



LAND OF THE CURIOUS



Solar Economy team

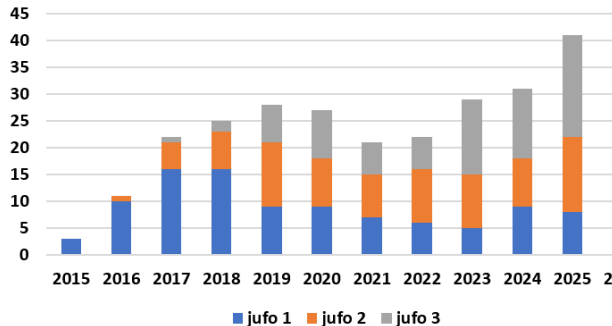


Brief team structure:

- 1 Professor
 - 5 Post doc researchers
 - 10 PhD researchers internal
 - 1 PhD researchers external
 - 2 project researchers (leads to PhD)
 - 7 M.Sc. students finishing June/ July
 - 2 summer internship workers
-
- Male researchers: 20
 - Female researchers: 8
 - 12 nationalities from 4 continents
 - Diversity is key, while the common vision is 100% renewable energy supply for all people
 - Well-being activities: summer outdoor, winter sauna
-
- Our core research field is **100% renewable energy system analyses**
 - 5+ in top25 researchers in the world according to published articles in our field are from LUT (active or former team members)

Research Output and Highlights

journal articles



IEEE Access

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TOPICAL REVIEW

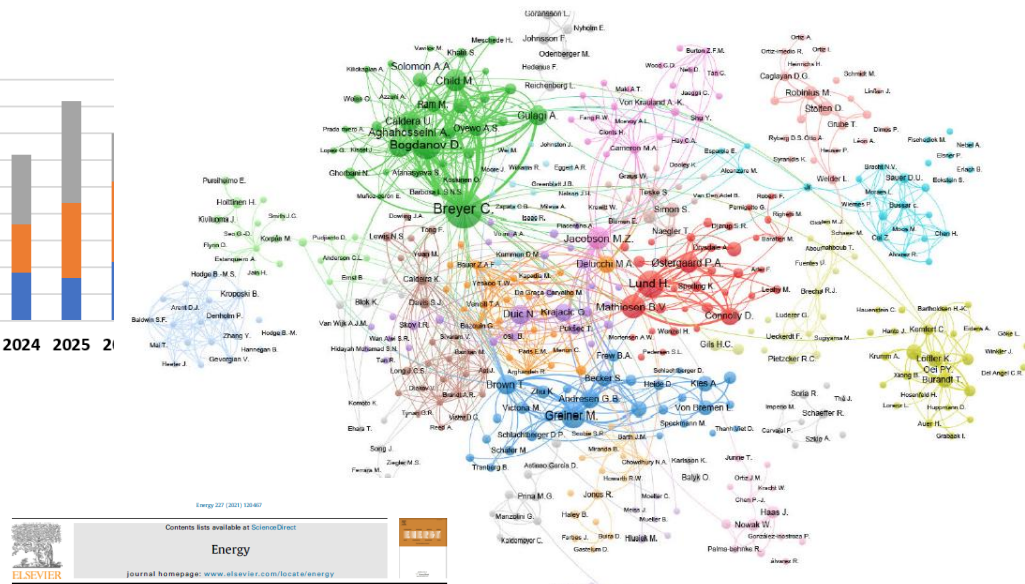
On the History and Future of 100% Renewable Energy Systems Research

CHRISTIAN BREYER¹, SIVASH KHALIL¹, DMITRI BOGDANOV², MANISH RAM¹, AYOBAMI SOLOMON OYEVO³, ARMAN AGHACHOSEINI⁴, ASHISH GULAGI⁵, A. A. SOLOMON⁶, DOMINIK KEINER⁷, GABRIEL LOPEZ⁸, POUL ALBERG ØSTERGAARD⁹, HENRIK LUND¹⁰, BRIAN V. MATHIESEN¹¹, MARK Z. JACOBSON¹², MARTA VICTORIA¹³, SVEN TESKE¹⁴, THOMAS PREGGER¹⁵, VASILIS FTHENAKIS¹⁶, (Fellow, IEEE), MARCO RAUGE¹⁷, HANNELE HOULTINEN^{18,19}, (Senior Member, IEEE), UGO BARDI²⁰, AUKE HOEKSTRA²¹, AND BENJAMIN K. SOVACOLLO^{22,23,24}

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ABSTRACT Research on 100% renewable energy systems is a relatively recent phenomenon. It was initiated in the mid-1970s, catalyzed by skyrocketing oil prices. Since the mid-2000s, it has quickly evolved into a prominent research field encompassing an expansive and growing number of research groups and organizations across the world. The main conclusion of most of these studies is that 100% renewables is feasible worldwide at low cost. Advanced concepts and methods now enable the field to chart realistic as well as cost- or resource-optimized and efficient transition pathways to a future without the use of fossil fuels. Such proposed pathways in turn, have helped spur 100% renewable energy policy targets and actions, leading to more research. In most transition pathways, solar energy and wind power increasingly emerge as the central pillars of a sustainable energy system combined with energy efficiency measures. Cost-optimization modeling and greater resource availability tend to lead to higher solar photovoltaic shares, while emphasis on energy supply diversification tends to point to higher wind power contributions. Recent research has focused on the challenges and opportunities regarding grid congestion, energy storage, sector coupling, electrification of transport and industry implying power-to-X and hydrogen-to-X, and the inclusion of natural and technical carbon dioxide removal (CDR) approaches. The result is a holistic vision of the transition towards a net-negative greenhouse gas emissions economy that can limit global warming to 1.5°C with a clearly defined carbon budget in a sustainable and cost-effective manner based on 100% renewable energy-industry-CDR



Low-cost renewable electricity as the key driver of the global energy transition towards sustainability

Dmitri Bogdanov^{1,2}, Manish Ram¹, Arman Aghachoseini³, Ashish Gulagi⁴, Ayobami Solomon Oyevo⁵, Michael Chidi⁶, Upeksha Caldera⁷, Kristina Sadotkova⁸, Javier Farfan⁹, Larissa De Souza Noel Simas Barbosa¹⁰, Mahdi Bashir¹¹, Sivash Khalil¹², Thure Traber¹³, Christian Breyer¹⁴

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Decarbonization
Energy system optimization
Power sector
Heat sector
Transport sector

1. Introduction
The Sustainable Development Goals (SDGs) report [1] highlights risks posed by the impact of climate change in ending and reversing decades of progress on inequality, food security and other SDGs. In this context, a transition of the global energy system to net-zero renewable energy use is responsible for the majority of the global energy system's decarbonization. Higher shares of renewable energy (RE) will simplify achieving universal access to clean and affordable energy, reducing GHG emissions and decreasing water scarcity by eliminating freshwater use in thermal power plants [3]. This transition has already started with renewables providing more than 27% of the global electricity generation by end of 2019 [4], including about 11%

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Some research highlights:

- State-of-the-art for temporal and spatial resolution in global ET (1h, 145 regions) – was called ‘impossible’
- Only energy-industry-CDR 1-h & 100% RE ET model
- First and only team with e-fuels, e-chemicals, e-CO₂ in 1-h & 50-km optimisation globally
- Power-to-X expertise for e-fuels, e-chemicals, e-materials, e-food, e-CDR, e-forests
- Offshore renewables (wave, wind, PV, OTEC, tidal)
- Global leading solar PV institutions adopted our results: Fraunhofer ISE, NREL, AIST, Longi, ITRPV
- ‘Power-to-X Economy’ & ‘Solar-to-X Economy’ placed
- Energy transition research for Finland
- Collaboration with KIT, DTU, Stanford, JRC, UNSW, etc.
- suffering from rejections of breakthrough proposals that are too early for ‘standard’ reviewers – while we get all our results published and highest citations

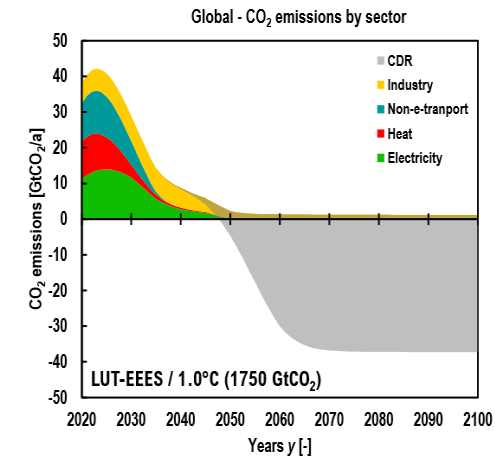
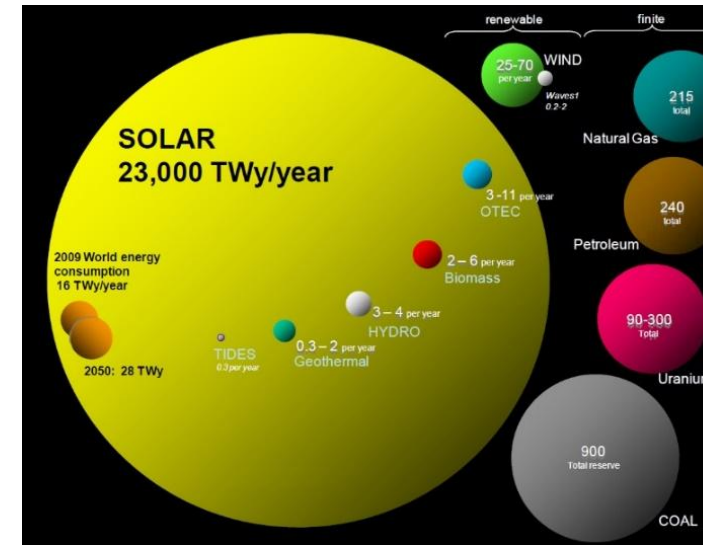
Key research metrics:

- No 1 team for 100% RE systems articles in total, annual citations, not yet lifetime
- No 1 team for 100% RE systems articles for Finland, Americas, Africa, MENA, India, Pakistan, Iran, Islands, Arctic regions
- Articles in *Nature Energy*, *Nature Communications*, *Nature Sustainability*, *Joule*, *Energy & Environmental Science*, *PNAS*, *Science*
- i100 articles total: 73

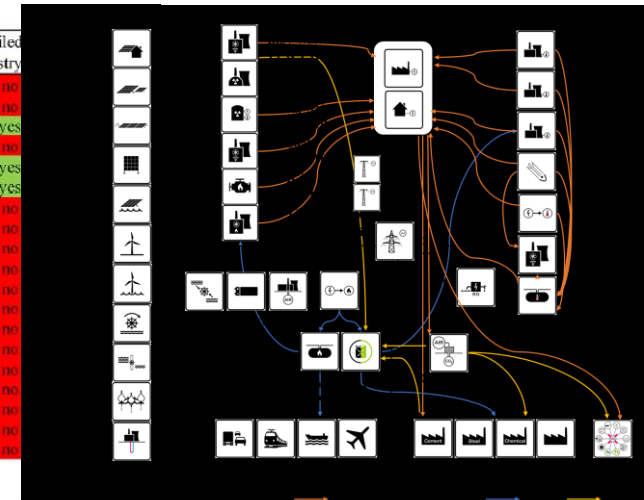
Research Plans for the next Years

Core activities:

- Energy-industry transition research for Finland, Europe, Global with some further special regions of interest, such as the US, India, Africa, Arctic regions, Islands
- Food systems research in close coupling to the energy-industry system
- Prospective LCA with focus on scenario thinking
- Expanding impact of energy-industry transition research with EROI, CROI, critical materials
- Planetary boundary research, starting with 1.0°C pathways for the first central planetary boundary
- Linking energy transition research with climate science (e.g. AMOC slowdown, Monsoon distortion)
- Power-to-X & Power-to-X Economy research for refined and new e-products
- Integration of systems, such as agrivoltaics
- Facilitating insights on highly RE systems research
- Supporting the community with open science tools, such as SI-ESTM (next iteration of LUT-ESTM), EP-ALISON-LUT, LUT-DEMAND, LUT-EROI, datasets for various energy resources, and more to come
- among others ...



Model	articles	citations total	citations 2024	model earliest	used latest	multi-node	full hourly	multi-sector	detailed industry
HOMER [290]	121	11,856	2128	2007	2023	no	yes	no	no
EnergyPLAN [292]	118	13,105	1543	2006	2023	yes	yes	yes	no
LUT-ESTM [32]	86	7566	1582	2015	2023	yes	yes	yes	yes
Balmorel [281]	36	1828	303	2008	2023	yes	yes	yes	no
PyPSA [284]	29	2072	447	2017	2023	yes	yes	yes	yes
TIMES [283]	29	1620	260	2011	2023	yes	no	yes	yes
LOADMATCH [302]	19	5236	496	2005	2023	no	yes	yes	no
REMIX [288]	17	1152	152	2015	2023	yes	yes	yes	no
AU model [294]	16	1667	99	2010	2018	yes	yes	no	no
GENESYS-MOD [152]	15	943	260	2017	2023	yes	no	yes	no
OSeMOSYS [286]	12	266	85	2019	2023	yes	no	yes	no
NEMO [295]	11	966	101	2012	2023	yes	yes	no	no
ISA model [296]	9	356	63	2016	2023	yes	yes	yes	no
H2RES [298]	8	946	82	2004	2023	no	yes	yes	no
LEAP [301]	7	384	143	2015	2023	yes	yes	yes	no
PLEXOS [304]	7	935	182	2018	2021	yes	yes	yes	no
MESAP/PlaNet [150]	6	468	54	2009	2020	no	no	no	no
REMIND [305]	6	545	161	2017	2023	yes	no	yes	no
LEELO [306]	5	201	48	2018	2022	yes	yes	no	no
others	510	25,478	4628						
total	1067	77,590	12,817						



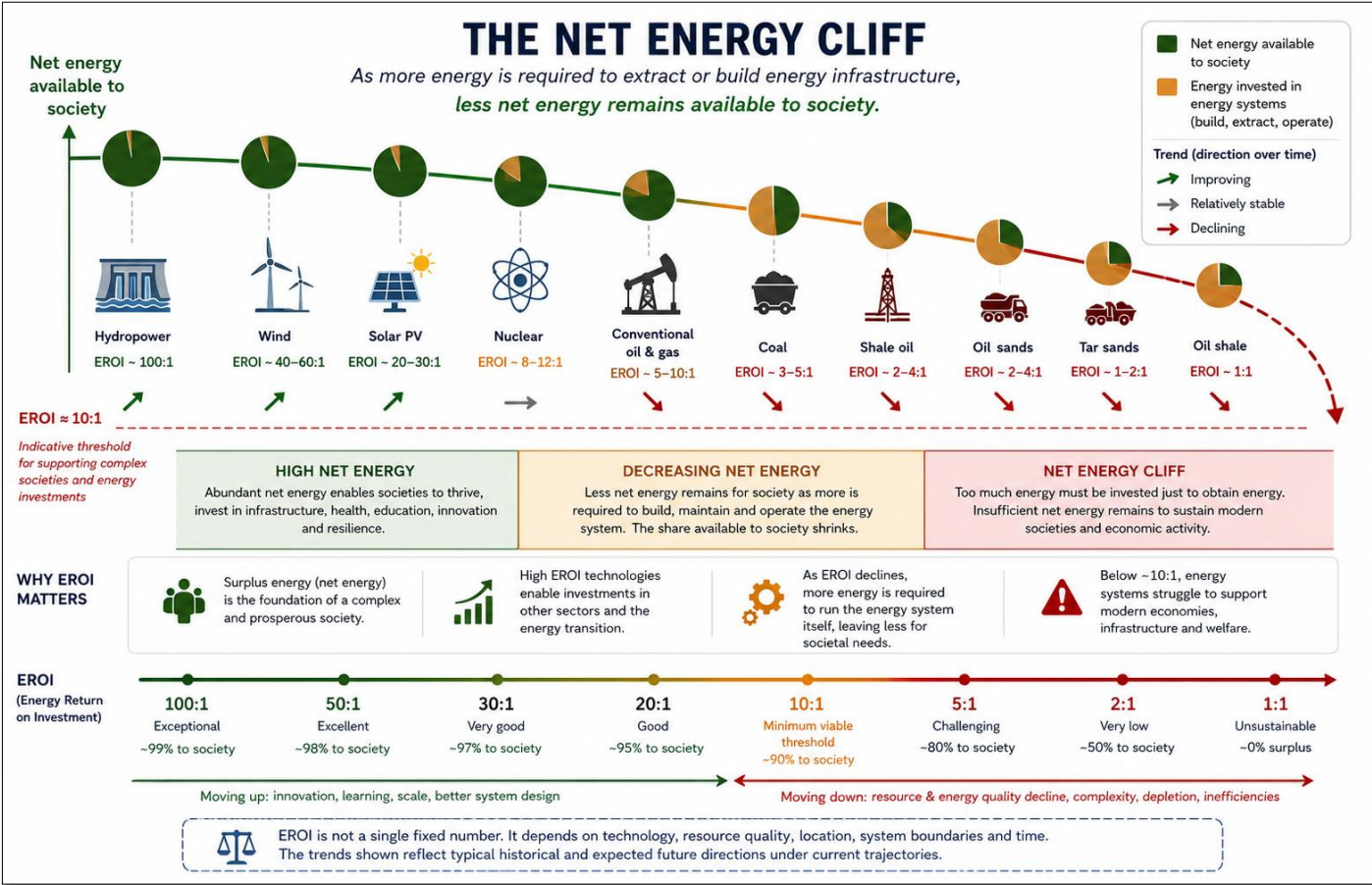


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Systemwide energy return on investment for power systems

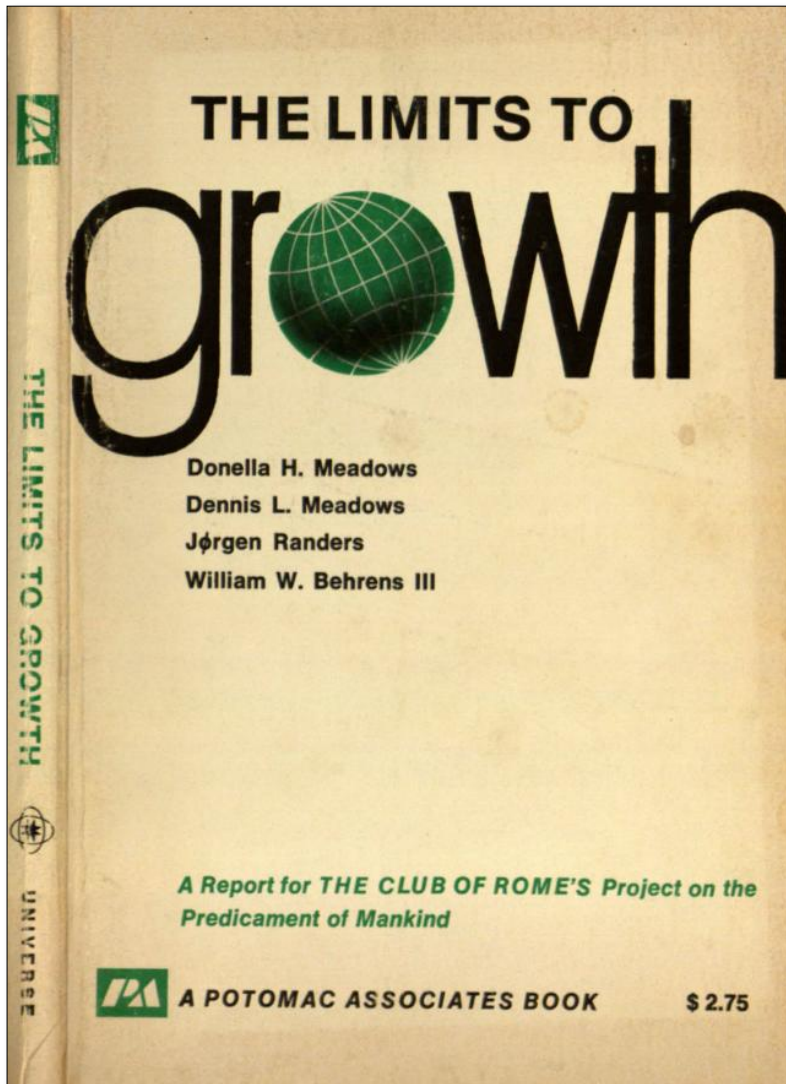
August 2026



Hasret Sahin

Postdoctoral researcher
Solar Economy Team
LUT University, Lappeenranta, Finland





“A finite planet cannot support infinite physical demands.”

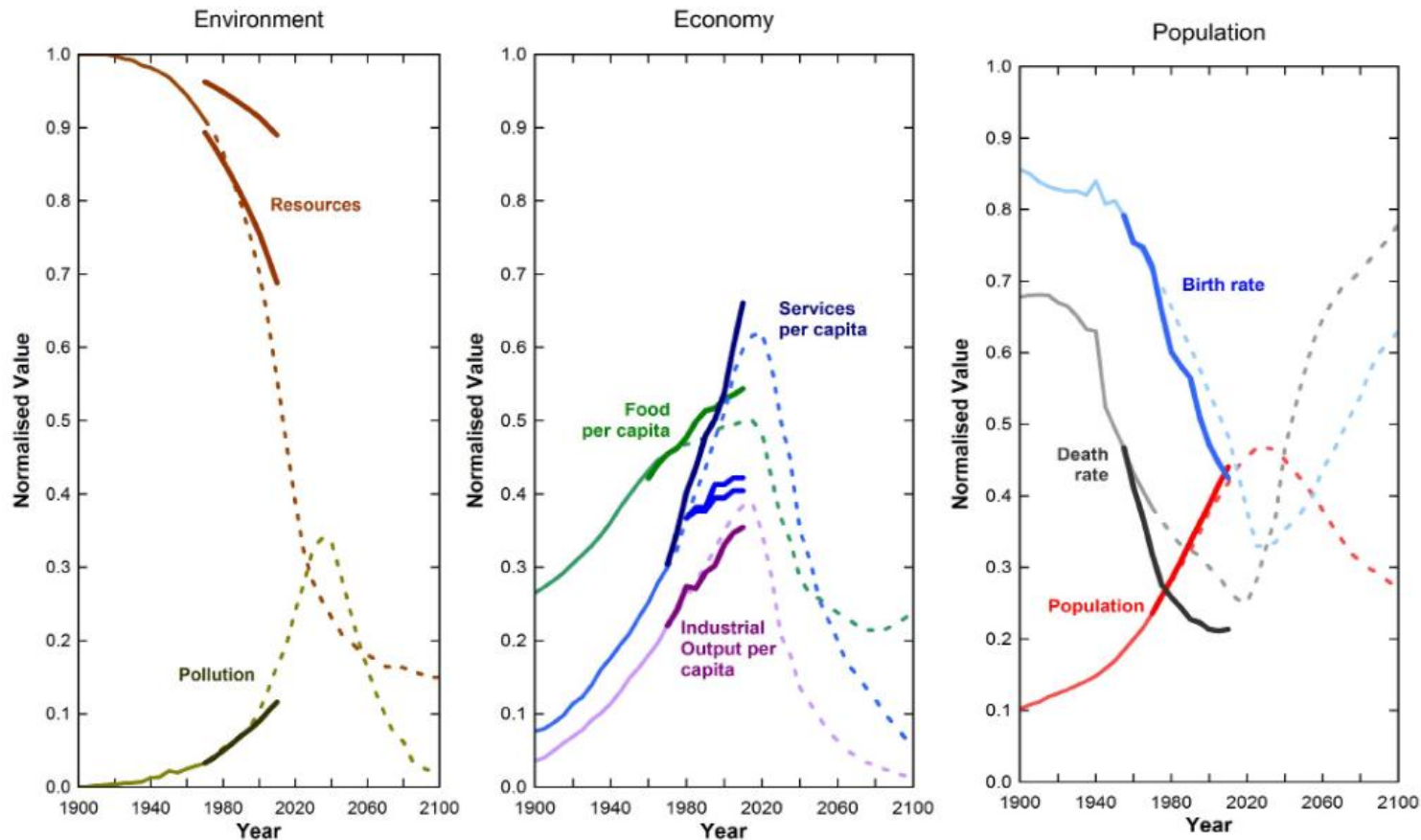
1968 – The Club of Rome : Led by Italian industrialist **Aurelio Peccei**, examining the long-term consequences of **population growth**, **resource depletion** and **environmental pressures**.

A system approach: Influenced by **Jay Forrester's** system dynamics at MIT, focusing on interactions and feedbacks within the global system.

1972 – The Limits to Growth: Demonstrated how continued growth could lead to overshoot and **instability as physical** and **resource constraints** emerge.

12 million copies sold, translated 37 languages

<https://www.clubofrome.org/publication/the-limits-to-growth/>



Limits the growth standard business as usual scenario (dotted lines) compared with historical data for the period 1970–2010 (solid lines)

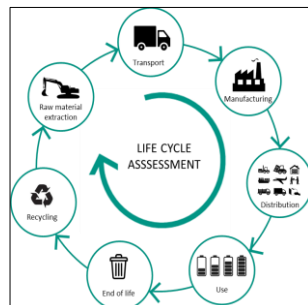
What are the biophysical limits of the energy transition?

Turner, G. Is Global Collapse Imminent? Melbourne Sustainable Society Institute, The University of Melbourne. 2014.
https://strategicriskinstitute.com/resources/Third_Party_Scenarios/Older-Scenarios/Updated-Limits-to-Growth.pdf

The biophysical limits of the energy transition



Higher energy requirements for manufacturing, construction, operation, and decommissioning.



Leading to **direct and indirect environmental impacts** at the aggregated system level (planetary boundaries).



Driving **substantial demand for critical raw materials**.

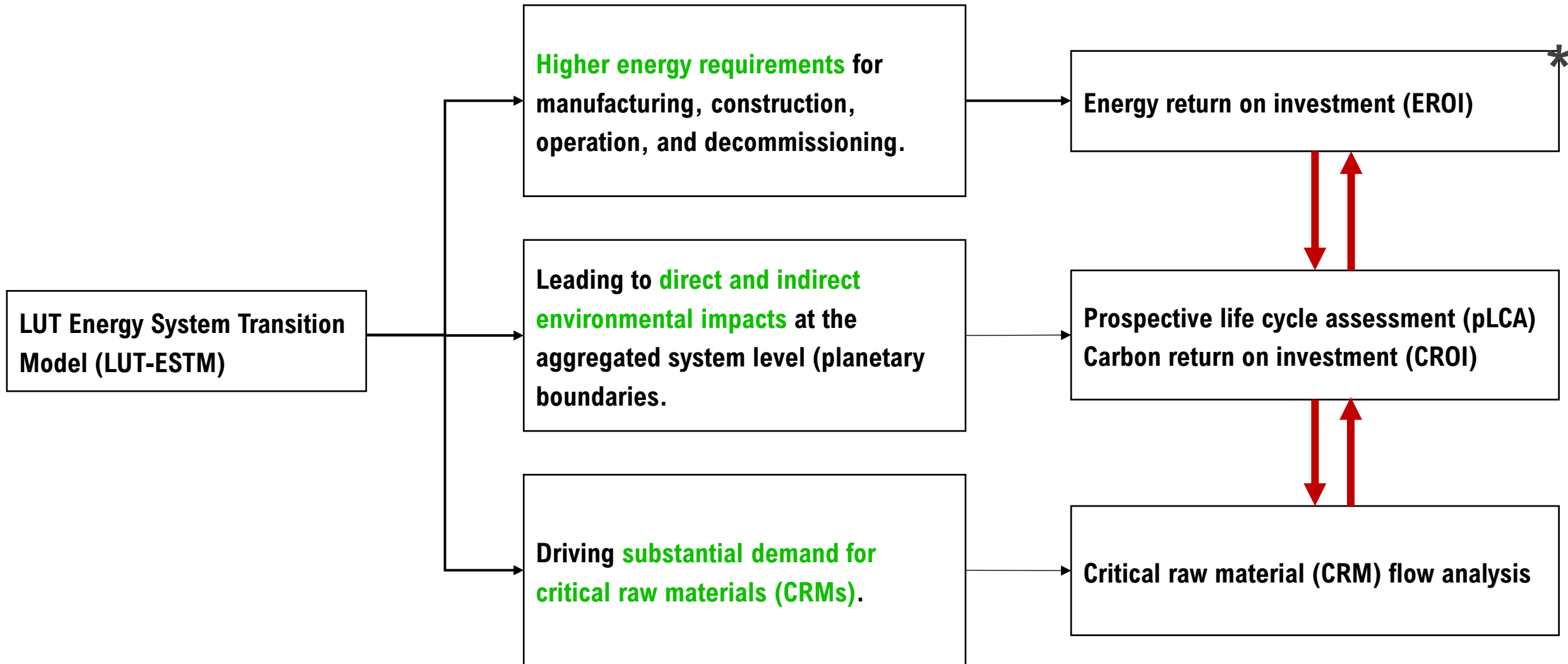
Land use

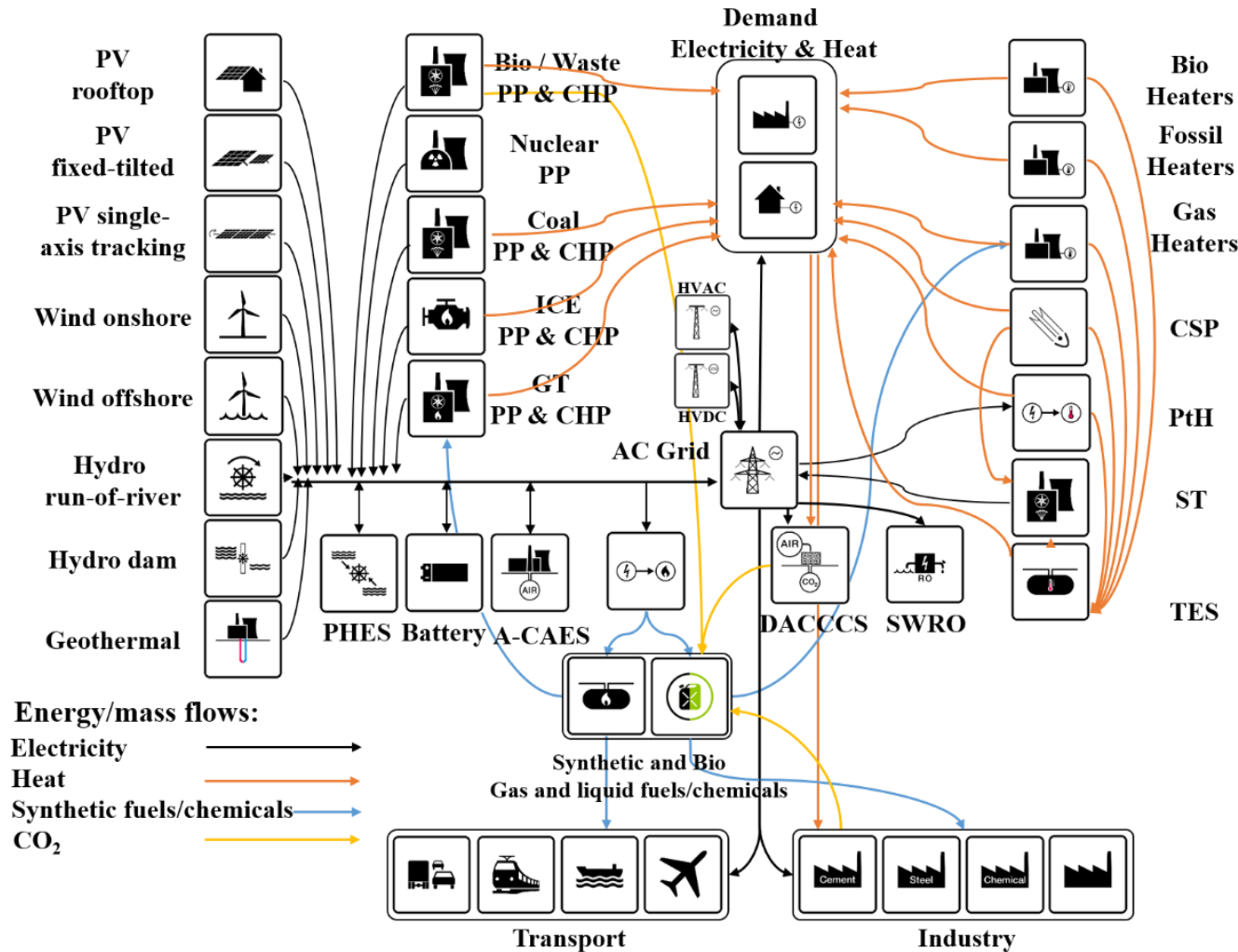
The biophysical limitations

Biodiversity

Staying in the safe operating space
Planetary boundaries

How do we address these challenges?





Mapping of technologies and connections within LUT-ESTM.

Technology-oriented, bottom-up cost-optimisation model.

Covers ~180 energy technologies.

Operates with full hourly resolution over an entire year.

Structured at country, regional, and global levels.

Uses 5-year time steps to capture transition dynamics and their changes.

Identifies short- and medium-term pathways guided by long-term targets.

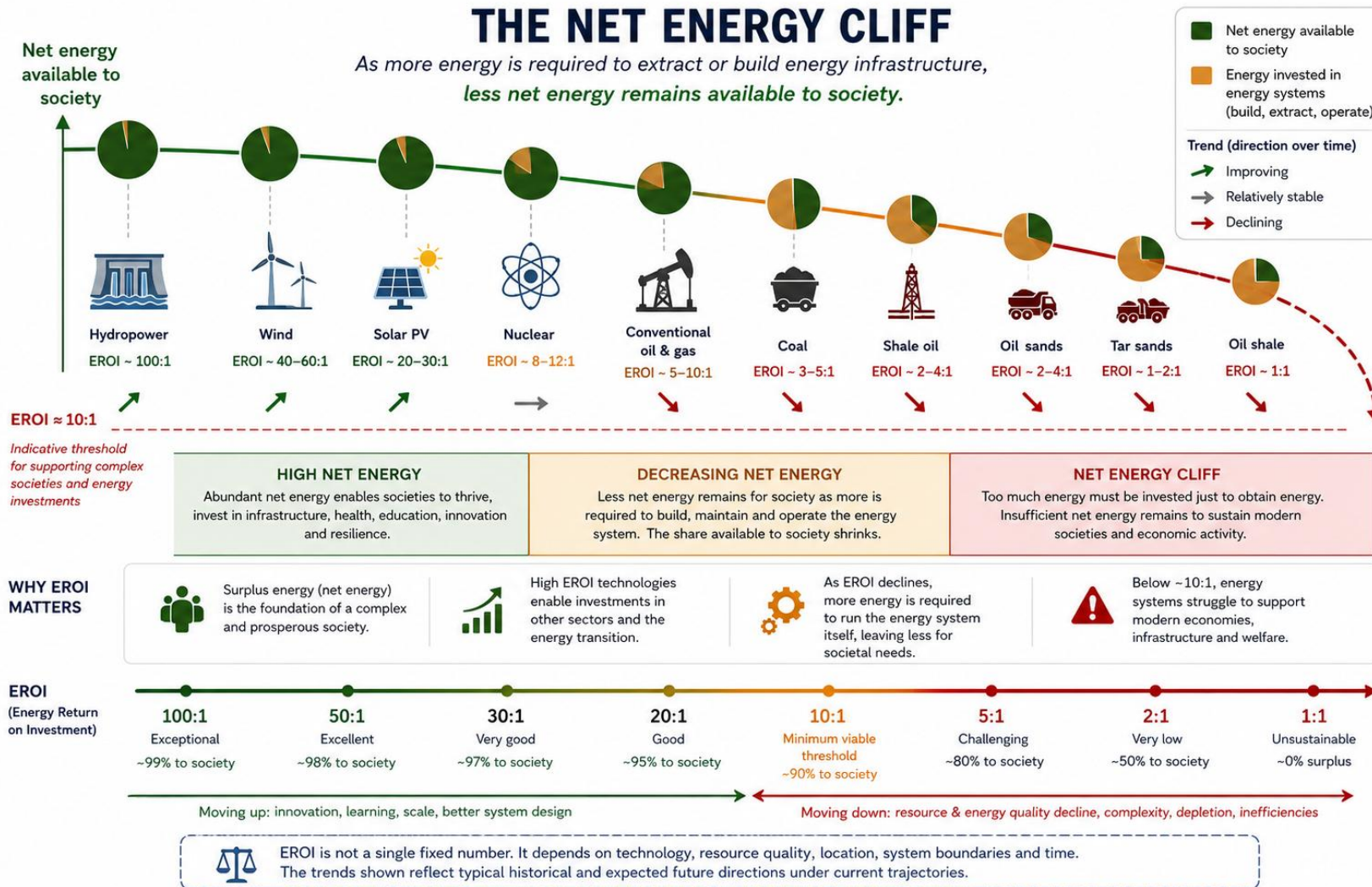
Minimises system costs while ensuring technology feasibility.

[Bogdanov, D., Ram, M., Satymov, R., Lopez, G., Mensah, T., Sadovskaia, K., & Breyer, C. \(2025\). Costs and benefits of highly ambitious energy transition pathways for Europe. *Energy*, 138477.](#)

[Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A. S., Child, M., ... & Breyer, C. \(2021\). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy*, 227, 120467.](#)

Section I

Systemwide EROI for power systems



EROI measures the ratio of usable energy gained vs. energy invested.

The minimum EROI threshold for the society (**Critical minimum: ~10**)

» Below this, too much energy is reinvested into the system itself.

» Leaves insufficient surplus energy for essential societal functions.

EROI ≈ 10–20: sustainable but limited societal growth.

EROI > 20: enabled industrial growth and high living standards.

Murphy DJ, Hall CA. (2010). Year in review—EROI or energy return on (energy) invested. *Annals of the new york academy of sciences*, 1185(1), 102-118.

Sahin H, Solomon AA, Aghahosseini A, Breyer C. (2024). Systemwide energy return on investment in a sustainable transition towards net zero power systems. *Nature Communications*, 15(1), 208.

Energy return on investment (EROI) is the division of usable energy delivered by the total energy required to deliver that energy of a system and/or an energy source through a lifetime.

$$\text{EROI} = \frac{\text{Energy Output}}{\text{Energy Input}}$$

Systemwide EROI considers the energy system as an integrated whole, accounting for both individual technologies and the interactions between technologies, processes, and energy flows.

[Solomon, A. A., Manjong, N. B., & Breyer, C. \(2023\). The necessity to standardise primary energy quality in achieving a meaningful quantification of related indicators. Smart Energy, 12, 100115.](#)

[Sahin H, Solomon AA, Aghahosseini A, Breyer C. \(2024\). Systemwide energy return on investment in a sustainable transition towards net zero power systems. Nature Communications, 15\(1\), 208.](#)

What will be surplus energy?

Simple technology-based analysis.

Non-uniformity in primary energy quality (PEQ).

Lacks capability to account for system design and operational issues.

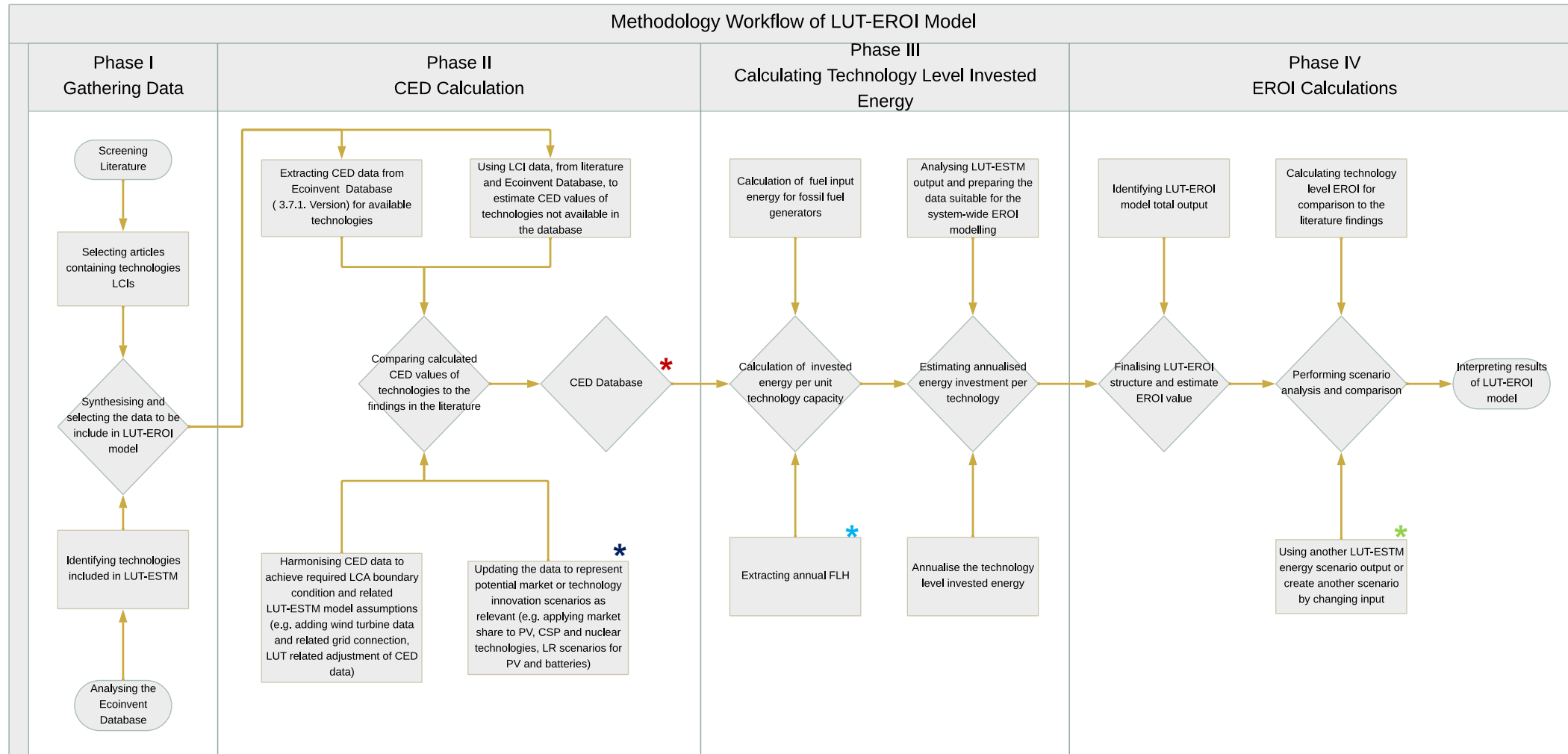
How can the reliability and consistency of energy supply be ensured throughout the energy transition?

Consistent PEQ at the electricity level.

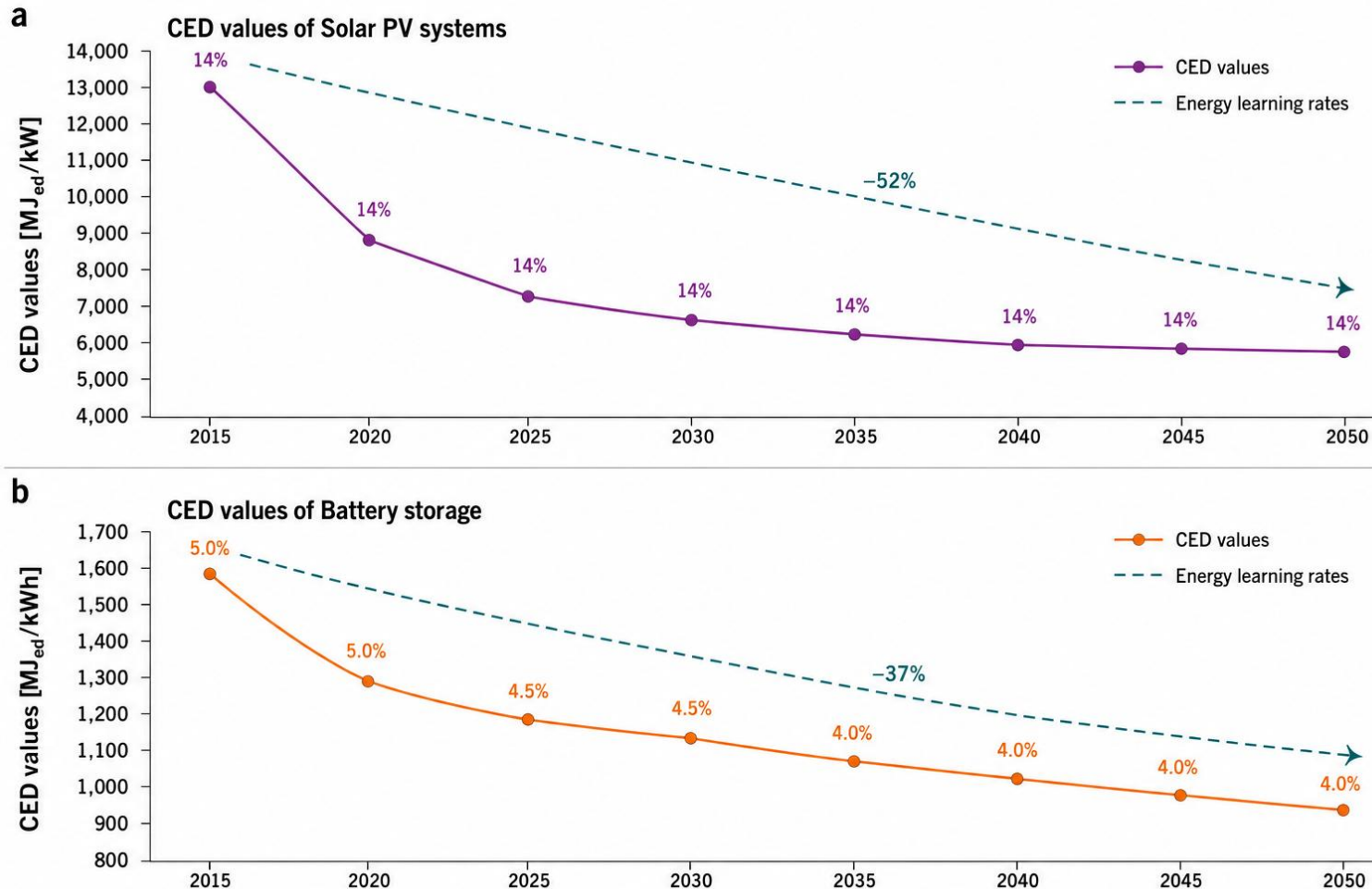
Hourly optimised system modelling (operational conditions, process interactions and commodity exchanges).

Life cycle assessment (LCA) based Cumulative Energy Demand (CED) to quantify systemwide energy investments.

Methodological flow of systemwide EROI



Sahin H, Solomon AA, Aghahosseini A, Breyer C. (2024). Systemwide energy return on investment in a sustainable transition towards net zero power systems. *Nature Communications*, 15(1), 208.

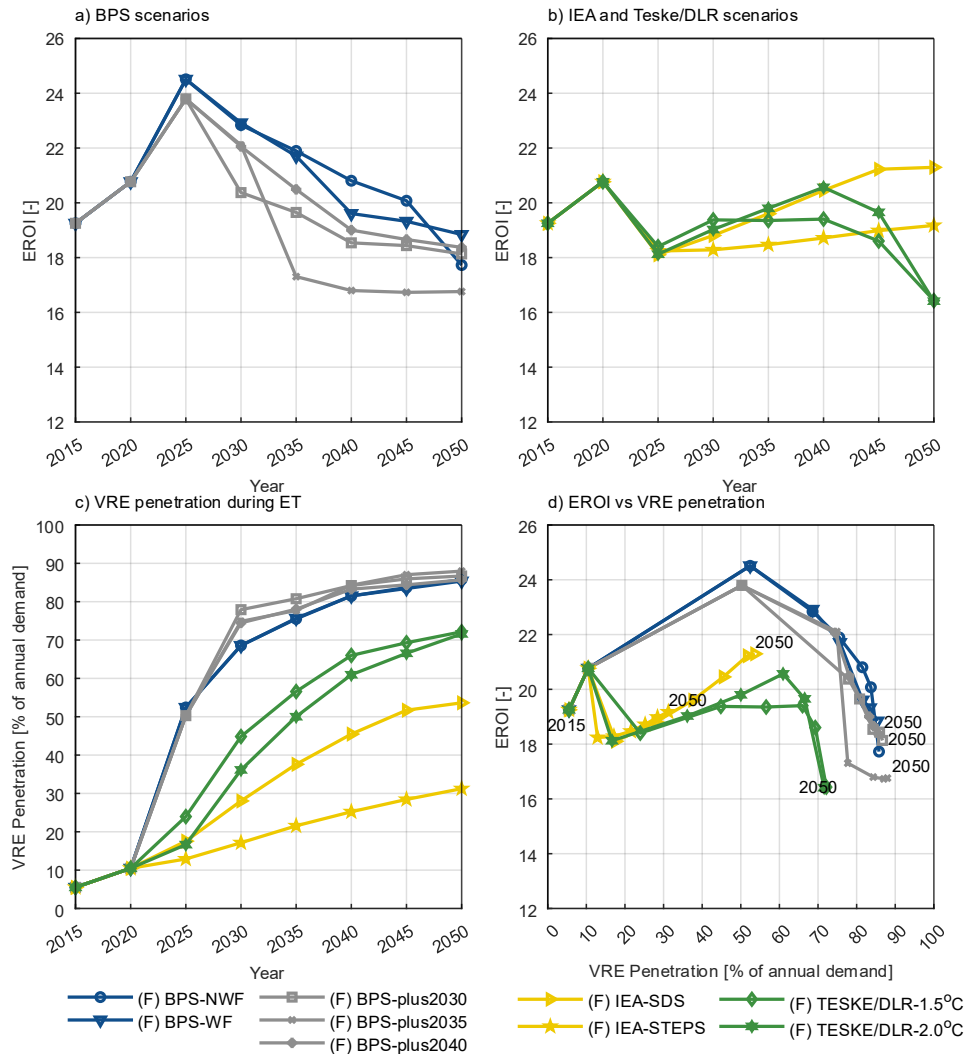


Görig M, Breyer C. (2016). Energy Learning Curves of PV Systems. *Environmental Progress & Sustainable Energy*, 35(3), 914–923. <https://doi.org/10.1002/ep.12340>.

Sahin H, Solomon AA, Aghahosseini A, Breyer C. (2024). Systemwide energy return on investment in a sustainable transition towards net zero power systems. *Nature Communications*, 15(1), 208.

Solomon AA, Sahin H, Breyer C. (2024). The pitfall in designing future electrical power systems without considering energy return on investment in planning. *Applied Energy*, 369, 123570.

Changes in the CED values of solar PV systems (a) and of battery storage (b) over the years, considering ELR values.



Global systemwide EROI trends

All scenarios are **feasible** from techno-economic point of view, so none of global EROIs goes below 10, which is the upper limit of the net energy cliff.

Best Policy Scenarios (BPS): No Wind Force (NWF) and Wind Force (WF) while BPS-plus scenarios (accelerated energy transition)

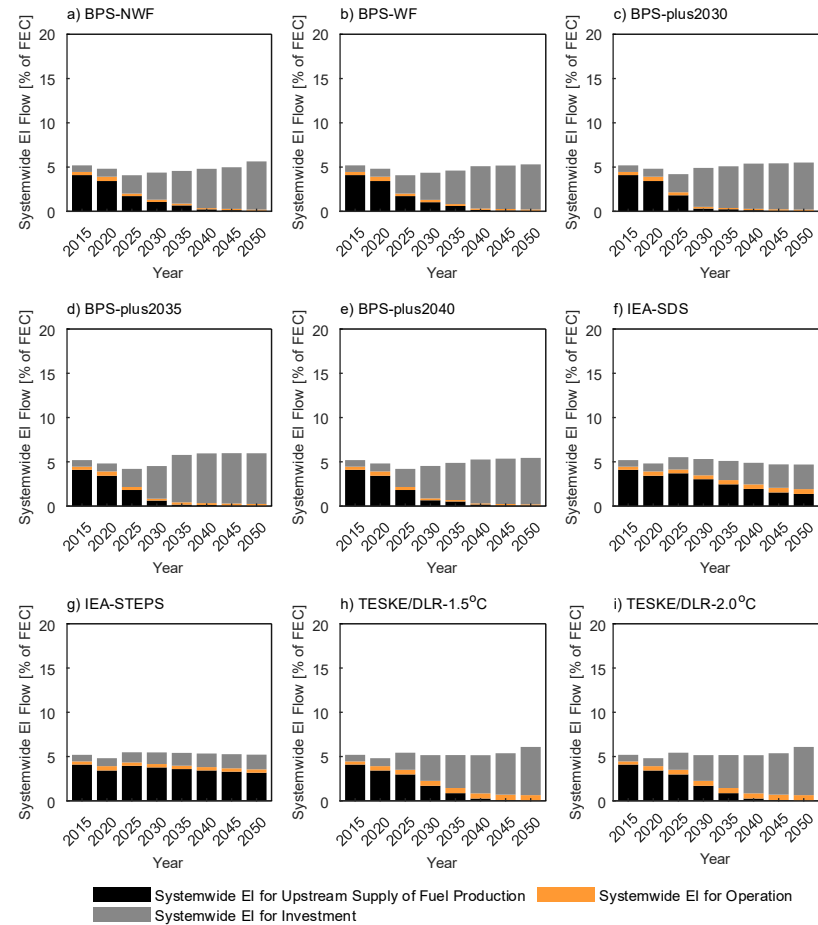
IEA Scenarios : Sustainable Development Scenario (SDS) and Stated Policy Scenario (STEPS);

Teske and the German Aerospace Centre (TESKE/DLR) Scenarios: 1.5°C and 2.0°C.

[Sahin H, Solomon AA, Aghahosseini A, Breyer C. \(2024\). Systemwide energy return on investment in a sustainable transition towards net zero power systems. Nature Communications, 15\(1\), 208.](#)

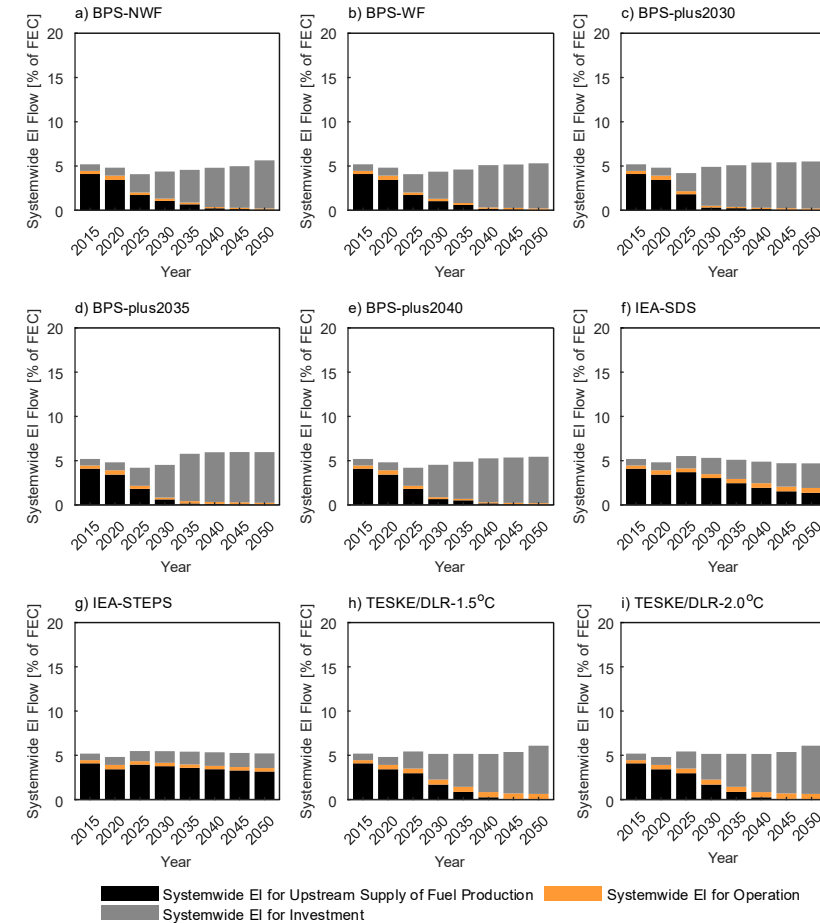
Systemwide and annual energy flow estimations for the power sector

Total energy requirements: < 7% of final energy consumption



Systemwide energy investment flow for the global power system

Total energy requirements: < 16% of final energy consumption



Annual energy investment flow for the global power system

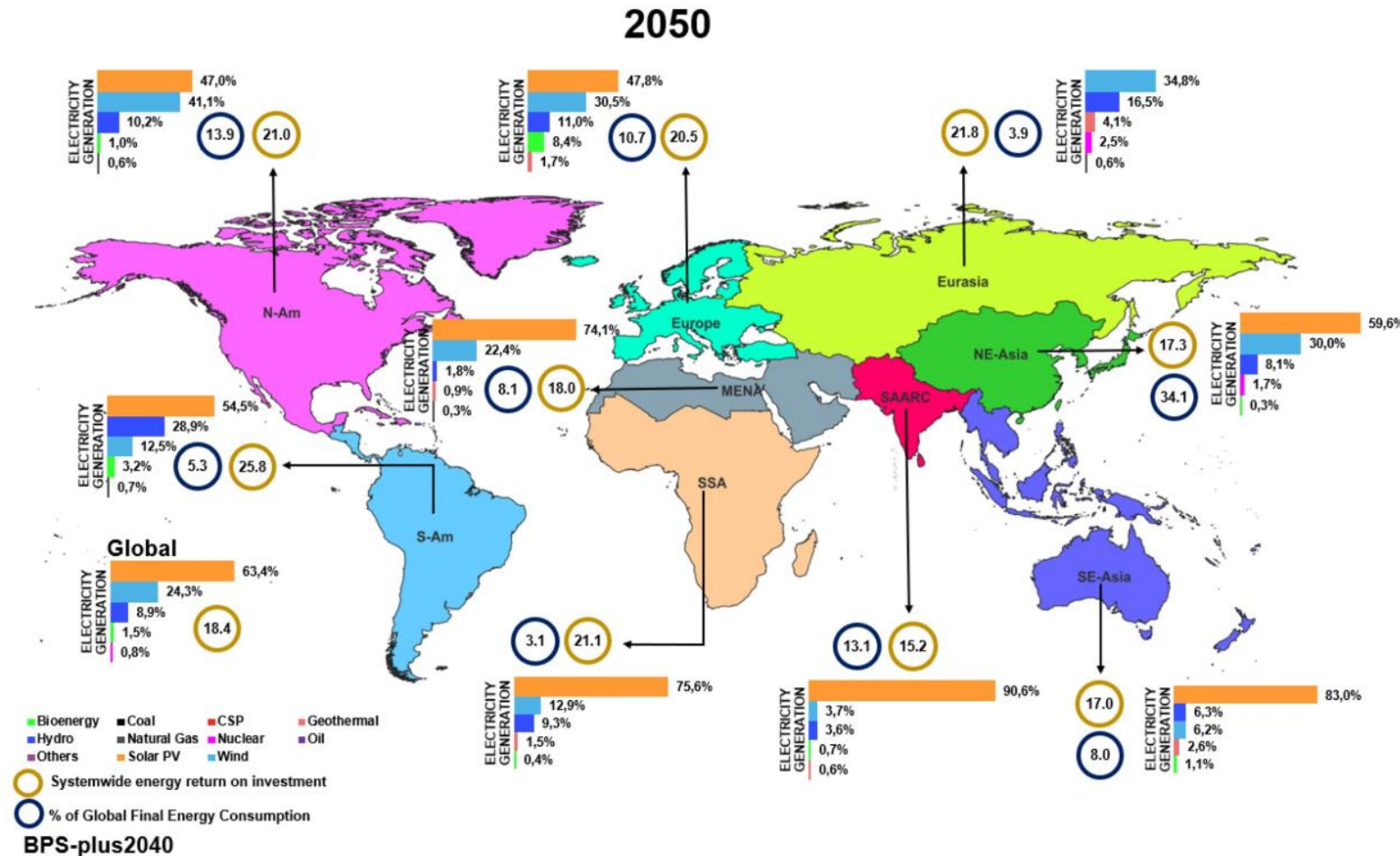
Section II

Regionalised systemwide EROI

vs

Resource Curse

Regional systemwide EROI trends



Europe, SE-Asia and Eurasia show **strong EROI sensitivity** to specific technology pathways, including wind repowering, geothermal expansion and Power-to-X infrastructure.

MENA and SSA experience **EROI declines with rapid solar PV deployment**, while Europe, SAARC, NE-Asia and S-America remain largely **unaffected by an accelerated transition timeline**.

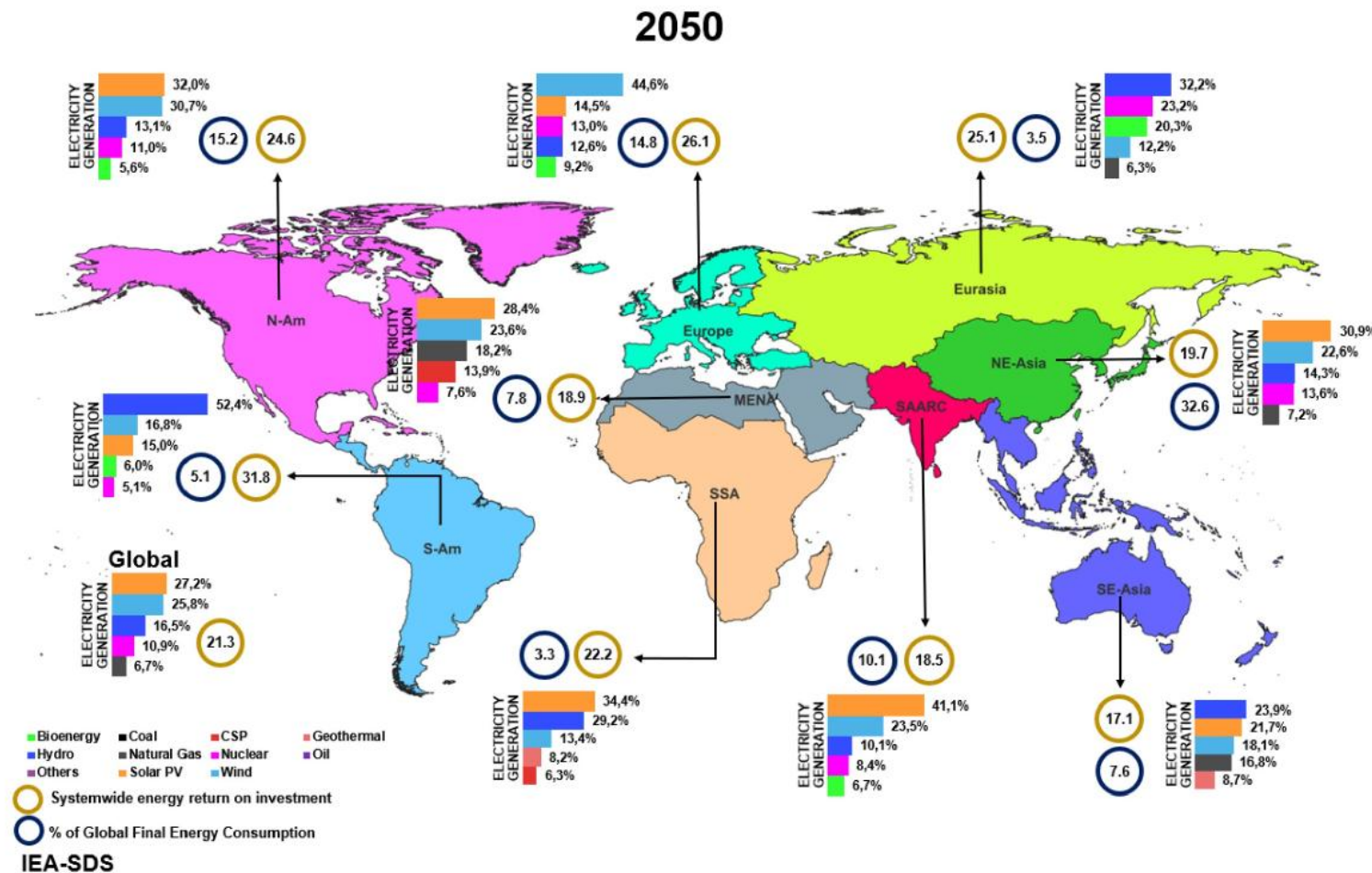
Regions: Europe, Eurasia, Middle East and North Africa (MENA), Sub-Saharan Africa (SSA), South Asian Association for Regional Cooperation (SAARC), Northeast Asia (NE-Asia), Southeast Asia (SE-Asia), North America (N-Am), South America (S-Am).

[Sahin, H., Solomon, A. A., Aghahosseini, A., & Breyer, C. \(2026\). Uneven distribution of natural energy resources impacts on systemwide energy return on investment. Earth's Future, 14\(1\), e2025EF006183.](#)

Regional systemwide EROI trends for BPS-plus2040 scenario

Systemwide energy return on investment for power systems

More information ► Hasret Sahin, hasret.sahin@lut.fi



Europe, SAARC, NE-Asia and South America: **Coal** and **gas** are progressively replaced by nuclear and renewables, helping to **stabilise** regional EROI trends.

Eurasia, SE-Asia and North America: Regional EROI trends are more strongly influenced particularly by **fuel switching** and **the deployment of electrolysis, methane and gas storage technologies**.

Regions: Europe, Eurasia, Middle East and North Africa (MENA), Sub-Saharan Africa (SSA), South Asian Association for Regional Cooperation (SAARC), Northeast Asia (NE-Asia), Southeast Asia (SE-Asia), North America (N-Am), South America (S-Am).

[Sahin, H., Solomon, A. A., Aghahosseini, A., & Breyer, C. \(2026\). Uneven distribution of natural energy resources impacts on systemwide energy return on investment. Earth's Future, 14\(1\), e2025EF006183.](#)

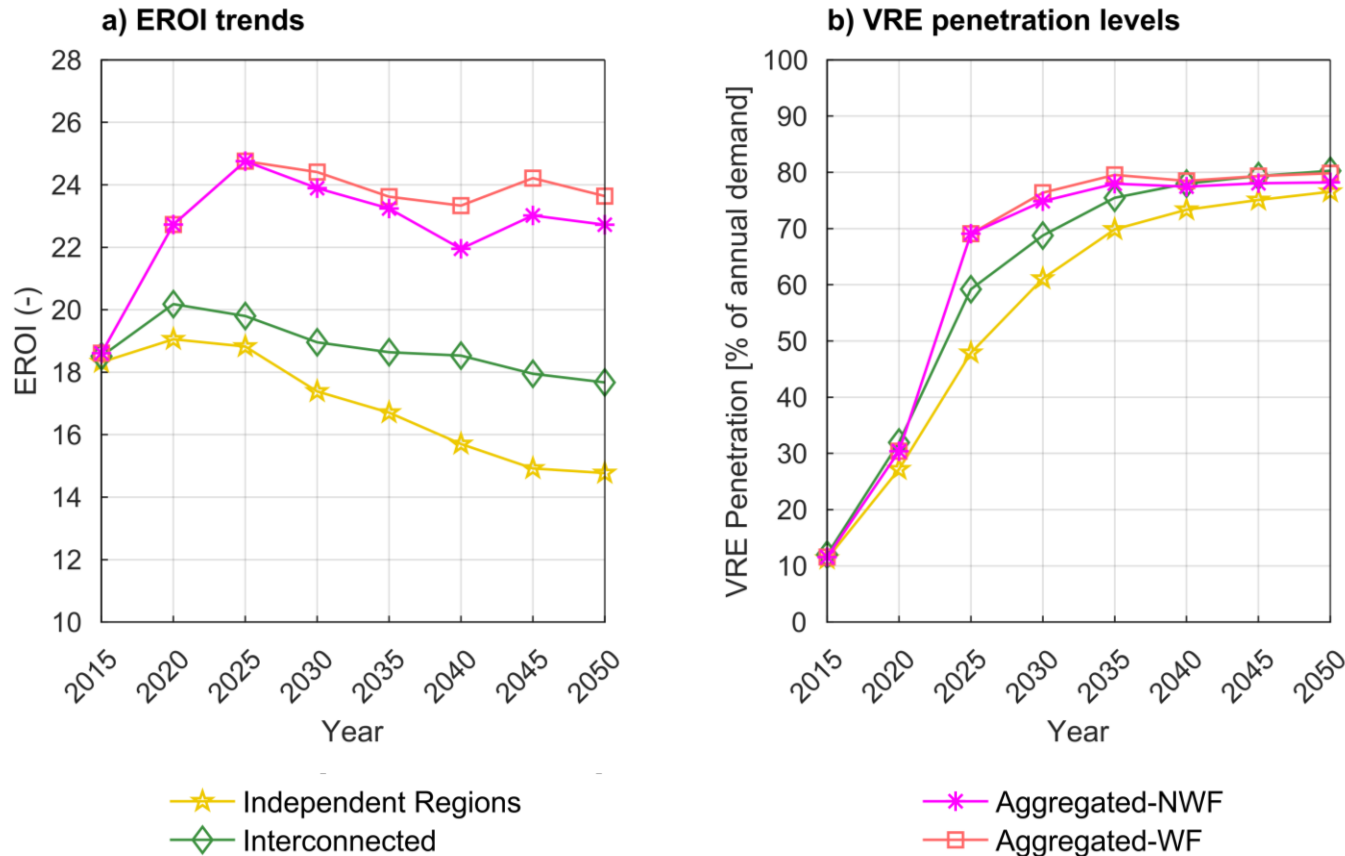
Regional systemwide EROI trends for IEA-SDS scenario

Systemwide energy return on investment for power systems

More information ► Hasret Sahin, hasret.sahin@lut.fi

Section III

Impact of spatial representation



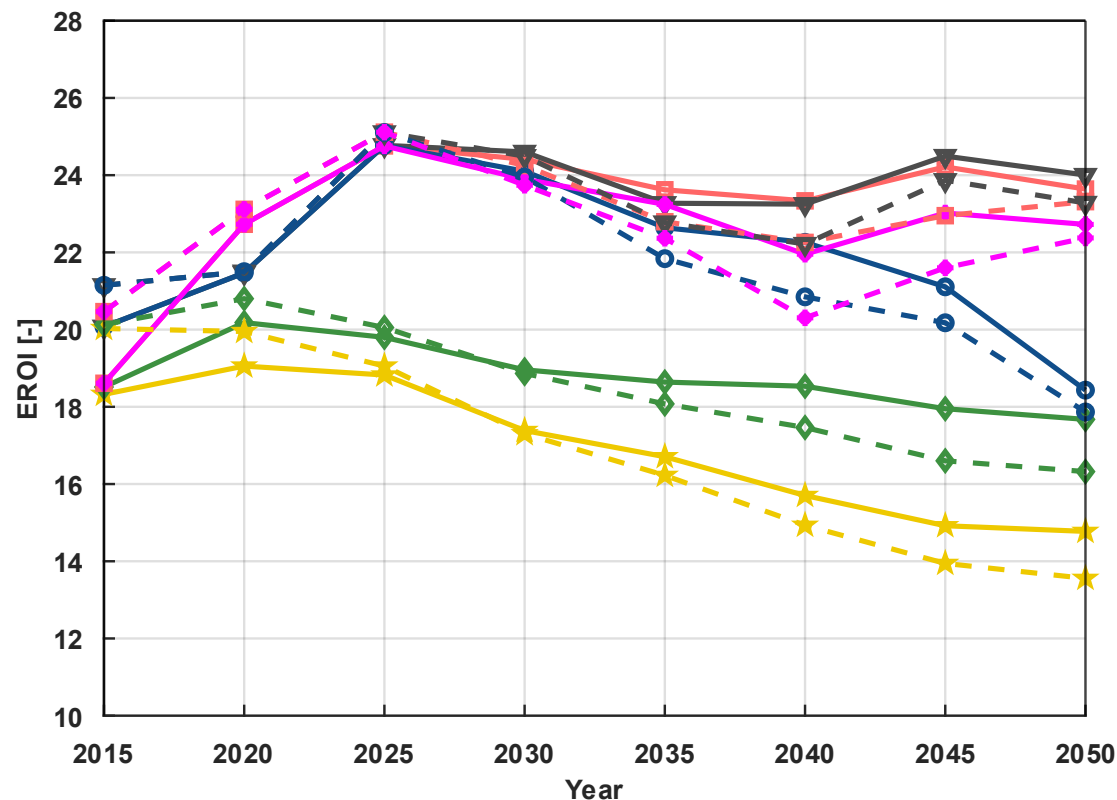
Europe as a case study

Spatial aggregation masks regional differences, leading to larger deviations and potentially misleading systemwide EROI trends.

The Variable Renewable Energy (VRE)–storage–curtailment relationship is strongly affected by spatial representation.

Systemwide EROI trends for Europe under six different spatial representation scenarios

[Sahin, H., Solomon, A.A., Aghahosseini, A., Breyer, C.: The impact of spatial representation in energy transition modelling on systemwide energy return on investment. IET Renew. Power Gener. 18, 2706–2722 \(2024\). https://doi.org/10.1049/rpg2.13117](https://doi.org/10.1049/rpg2.13117)



Higher embodied energy demand for oil and gas could push Europe's EROI below 14, highlighting the long-term EROI risks of continued fossil fuel dependence.

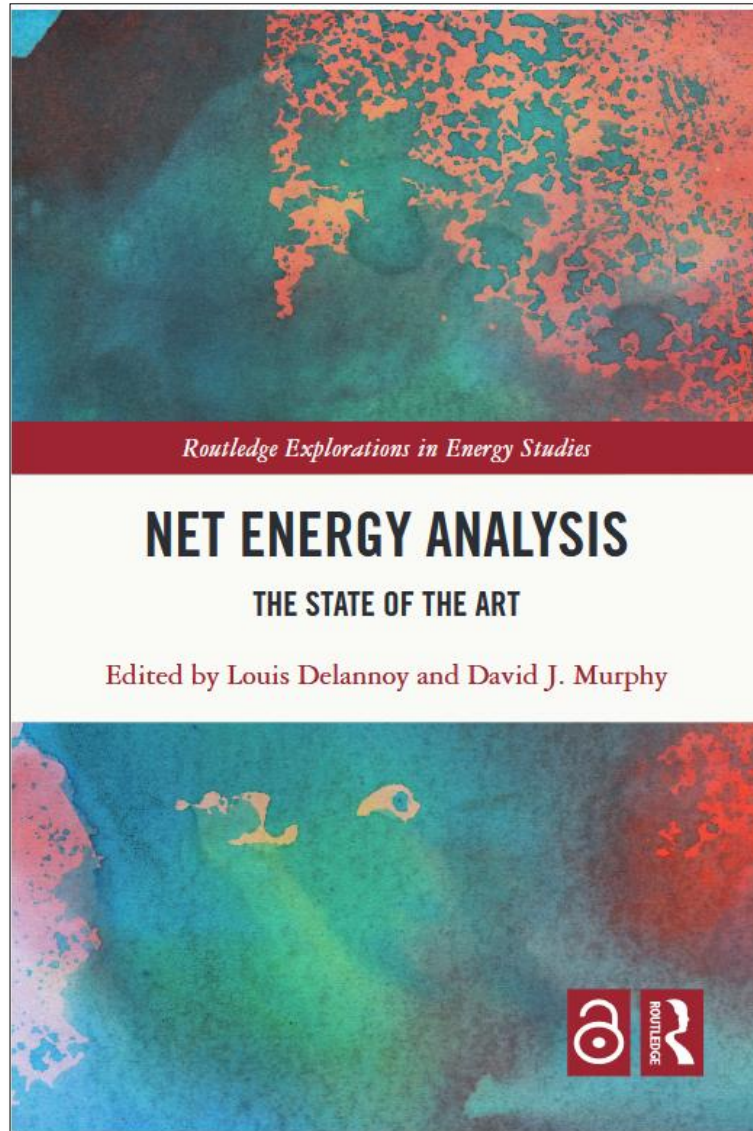
Europe EROI trends concerning the fossil fuels embodied energy demand changes

Sahin, H., Solomon, A.A., Aghahosseini, A., Breyer, C.: The impact of spatial representation in energy transition modelling on systemwide energy return on investment. IET Renew. Power Gener. 18, 2706–2722 (2024). <https://doi.org/10.1049/rpg2.13117>

- **System design matters:** Systemwide EROI trends are strongly shaped by the energy mix, technology choices and spatial representation.
- **Diversity and interconnection are critical:** Limited technology portfolios and isolated systems can lead to substantially lower EROI, whereas resource diversification and interconnection improve system performance.
- **The transition pathway matters more than resource geography:** Regional EROI trends are primarily driven by how the energy transition is designed and implemented, rather than by uneven renewable resource distribution alone.
- **High shares of variable renewables create a temporary challenge:** Beyond high penetration levels, additional solar, wind, storage and Power-to-X infrastructure can temporarily reduce systemwide EROI, before stabilisation as capacity deployment slows.
- **A rapid transition increases short-term energy requirements:** Accelerated infrastructure deployment can temporarily lower regional EROI, highlighting the importance of transition pace and planning.

A highly renewable energy system does not inherently lead to **low EROI**; its biophysical performance depends on how the system is designed, diversified, interconnected and deployed.

How technologies are manufactured, the materials and energy they require, and **their supply chains** can significantly shape **systemwide EROI**.



NEW BOOK

Net Energy Analysis: The State of the Art

Featuring contributions from the global EROI research community

Scan to explore



<https://doi.org/10.4324/9781003598206>

Thank you for your attention!
Q&A



Hasret Sahin
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