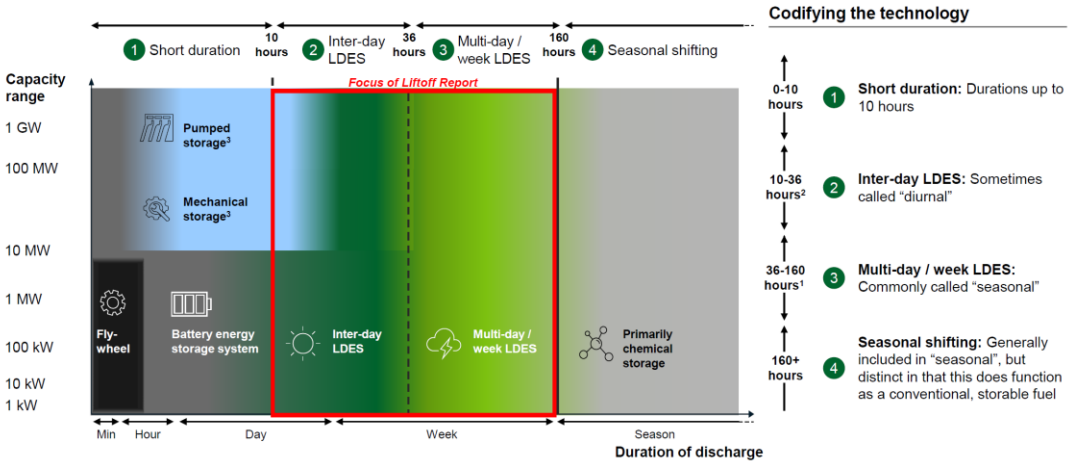
Storage across timescales

- Short duration → batteries
- Medium → thermal & flow batteries
- Long duration → hydrogen & e-fuels
- Seasonal → caverns, green molecules
- "No single technology can carry the transition."



Ref: DOE Pathways to Commercial Liftoff – LDES

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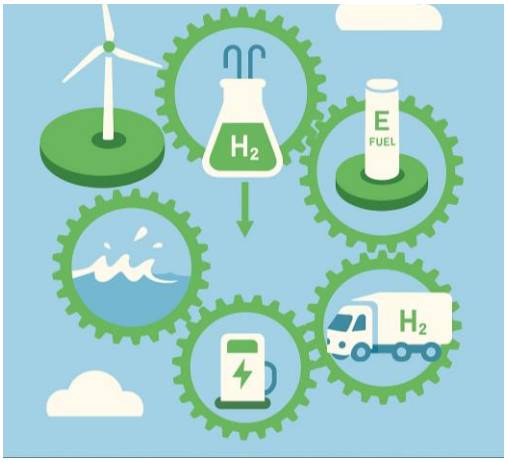
Balanced Energy Systems Framework

- Electrons (electricity)
- Molecules (H_2, fuels, e-fuels)
- Heat (thermal storage)
- Digital (control, AI, markets)



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What Batteries Are Excellent At

- Fast response and frequency control
- Local grid flexibility
- Mobility and distributed storage
- High round-trip efficiency

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Where Batteries Face Limits

- Long-duration storage is expensive
- Seasonal storage not feasible
- Raw material and recycling challenges
- Infrastructure and safety constraints

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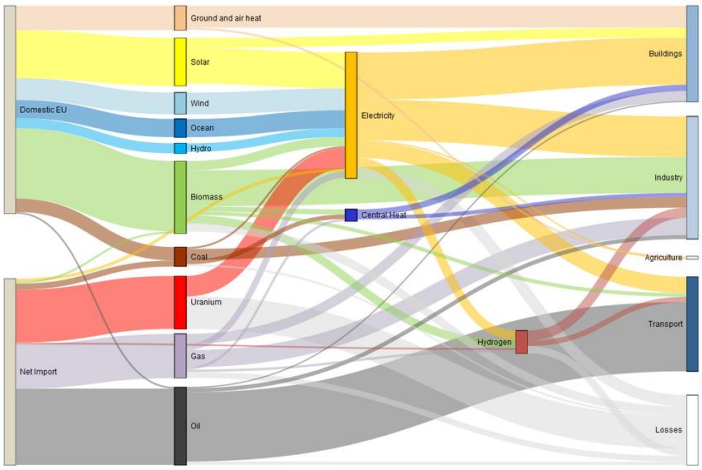
Role of Chemical Carriers

- Hydrogen, ammonia, methanol
- Long-duration and seasonal storage
- Sector coupling (industry, mobility, power)
- Use of existing gas infrastructure



Ref: Hidalgo et al, Report, 2015

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Batteries and Molecules: Complementary Roles

- Batteries: short-term, high power
- Molecules: long-term, high energy density
- Hybrid systems are key
- System design matters more than single tech

11 Ref: Mahadevan et al, Results in Engineering, 2025

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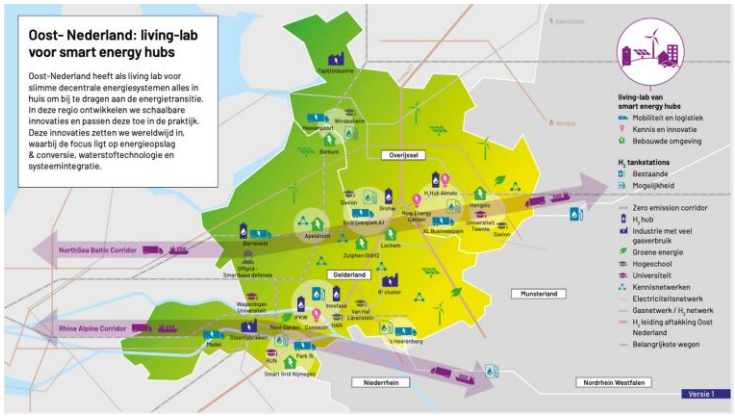
The Netherlands Energy Development

- Hydrogen backbone (HyNetwork)
- Grid congestion pilots
- Industrial clusters and ports
- Policy-driven experimentation

This is the environment in which BES must deliver solutions, while thinking and disseminating globally.

<u>The Netherlands is Europe's congestion living lab – and BES is positioned to turn this into solutions.</u>



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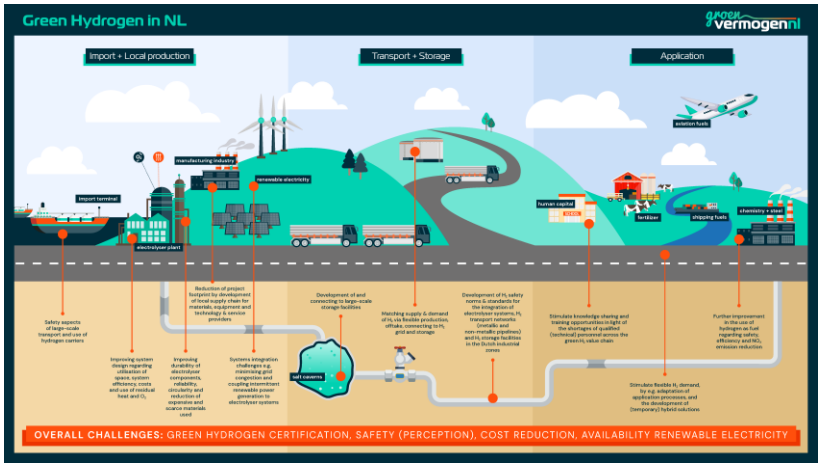
Europe's Strategic Opportunity

- Energy security
- Industrial competitiveness
- Green molecules for exports
- System-level innovation leadership



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Role of applied research (HAN / BES)

- System integration experiments
- Testing infrastructure (HAN H_2 Lab)
- Education–research–industry link
- Translating policy to engineering reality

Elaadnl CONNECTR energy innovation oost nl

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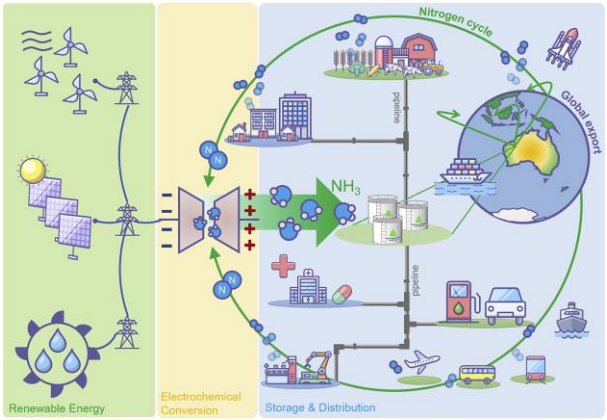
What Dutch funding priorities tell us

- HyCARB (GVNL)
- HyNITRO (GVNL)
- SPRONG Phase 2 (SIA)
- Strong demands for molecules, storage, system integration



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Ref: MacFarlane et al, Joule, 2020

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What This Means for the Future

- Hybrid storage architectures
- Integrated planning of electrons & molecules
- New market and control frameworks
- Strong role for applied universities

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Key Messages

- Storage is central to energy transition
- Batteries and molecules are complementary
- Systems thinking is the real innovation
- NL can lead in integrated storage systems