TATuP Zeitschrift für Technikfolgenabschätzung in Theorie und Praxis
Journal for Technology Assessment in Theory and Practice

oekom science

RESEARCH ARTICLE

Electrochemical technologies for deep decarbonization?: A heterodox technology assessment

Jorrit P. Smit*[,1], Nikola Biliškov[2], Marula Tsagkari[3]

Abstract • Increasingly, electrochemical energy storage and conversion technologies are considered key enablers of a deep decarbonization of society. However, given the real possibility that these technologies may delay rather than advance climate action, it is crucial that policymakers, industry, and researchers actively engage in developing principles for more responsible or 'convivial' use of these technologies. We demonstrate how current electrochemical research and innovation in green hydrogen and CO_2 utilization is embedded in orthodox political-economic discourses and infrastructures. As part of a technology assessment based on Zoellick and Bisht's (2018) degrowth perspective, we explore examples of electrochemical innovation that could fit heterodox political-economic scenarios and present approaches for future interdisciplinary research on convivial electrochemical innovation.

Elektrochemische Technologien für eine tiefgreifende Dekarbonisierung?*: Eine heterodoxe Technikfolgenabschätzung*

Zusammenfassung • *Elektrochemische Technologien zur Speicherung und Umwandlung von Energie gelten als zentrale Wegbereiter für eine tiefgreifende Dekarbonisierung der Gesellschaft. Da jedoch die reale Möglichkeit besteht, dass diese Technologien Klimaschutzmaßnahmen eher verzögern als vorantreiben, sollten sich Politik, Industrie und Forschung aktiv mit der Entwicklung von Prinzipien für einen verantwortungsvolleren oder ‚gesellschaftsfreundlicheren' Einsatz dieser Technologien befassen. Wir zeigen, wie die aktuelle elektrochemische Forschung und Innovation im Bereich der grünen Wasserstoff- und CO_2-Nutzung in orthodoxe politökonomische Diskurse und Infrastrukturen eingebettet sind. Im Rahmen einer Technikfolgenabschätzung aus der von Zoellick und Bisht (2018) entwickelten Degrowth-Perspektive untersuchen wir Beispiele elektrochemischer Innovationen, die sich in heterodoxen politökonomischen Szenarien wiederfinden, und stellen Ansätze für künftige interdisziplinäre Forschung zu konvivialer elektrochemischer Innovation vor.*

Keywords • *electrochemistry, energy storage and conversion, degrowth, political economy, convivial innovation*

This article is part of the Special topic "Deeply sustainable technologies: Beyond extractivism, exploitation, and exclusion," *edited by K. Kastenhofer, A. Schwarz, K. R. Srinivas, A. Vetter. https://doi.org/10.14512/tatup.7266*

Introduction

While the trade-off between economic growth and ecological care becomes impossible to ignore (Hickel 2020; Richardson et al. 2023), the long-running critical debate about the goals, beneficiaries, and socio-ecological costs of sustainable technological innovation is again burgeoning in technology assessment (TA) and related communities (Grunwald 2018; Pansera and Fressoli 2021). In that spirit, this paper directs critical attention to electrochemical (EC) technologies as tools for decarbonization (Johnson et al. 2025). Specifically, we focus on H_2O electrolysis and CO_2 capture and utilization. While governments promote EC technologies as fixes that will cut emissions and decarbonize hard-to-abate sectors, an expanding body of feasibility and sustainability studies identifies energy, material and ecological challenges (Sola et al. 2025; Sahu et al. 2024). Moreover, the political-economic framework and power regimes in which these innovations take place are scarcely challenged (Pansera 2011). To explore to what extent EC-based innovation could contribute to deep decarbonization, we build on work that uses principles from heterodox economics, like degrowth, to challenge orthodox

* *Corresponding author: j.p.smit@cwts.leidenuniv.nl*
[1] *Centre for Science and Technology Studies, Leiden University, Leiden, NL*
[2] *Ruđer Bošković Institute, Zagreb, HR*
[3] *Institut de Ciència i Tecnologia Ambientals, Universita Autònoma de Barcelona, Barcelona, ES*

https://doi.org/10.14512/tatup.7218
Received: 24. 04. 2025; revised version accepted: 03. 10. 2025; published online: 15. 12. 2025 (peer review)

innovation paradigms. In our conclusion, we propose principles to shape EC research and innovation in heterodox and convivial directions.

Background

From ortho- to heterodox technology assessment

Historically, the practice of technology assessment has been concerned with unintended side-effects of technology, challenging too optimistic technological premises of eco-modernism. More recently, and in close relation to the climate crisis and a decolonial turn, TA's tacit acceptance of established economic and social systems, including the economic growth paradigm, has been put up for discussion (Zoellick and Bisht 2018). Moreover, in Europe and the US, the rise of extreme-right governments is seen as a game changer for deliberative and evidence-based TA institutions, which are now being challenged by actors and movements that reject scientific consensus and seek to undermine pluralistic debate. Some argue that in this political-ecological context, TA needs to openly recognize its political nature, critically engage in democratic commitments (Delvenne and Parotte 2019) and start "thinking in alternatives" (Grunwald 2018, p. 1860).

Some argue that in this political-ecological context, technology assessment needs to openly recognize its political nature.

Authors in the field of science and technology studies (STS) and political economy have elaborated such alternatives, for example in terms of convivial or appropriate technology (Shanley 2021) and eco-innovation (Pansera 2011). All these approaches build on the systematic awareness that practices of framing, selecting, developing, deploying and infrastructuring technologies are intrinsically political. Since a few years, the insight that economic growth is fundamentally at odds with planetary boundaries (Richardson et al. 2023) has led to a renewed interest in post- or de-growth alternatives for technological innovation (Vetter 2018). Degrowth has been a central tenet of ecological economics that proposes alternatives to eco-modernism and scrutinizes the relationship between technology, productivity, and well-being (Pansera and Fressoli 2021). Degrowth directly critiques growth-oriented assumptions in mainstream technological innovation and policy discourses, calling instead for social and institutional change. Accordingly, different TA frameworks have been developed that move beyond questions of efficiency or equity towards assessing whether a technology is desirable, accessible, how ownership is arranged, and how socio-ecological costs and benefits are distributed (Vetter 2018; Zoellick and Bisht 2018; Ralph 2021).

Heterodox TA builds on these approaches to open-up space for the democratic deliberation of plural socio-technic futures, including care, feminist and indigenous perspectives (Arora and Van Dyck 2025). In this contribution, we follow the framework introduced by Zoellick and Bisht (2018) inspired by concepts of conviviality, degrowth and Marxism, because it is more compatible with high-tech innovations than other frameworks concerned with bottom-up innovation (Vetter 2018). Zoellick and Bisht (2018) propose five analytic dimensions: ecological impact, accessibility (for large part of the population), autonomy (individual and locally), decentralization (distributed and small-scale use) and innovation. These reflect foundational principles of heterodox economic thought such as sufficiency, democratic control, equity, and ecological embeddedness (Hickel 2020). Below, we use these dimensions to assess how EC research and innovation align with decarbonization and how they could be developed 'convivially' to fit a degrowth scenario.

Electrochemistry for decarbonization

EU and national governments promise to replace fossil fuels with new, often electrical technologies to decarbonize industrial and energy production, spurring investment in electrochemical solutions (Johnson et al. 2025). However, these technical fixes are still aligned with a growth paradigm, which is at odds with reducing ecological impact (Hickel 2020; Richardson et al. 2023). To scrutinize the potential to develop EC research in heterodox directions, we focus on emerging 'power-to-X' (P2X) technologies, more specifically H_2O electrolysis and CO_2 capture and utilization, which use EC principles to convert renewable electricity into chemical energy stored in molecules, which can be used as feedstock, fuel or energy storage (Epp and Pfaff 2019).

Hydrogen is most commonly classified with respect to methods of its production, in accordance to EU taxonomy. 'Green' hydrogen results from water electrolysis when renewable electricity is used and can replace CO_2-intensive 'grey' hydrogen in today's industrial uses, to decarbonize fertilizer, (petro)chemical and steel industries and realize seasonal energy storage (Johnson et al. 2025). While production of 'green' hydrogen currently makes up less than 0.1 % of total global hydrogen production (0.1 Mt of a total 97 Mt, IEA 2024), the European Commission aims to both produce and import 10 Mt per year by 2030 (or 200 times current global green hydrogen production). This stark gap between present capacity and future ambition is often overlooked in policy and industry, as they prioritize investment and geopolitical influence.

Compared to water electrolysis' mature development (Hassan et al. 2023), the electrocatalytic reduction of CO_2 into fuels and value-added chemicals has only in the last ten years experienced growing interest, pushing developments to prototype

TATuP · Zeitschrift für Technikfolgenabschätzung in Theorie und Praxis 34/3 (2025): 33–38
https://doi.org/10.14512/tatup.7218

stages (Chakravarty et al. 2025). CO_2 electrolysis promises to replace fossil feedstocks in fuels and chemical industry in order to lower life-cycle emissions of these production processes (Vogt and Weckhuysen 2024). After CO_2 is captured (at an industrial point-source or with direct air capture), a renewable-powered electrolyzer converts it into bulk chemicals like carbon monoxide, formate, methane or more complex carbon chains like ethylene and ethanol (Detz et al. 2023). For both water electrolysis and CO_2 capture and utilization technologies, a range of options exist for cell designs, reaction conditions (e.g., temperature, pressure), operational lifetimes, and material use (for membranes, catalysts and electrodes).

Methods and approach

Through an exploratory analysis of recent EC literature, we assess whether P2X technologies could be suitable for degrowth scenarios. We performed two complementary literature searches, one based on recent reviews of techno-economic and life-cycle studies to grasp the (mis)alignment of P2X with heterodox perspectives. Next, to specifically explore the heterodox potential of P2X, we created a focused sample of journal articles published between 2020–2025 from the Web of Science database by using search queries combining the technologies (water electrolys*, CO_2 electrolys*, Power-to-X) with five analytic dimensions (decentral*, autonom*, etc.; Zoellick and Bisht 2018), and limited snow-balling via citations (Smit et al. 2025, see Research Data). Abstracts were screened to select papers addressing at least one criterion (total: 54). Next, we conducted a thematic analysis for each paper to assess in what way they aligned with one or more criteria and to what extent they proposed alternative ways to direct EC research towards a heterodox paradigm.

In our analysis of P2X technologies, we realized that the five dimensions were not fully independent as each related back to the same material need for renewable energy provision. In our results, therefore, we present the dimensions implicitly as part of two narratives, focusing respectively on the limitations as well as potential for P2X technologies to align with a heterodox perspective.

Results

In this section we present narrative syntheses that convey the results from our literature analysis, one focusing on the mainstream P2X approach, the other on a potential heterodox paradigm.

Assessment of established P2X scenarios

In principle, P2X technologies can substantially reduce greenhouse gas emissions but are still associated with substantial unintended negative impacts. Moreover, they are structured in a centralized, capital- and technology-intensive manner that makes them costly and complex.

Recent research including assessments of infrastructure, transport and leakages shows that full life cycle emissions of P2X technologies remain relatively high, depending strongly on energy source and location (de Kleijne et al. 2024). Land use impacts like biodiversity loss and habitat fragmentation arise from the expansion of renewable energy infrastructure, while CO_2 electrolysis' territorial impact depends on the source of carbon (Sahu et al. 2024). Fresh water as input for electrolysis can be challenging in arid regions (Tonelli et al. 2023).

Socio-ecological impacts arise from the mining required for catalyst and electrode materials. This implies the extraction of rare earths and scarce metals like platinum-group metals, cobalt, nickel, copper, as well as iridium, yttrium, and high-purity graphite (Sahu et al. 2024; Sola et al. 2025). Large-scale deployment of P2X systems depends on geopolitically sensitive materials, with negative social effects in 'green sacrifice zones' like Democratic Republic of Congo (cobalt) and Indonesia (nickel) (Andreucci et al. 2023). Moreover, recent analyses (IEA 2025) highlight the difficulty of diversifying global supply chains and redistributing manufacturing to more localized or democratic contexts.

Most national policy plans focus on centralized hydrogen production and CO_2 capture and utilization at large scale, partly to improve energy security (Johnson et al. 2025). These are envisioned as integrated in global markets (Ueckerdt et al. 2021) that overlap with existing fossil infrastructures (such as gas pipelines and port infrastructures) and reproduce North-South dependencies (Cezne and Otsuki 2025). Also, the manufacturing of electrolyzers is highly specialized and centralized (Johnson et al. 2025) and the transport of P2X products requires complex infrastructure for compression, transport and storage (Mekonnin et al. 2025) and advanced expertise (Schotten et al. 2020). With the need for stable electricity provision and constrained access to critical resources, the possibility for autonomous production and use of P2X technologies at smaller scales is limited.

Thus, the application of water and CO_2 electrolyzers remains restricted to current hydrogen users in highly industrialized sectors, such as energy production, transport, petro- and agro-chemical industries (Johnson et al. 2025). Accessibility is limited by high capital expenditure (Detz et al. 2023) and potentially substantial operational costs (Henry et al. 2023). The higher cost of products from P2X processes may reduce their accessibility to smaller users. For instance, 'green' hydrogen is currently 2–3 times more expensive than 'blue' hydrogen, and products obtained by chemical transformation of CO_2 are also generally more expensive than conventional products (Johnson et al. 2025). This will provide an advantage to large industries and reinforces geographical inequalities (Dejonghe and Van De Graaf 2025).

Towards a heterodox P2X paradigm?

The above assessment suggests misalignment between P2X technology scenarios and heterodox aims of overall energy and material throughput reduction (Ueckerdt et al. 2021), affordability, small-scale operation, creative use and communal ownership

(Zoellick and Bisht 2018). Here, we explore potential directions to develop and structure P2X otherwise.

A heterodox P2X paradigm would focus on abundant materials locally sourced, ideally from waste streams, whereas recycling is currently underdeveloped for electrolyzers (Sola et al. 2025). E-waste and urban mining could be used to source metals for catalysts in electrolysis (Seif et al. 2023) or upcycle (plastic) waste into synthetic fuels. Also, fresh water use can be reduced by turning to waste-, sea- or atmospheric water, also enabling accessibility and decentralization by using local nontraditional sources (Winter et al. 2022).

lization (Johnson et al. 2025; Chakravarty et al. 2025), concluding that P2X might just create "new patterns of unequal exchange through renewable power" (Brannstrom 2023, p.104), where the Global South supplies electricity and materials to the Global North without securing energy needs domestically (Cezne and Otsuki 2025).

Efficiency is not enough for deeply sustainable innovation (Zoellick and Bisht 2018), and this also applies to P2X technologies. This is due, first, to a practical barrier because many P2X processes like CO_2 capture and utilization suffer from low energy efficiency, high material costs, and limited scalability, as

Electrochemical research is tied strongly to the proprietary, growth-oriented innovation system and the fossil-dependent production structure.

compared to fossil alternatives. But from a wider perspective, a sole focus on efficiency is especially inadequate because it obscures concerns like justice, extractivism, inequal dependence, and misalignment with energy and material reduction. Similar to Muraca and Neuber's (2018) argument for geo-engineering, we call for political and institutional interventions in order for P2X to be able to play a role in a degrowth future.

Decentralized P2X technology could play a role in more convivial scenarios by serving localized energy and material needs independent from centralized (and fossil) infrastructures and by supporting decentralized energy systems, e.g., as seasonal energy storage. Many studies consider how this improves national or regional energy security. Decentralized chemicals production is feasible for syngas (Wiltink et al. 2023). However, modelling studies of micro-grids or off-grid hydrogen point at high relative costs (Grunow 2022) and therefore call for miniaturization or co-location with, e.g., e-methanol production to buffer against market variability (Alamia 2024).

Still, case studies of 'mini-plants' for hydrogen production, for example on islands, in buildings, or in a hospital (Assunçao et al. 2025), are promising, as they go beyond cost-efficiency to align with other values like self-sufficiency, energy autonomy and reduced ecological impact. Furthermore, food security goals (Cezne and Otsuki 2025) could inspire further development, as experiments exist with small-scale integrated production systems that locally convert solar energy into fertilizers (Sahu et al. 2024) or food components (Buchner et al. 2024), especially relevant to remote regions. Most of this research still requires advanced equipment, but a low-cost 3D printable flow cell design could give more researchers access to research reactors to further reduce barriers to EC knowledge (Heeschen et al. 2024).

A heterodox agenda for convivial electrochemistry

Today, EC research is tied strongly to the proprietary, growth-oriented innovation system and the fossil-dependent production structure. We found few examples of decentralized, low-impact, and socially embedded alternatives driven by concerns like sufficiency or energy democracy. Recent reviews further temper degrowth expectations around green hydrogen and carbon uti-

To move the agenda at the junction of EC, TA and degrowth more into this direction, we conclude with a set of principles to inform critical discussions between scientists, engineers and societal stakeholders (Smit 2025), and foster value-sensitive design (Tsagkari et al. 2024):

- **Respect socio-ecological constraints**: Beyond CO_2 emissions, limits on material, water and land use can be drivers for new research, focusing on earth abundant metals, non-toxic cell designs and waste or seawater inputs. Similarly, designing systems that limit energy use and transportation reduces land pressures. Principles of recycling, repair and reuse could redirect research to other designs and less extractivist relations. Inclusive and interdisciplinary agenda-setting processes for EC research can be pivotal.
- **Democratize application**: Heterodox EC development would move beyond the proposal to prioritize 'hard-to-abate' sectors (Vogt and Weckhuysen 2024; Johnson et al. 2025), such as refining and fertilizer industries, to critically discuss adequate roles and scales of such sectors and their products in a post-growth society. To democratize EC technologies, early-stage participation of local communities and potential small-scale users (like farmers or start-ups) could help align technological features with their needs instead.
- **Rethink lifecycles**: Life-cycle studies are used by many in the policy field to inform decisions about investment in and use of EC technologies. However, these typically do not con-

https://doi.org/10.14512/tatup.7218

sider the more fundamental criticisms offered by heterodox scholarship, and are ultimately embedded in the current economic paradigm. It could prove instructive if environmental economists and process engineers collaborated more closely with ecological economists to probe life cycle studies in degrowth scenarios.

- **Open up innovation**: Immersed in the global neoliberal and high-tech research and development system, current proprietary EC innovation is dominated by a few countries from the Global North (Chakravarty et al. 2025; Dejonghe and Van De Graaf 2025). Access to the latest developments is thus restricted to a small industrial and political elite (Cezne and Otsuki 2025). More heterogeneous knowledge ecologies are required (Smit 2025), including marginalized, local knowledges (Arora and Van Dyck 2025). Public institutions could support open, collaborative innovation focused on modularity, repairability, local production and decentralized control (Heeschen et al. 2024; Amoretti 2011).

Conclusion

While P2X technologies show potential to support decarbonization, their current development does not align with principles of degrowth, sufficiency or conviviality. What is more, without rigorous realignment, EC innovation risks further deepening inequalities and ecological harm. We conclude that substantial changes in the organization and orientation of EC research are needed to align with and contribute to deep decarbonization. We invite political decision makers, social and natural science researchers, engineers, and activists to take these principles in local trans-disciplinary settings as a starting point for the development of situated, degrowth-oriented agenda's for convivial electrochemical research and innovation.

Funding • This article received no funding.

Competing interests • The authors declare no competing interests.

Ethical oversight • The authors confirm that all procedures were performed in compliance with relevant laws and institutional guidelines.

Research data

A bibliographic file of the literature sample is stored in the OSF repository as: Smit, Jorrit; Tsagkari, Marula; Biliskov, Nikola (2025): Degrowth electrochemistry. In: Open Science Framework. https://doi.org/10.17605/OSF.IO/8KF9X

References

Amoretti, Michele (2011): Towards a peer-to-peer hydrogen economy framework. In: International Journal of Hydrogen Energy 36 (11), pp. 6376–6386. https://doi.org/10.1016/j.ijhydene.2011.03.039

Andreucci, Diego et al. (2023): The coloniality of green extractivism. Unearthing decarbonisation by dispossession through the case of nickel. In: Political Geography 107, p. 102997. https://doi.org/10.1016/j.polgeo.2023.102997

Alamia, Alberto; Partoon, Behzad; Rattigan, Eoghan; Bruun Anderson, Gorm (2024): Optimizing hydrogen and e-methanol production through Power-to-X integration in biogas plants. In: Energy Conversion and Management 322, p. 119175. https://doi.org/10.1016/j.enconman.2024.119175

Arora, Saurabh; Van Dyck, Barbara (2025): Decolonizing technology assessment. Towards a radical transformation of the modern world. In: TATuP – Journal for Technology Assessment in Theory and Practice 34 (1), pp. 15-21. https://doi.org/10.14512/tatup.7166

Assunçao, Ricardo; Ajeeb, Wagd; Eckl, Florentin; Gomes, Diogo; Neto, Rui Costa (2025): Decentralized hydrogen-oxygen co-production via electrolysis for large hospitals with integrated hydrogen refueling station. In: International Journal of Hydrogen Energy 103, pp. 87–98. https://doi.org/10.1016/j.ijhydene.2025.01.169

Brannstrom, Christian (2023): The emerging energy future(s) of renewable power and electrochemistry. Advancing or undermining energy democracy? In: Energy Democracies for Sustainable Futures, pp. 99–106. https://doi.org/10.1016/B978-0-12-822796-1.00011-5

Buchner, Markus et al. (2024): Deployment of power-to-protein technology in Ethiopia to provide drought-related emergency relief and mitigate food insecurity. In: Frontiers in Sustainable Food Systems 8, p. 1429171. https://doi.org/10.3389/fsufs.2024.1429171

Cezne, Eric; Otsuki, Kei (2025): The making of H2-scapes in the global south. Political geography perspectives on an emergent field of research. In: Political Geography 118, p. 103294. https://doi.org/10.1016/j.polgeo.2025.103294

Chakravarty, Sanghamitra; de Bruijn, Hans; Pérez-Fortes, Mar (2025): Governing the development of CO2 electrolysis. How do we give an emerging technology a chance to contribute to a carbon neutral Europe? In: Energy Research & Social Science 121, p. 103942. https://doi.org/10.1016/j.erss.2025.103942

Dejonghe, Marie; Van De Graaf, Thijs (2025): Green colonialism or green transformation? The equity implications of clean hydrogen trade. In: Political Geography 120, p. 103338. https://doi.org/10.1016/j.polgeo.2025.103338

de Kleijne, Kiane et al. (2024): Worldwide greenhouse gas emissions of green hydrogen production and transport. In: Nature Energy 9, pp. 1139–1152. https://doi.org/10.1038/s41560-024-01563-1

Delvenne, Pierre; Parotte, Céline (2019): Breaking the myth of neutrality. Technology assessment has politics, technology assessment as politics. In: Technological Forecasting and Social Change 139, pp. 64–72. https://doi.org/10.1016/j.techfore.2018.06.026

Detz, Remko et al. (2023): Electrochemical CO_2 conversion technologies. State-of-the-art and future perspectives. In: Sustainable Energy & Fuels 7 (23), pp. 5445–5472. https://doi.org/10.1039/D3SE00775H

Epp, Julia; Pfaff, Theresa (2019): Energiezukünfte für Power-to-X-Technologien. Eine Betrachtung der Akzeptabilität. In: TATuP – Journal for Technology Assessment in Theory and Practice 28 (3), pp. 41–47. https://doi.org/10.14512/tatup.28.3.41

Grunow, Paul (2022): Decentral hydrogen. In: Energies 15 (8), p. 2820. https://doi.org/10.3390/en15082820

Grunwald, Armin (2018): Diverging pathways to overcoming the environmental crisis. A critique of eco-modernism from a technology assessment perspective. In: Journal of Cleaner Production 197, pp. 1854–1862. https://doi.org/10.1016/j.jclepro.2016.07.212

Hassan, Qusay et al. (2023): A review of green hydrogen production based on solar energy. Techniques and methods. In: Energy Harvesting and Systems 11 (1), p. 20220134. https://doi.org/10.1515/ehs-2022-0134

Heeschen, Erin; DeLucia, Elena; Manav, Yilmaz; Roberts, Daisy; Davaji, Benyamin; Barecka, Magda (2024): Low cost 3D printable flow reactors for electrochemistry. In: HardwareX 17, p. e00505. https://doi.org/10.1016/j.ohx.2023.e00505

Henry, Ashleigh; McStay, Daniel; Rooney, David; Robertson, Peter; Foley, Aoife (2023): Techno-economic analysis to identify the optimal conditions for green hydrogen production. In: Energy Conversion and Management 291, p. 117230. https://doi.org/10.1016/j.enconman.2023.117230

Hickel, Jason (2020): Less is more. How degrowth will save the world. London: William Heinemann.

IEA – International Energy Agency (2024): Global hydrogen review 2024. Paris: IEA.

IEA (2025): Global critical minerals outlook 2025. Paris: IEA.

Johnson, Nathan; Liebreich, Michael; Kammen, Daniel; Ekins, Paul; McKenna, Russell; Staffell, Iain (2025): Realistic roles for hydrogen in the future energy transition. In: Nature Reviews Clean Technology 1 (5), pp. 351–361. https://doi.org/10.1038/s44359-025-00050-4

Mekonnin, Abdisa; Wacławiak, Krzysztof; Humayun, Muhammad; Zhang, Shaowei; Ullah, Habib (2025): Hydrogen storage technology, and its challenges. A review. In: Catalysts 15 (3), p. 260. https://doi.org/10.3390/catal15030260

Muraca, Barbara; Neuber, Frederike (2018): Viable and convivial technologies. Considerations on climate engineering from a degrowth perspective. In: Journal of Cleaner Production 197, pp. 1810–1822. https://doi.org/10.1016/j.jclepro.2017.04.159

Pansera, Mario (2011): The origins and purpose of eco-innovation. In: Global Environment 4 (7–08), pp. 128–155. https://doi.org/10.3197/ge.2011.040706

Pansera, Mario; Fressoli, Mariano (2021): Innovation without growth. Frameworks for understanding technological change in a post-growth era. In: Organization 28 (3), pp. 380–404. https://doi.org/10.1177/1350508420973631

Ralph, Natalie (2021): A conceptual merging of circular economy, degrowth and conviviality design approaches applied to renewable energy technology. In: Journal of Cleaner Production 319, p. 128549. https://doi.org/10.1016/j.jclepro.2021.128549

Richardson, Katherine et al. (2023): Earth beyond six of nine planetary boundaries. In: Science Advances 9 (37), p. eadh2458. https://doi.org/10.1126/sciadv.adh2458

Sahu, Saket et al. (2024): Techno-enviro-economic evaluation of decentralized solar ammonia production plant in India under various energy supply scenarios. In: Energy Conversion and Management 318, p. 118908. https://doi.org/10.1016/j.enconman.2024.118908

Seif, Rania; Salem, Fatma; Allam, Nageh (2023): E-waste recycled materials as efficient catalysts for renewable energy technologies and better environmental sustainability. In: Environment, Development and Sustainability 26 (3), pp. 5473–5508. https://doi.org/10.1007/s10668-023-02925-7

Schotten, Christiane; Nicholls, Thomas; Bourne, Richard; Kapur, Nikil; Nguyen, Bao; Willans, Charlotte (2020): Making electrochemistry easily accessible to the synthetic chemist. In: Green Chemistry 22 (11), pp. 3358–3375. https://doi.org/10.1039/D0GC01247E

Shanley, Danielle (2021): Imagining the future through revisiting the past. The value of history in thinking about R(R)I's possible future(s). In: Journal of Responsible Innovation 8 (2), pp. 234–253. https://doi.org/10.1080/23299460.2021.1882748

Smit, Jorrit (2025): (De)naturalizing knowledge ecosystems. On the use of ecological metaphors in STS and innovation studies. In: Science as Culture 34 (3), pp. 355–383. https://doi.org/10.1080/09505431.2025.2457731

Sola, Antonella; Rosa, Roberto; Ferrari, Anna (2025): Green hydrogen and its supply chain. A critical assessment of the environmental impacts. In: Advanced Sustainable Systems 9 (2), p. 2400708. https://doi.org/10.1002/adsu.202400708

Tonelli, Davide; Rosa, Lorenzo; Gabrielli, Paolo; Caldeira, Ken; Parente, Alessandro; Contino, Francesco (2023): Global land and water limits to electrolytic hydrogen production using wind and solar resources. In: Nature Communications 14 (1), p. 5532. https://doi.org/10.1038/s41467-023-41107-x

Tsagkari, Marula; van de Poel, Ibo; Pérez-Fortes, Mar (2024): Sustainable design of multiscale CO2 electrolysis. A value sensitive design-based approach. In: Energy Research & Social Science 116, p. 103671. https://doi.org/10.1016/j.erss.2024.103671

Ueckerdt, Falko; Bauer, Christian; Dirnaichner, Alois; Everall, Jordan; Sacchi, Romain; Luderer, Gunnar (2021): Potential and risks of hydrogen-based e-fuels in climate change mitigation. In: Nature Climate Change 11 (5), pp. 384–393. https://doi.org/10.1038/s41558-021-01032-7

Vetter, Andrea (2018): The matrix of convivial technology. Assessing technologies for degrowth. In: Journal of Cleaner Production 197, pp. 1778–1786. https://doi.org/10.1016/j.jclepro.2017.02.195

Vogt, Eelco; Weckhuysen, Bert (2024): The refinery of the future. In: Nature 629 (8011), pp. 295–306. https://doi.org/10.1038/s41586-024-07322-2

Wiltink, Thijmen; Yska, Stijn; Ramirez, Andrea; Pérez-Fortes, Mar (2023): Evaluation of centralized/decentralized configuration schemes of CO2 electrochemical reduction-based supply chains. In: Computer Aided Chemical Engineering 52, pp. 3417–3422. https://doi.org/10.1016/B978-0-443-15274-0.50545-X

Winter, Lea; Cooper, Nathanial; Lee, Boreum; Patel, Sohum; Wang, Li; Elimelech, Menachem (2022): Mining nontraditional water sources for a distributed hydrogen economy. In: Environmental Science & Technology 56 (15), pp. 10577–10585. https://doi.org/10.1021/acs.est.2c02439

Zoellick, Jan; Bisht, Arpita (2018): It's not (all) about efficiency. Powering and organizing technology from a degrowth perspective. In: Journal of Cleaner Production 197, pp. 1787–1799. https://doi.org/10.1016/j.jclepro.2017.03.234

DR. JORRIT P. SMIT
received his PhD from Leiden University in 2021 with a dissertation on the utility of science. As postdoctoral researcher in Leiden and Brussels, he works on the politics and promissory economy of green and natural hydrogen research.

DR. NIKOLA BILIŠKOV
currently works at the Ruđer Bošković Institute in Zagreb. Nikola does research mainly in the field of preparation and characterization of materials for solid-state hydrogen storage.

DR. MARULA TSAGKARI
received her PhD from the University of Barcelona in 2022 with a dissertation on renewable energy communities. As postdoctoral researcher at TU Delft she worked on value sensitive design for CO_2 electrolysis. At Autonomous University of Barcelona, she studies post-growth transitions.