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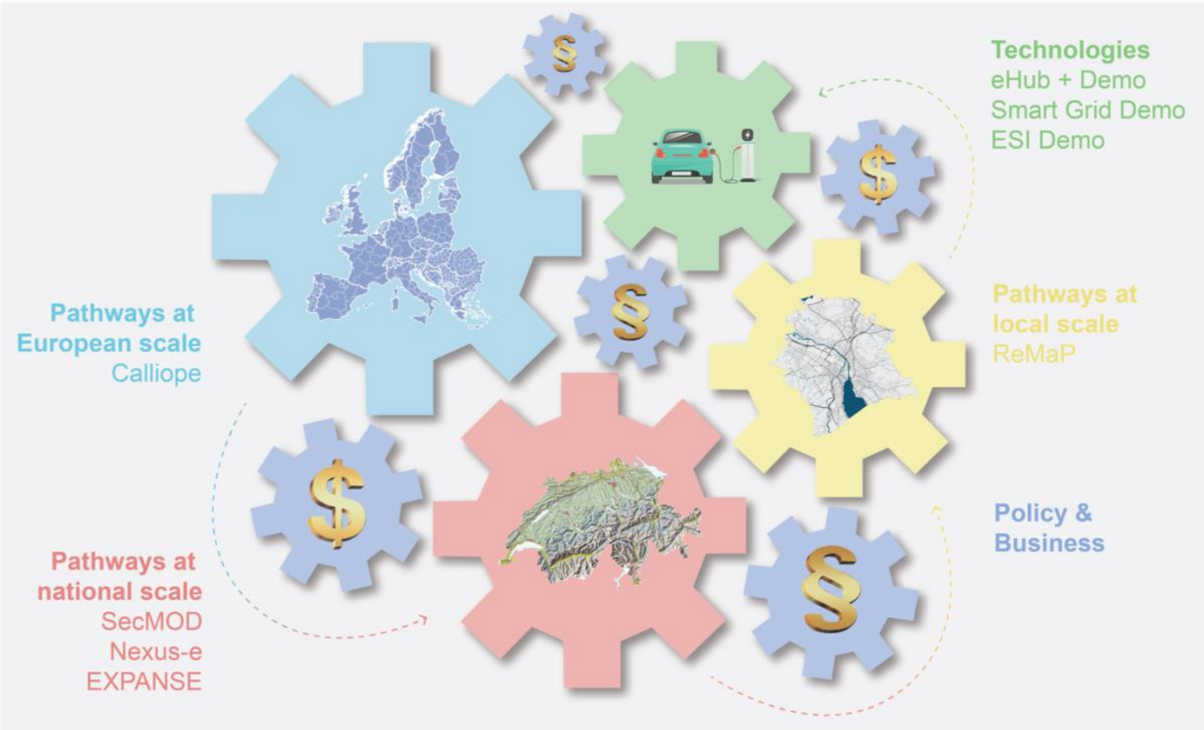
Highlights Report Year 2

PATHFNDR



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sweet swiss energy research for the energy transition

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The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.

Highlights

The main highlights (results, challenges, learnings, etc.) during the reporting period were the following:

- The development of a methodology to create four to six project-wide scenarios based on two dimensions (energy system integration and policy, and technological development) and two variants (moderate and progressive).
- Identification of project-wide synthesis topics serving as pilot studies for the PATHFNDR machine.
- Linking the Euro-Calliope model (provides predicted European developments towards net zero) and the Nexus-e model (a detailed model focusing on Swiss developments).
- The development of algorithms for EV charging scheduling, estimation of electricity load, and prediction of the heat load as well as their validation with real-world measurement data.
- Generating a technology map for sector coupling and flexibility, categorizing them into three pillars: thermal, electrical and gas.
- The development of a high-fidelity model for hydrogen-based energy storage, and the evaluation of seasonal thermal energy storage.
- The analysis of five decarbonization strategies (i.e., energy efficiency, electrification, low-carbon fuels, CO2 removal and radical demand side changes).
- The development of a framework to compare long-term policy strategies for deep decarbonization comparing Switzerland, EU, UK and Norway.
- The submission and approval of a pilot and demonstration (P&D) project on dynamic network tariffs. The first SWEET P&D awarded.
- The launch of an energy challenge initiative to provide science-based evidence on energy markets, energy independency, seasonal heat storage, and hydro reserves (in response to the energy supply crisis).

Faits marquants

Les principaux faits marquants (résultats, défis, apprentissages, etc.) pendant la période de référence ont été les suivants:

- Le développement d'une méthodologie pour créer quatre à six scénarios basés sur deux dimensions (intégration du système énergétique et politique, et développement technologique) et deux variantes (modérée et progressive).
- Identification de thèmes de synthèse à l'échelle du projet qui serviront d'études pilotes pour le moteur PATHFNDR.
- Le lien entre le modèle Euro-Calliope (qui fournit des prévisions sur l'évolution de l'Europe vers le zéro net) et le modèle Nexus-e (un modèle détaillé axé sur l'évolution de la Suisse).
- Le développement d'algorithmes pour la programmation de la charge des VE, l'estimation de la charge électrique et la prédiction de la charge thermique, ainsi que leur validation avec des données de mesure réelles.
- La génération d'une liste de technologies qui permettent le couplage des secteurs et améliorent la flexibilité, en les classant en trois catégories : thermique, électrique et gazière.
- Le développement d'un modèle de haute fidélité pour le stockage de l'énergie à base d'hydrogène et l'évaluation du stockage saisonnier de l'énergie thermique.
- L'analyse de cinq stratégies de décarbonisation (efficacité énergétique, électrification, combustibles à faible teneur en carbone, élimination du CO2 et changements radicaux au niveau de la demande).
- Le développement d'un cadre pour comparer les stratégies politiques à long terme pour une décarbonisation profonde entre la Suisse, l'UE, le Royaume-Uni et la Norvège.
- La soumission et l'approbation d'un projet pilote et de démonstration (P&D) sur les tarifs de réseau dynamiques. Le premier projet pilote et de démonstration SWEET a été attribué.
- Le lancement d'une initiative de défi énergétique pour fournir des preuves scientifiques sur les marchés de l'énergie, l'indépendance énergétique, le stockage saisonnier de la chaleur et les réserves hydroélectriques (en réponse à la crise de l'approvisionnement énergétique).

Highlights

Die wichtigsten Highlights (Ergebnisse, Herausforderungen, Lehren, usw.) während des Berichtszeitraums waren die folgenden:

- Die Entwicklung einer Methode zur Erstellung von vier bis sechs Szenarien auf der Grundlage von zwei Dimensionen (Integration des Energiesystems und Policy sowie technologische Entwicklung) und zwei Varianten (moderat und progressiv).
- Die Identifizierung von projektweiten Synthesethemen, die als Pilotstudien für die PATHFNDR-Maschine dienen.
- Die Verknüpfung des Euro-Calliope-Modells (liefert Prognosen zur europäischen Entwicklung in Richtung Netto-Null) und des Nexus-e-Modells (ein detailliertes Modell mit Schwerpunkt auf der Schweizer Entwicklung).
- Die Entwicklung von Algorithmen für die Planung von EV-Ladevorgängen, die Abschätzung der Stromlast und die Prognose der Wärmebelastung sowie deren Validierung mit realen Messdaten.
- Die Erstellung einer Liste von Technologien, die eine Sektorkopplung ermöglichen und die Flexibilität erhöhen, unterteilt in drei Bereiche: Wärme, Strom und Gas.
- Die Entwicklung eines High-Fidelity-Modells für die Energiespeicherung auf Wasserstoffbasis und die Bewertung der saisonalen thermischen Energiespeicherung.
- Die Analyse von fünf Dekarbonisierungsstrategien (d.h. Energieeffizienz, Elektrifizierung, kohlenstoffarme Brennstoffe, CO_2-Abscheidung und radikale Veränderungen auf der Nachfrageseite).
- Die Entwicklung einer Methode zum Vergleich langfristiger politischer Strategien für eine tiefgreifende Dekarbonisierung im Vergleich zwischen der Schweiz, der EU, Großbritannien und Norwegen.
- Die Einreichung und Genehmigung eines Pilot- und Demonstrationsprojekts (P&D) zu dynamischen Netztarifen. Das erste SWEET-P&D-Projekt wurde vergeben.
- Die Lancierung einer Energy-Challenge-Initiative, um wissenschaftlich fundierte Erkenntnisse über Energiemärkte, Energieunabhängigkeit, saisonale Wärmespeicherung und Wasserreserven (als Reaktion auf die Energieversorgungskrise) zu liefern.

Punti salienti

I principali punti salienti (risultati, sfide, lezioni apprese, ecc.) durante il periodo di riferimento sono stati:

- Lo sviluppo di una metodologia per creare da quattro a sei scenari basati su due dimensioni (integrazione e politica del sistema energetico e sviluppo tecnologico) e due varianti (moderata e progressiva).
- Identificare argomenti di sintesi a livello di progetto da utilizzare come studi pilota per il motore PATHFNDR.
- Il collegamento tra il modello Euro-Calliope (che fornisce previsioni sugli sviluppi europei verso il net zero) e il modello Nexus-e (un modello dettagliato incentrato sugli sviluppi svizzeri).
- Lo sviluppo di algoritmi per la programmazione della ricarica dei veicoli elettrici, la stima del carico elettrico e la previsione del carico termico, nonché la loro validazione con dati di misura reali.
- La generazione di un elenco di tecnologie che consentono l'accoppiamento dei settori e migliorano la flessibilità, classificandole in tre pilastri: termico, elettrico e del gas.
- Lo sviluppo di un modello ad alta fedeltà per l'accumulo di energia basato sull'idrogeno e la valutazione dell'accumulo stagionale di energia termica.
- L'analisi di cinque strategie di decarbonizzazione (efficienza energetica, elettrificazione, combustibili a basso contenuto di carbonio, rimozione della CO2 e cambiamenti radicali della domanda).
- Lo sviluppo di un quadro di riferimento per confrontare le strategie politiche a lungo termine per la decarbonizzazione profonda tra Svizzera, UE, Regno Unito e Norvegia.
- La presentazione e l'approvazione di un progetto pilota e dimostrativo (P&D) sulle tariffe di rete dinamiche. Il primo P&D SWEET è stato premiato.
- Il lancio di un'iniziativa di sfida energetica per fornire prove scientifiche sui mercati energetici, l'indipendenza energetica, lo stoccaggio stagionale del calore e le riserve idroelettriche (in risposta alla crisi dell'approvvigionamento energetico).

1 Highlights of the reporting period

PATHFNDR is a project that aims to develop and analyse transition pathways for renewable energy integration in Switzerland. The pathways will help to reach the net zero target and to exploit the potential of flexibility and sector coupling. To achieve these goals, a PATHFNDR machine will be created, by integrating multiple disciplines and stakeholder perspective to generate feasible pathways, planning and operational tools, pilot and demonstration projects, new business opportunities and innovation strategies, and potential policies.

During the reporting period, a major task was the coordination of wide range of perspectives that shape the PATHFNDR machine: from technical and socio-economic research activities to local, national, and European scales. The machine will be developed in several phases throughout the project. In the first phase, we consolidated the technical interfaces. The key concepts and metrics for sector coupling and flexibility have been defined, the dimensions and variables of scenarios have been identified, and a set of technologies from different sectors have been selected for in-depth analysis. In the second phase, we plan to consolidate the socio-economic interfaces. Policies and business strategies will be identified, providing new insights for selecting technologies, use cases, and scenario dimensions/variables.

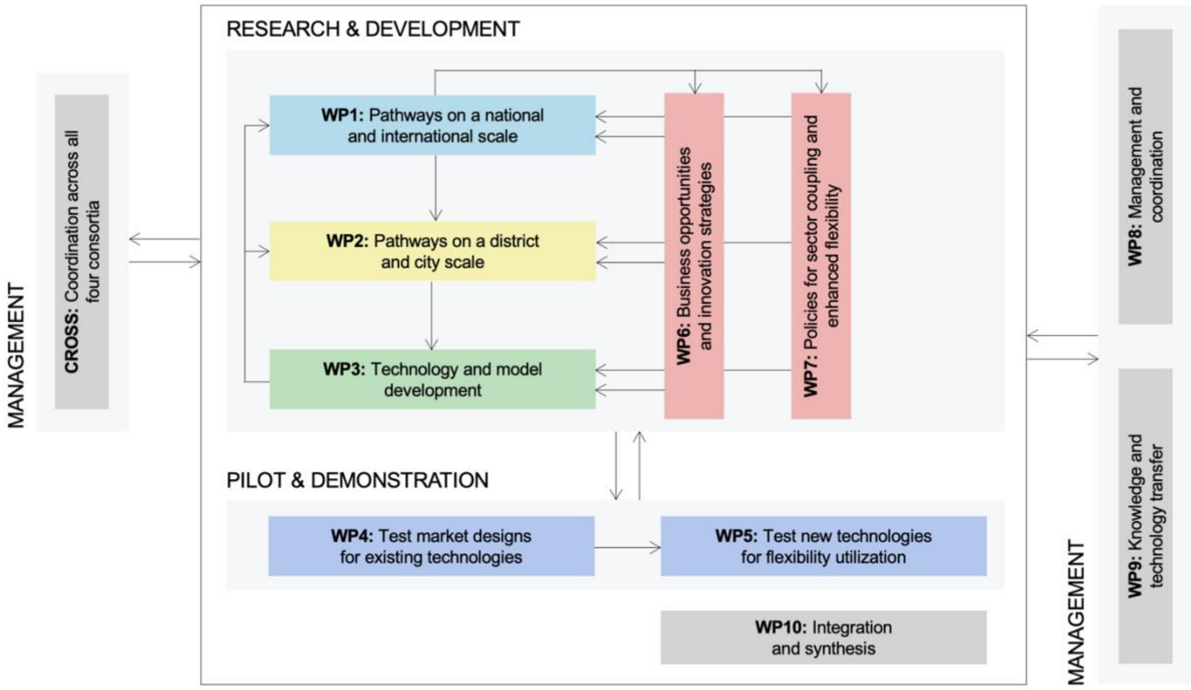

Figure 1: Relationship between work packages © PATHFNDR 2021

The first work package (WP1) dealing with pathways at national and European scale, has developed a methodology to create scenarios based on two dimensions: energy system integration and policy, and technological development, and two variants: moderate and progressive (figure 2). The scenarios are aligned with the other WPs to allow for a consistent project-wide setup. In preparation of the scenario assessment, the Euro-Calliope model, which provides predicted European developments towards net zero, was linked with the Nexus-e model, a detailed model focusing on Swiss developments towards net zero. Also, the EXPANSE model was extended to include electric vehicles at municipal scale.

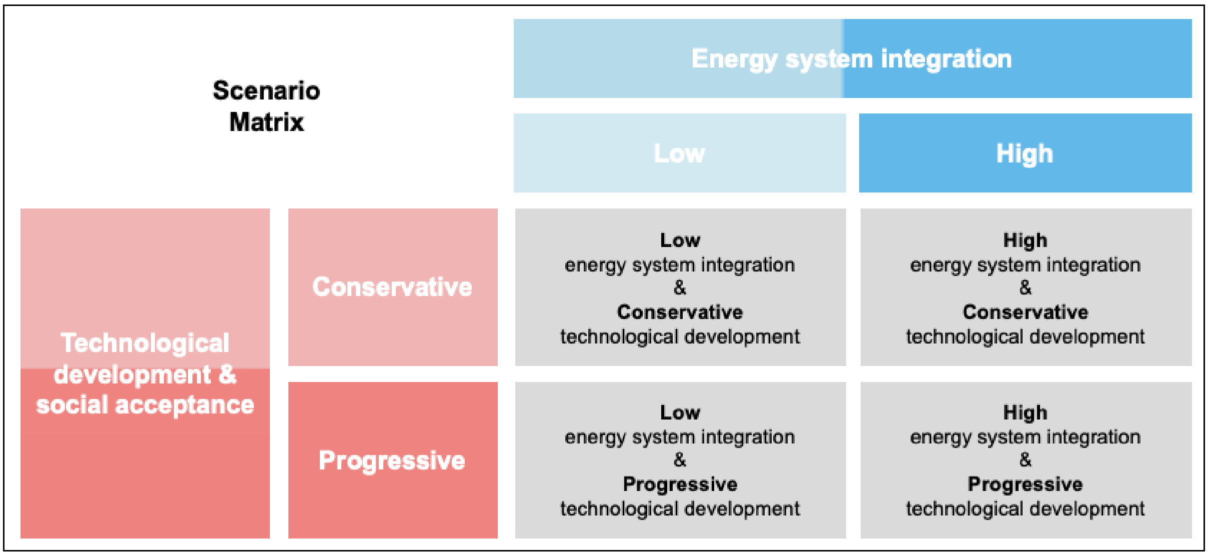

Figure 2: Scenario Matrix © PATHFNDR 2022

The second WP (WP2), addressing pathways at local scale, has developed various algorithms. An algorithm for EV charging scheduling was generated to provide demand-side flexibility, and a cost-benefit analysis was conducted for providing flexibility for specific uses-cases. An algorithm for estimating the electricity load, and an algorithm for predicting the heat load, both based on building properties, was also developed, and validated with real-world measurement data.

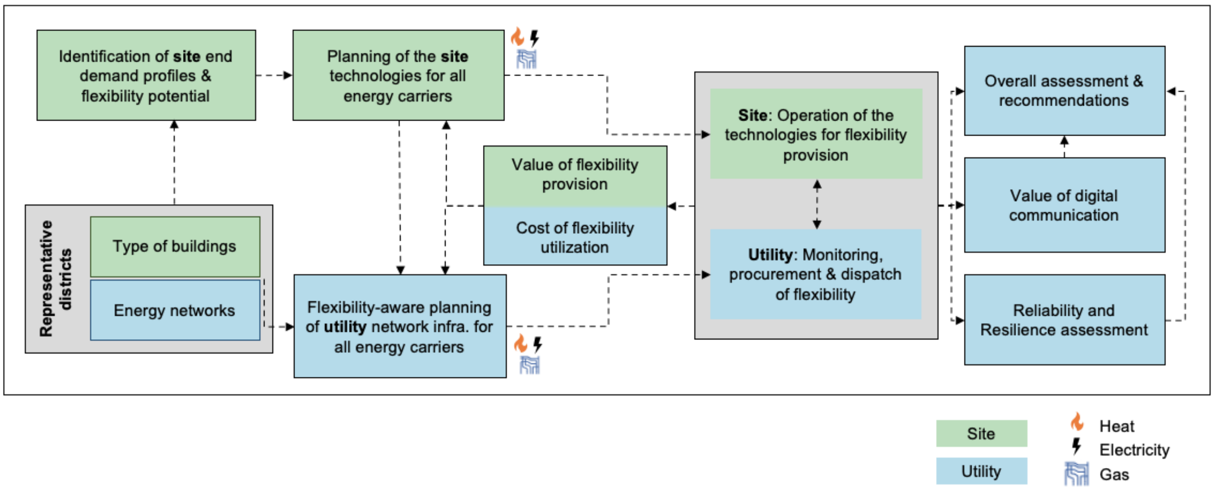

Figure 3: Diagram of the workplan of WP2 © PATHFNDR 2022

The third WP (WP3), focusing on technology and model development, has generated a map of technologies that enable sector coupling and enhances flexibility, categorizing them into three pillars: thermal, electrical and gas (figure 4). On the technology-specific side, a high-fidelity model for hydrogen-based energy storage was developed, and seasonal thermal energy storage was evaluated. Methods for grid-aware operation and planning of active distribution networks to maximize the use of flexibility were also developed and validated with the EPFL Smart Grid Demonstrator.

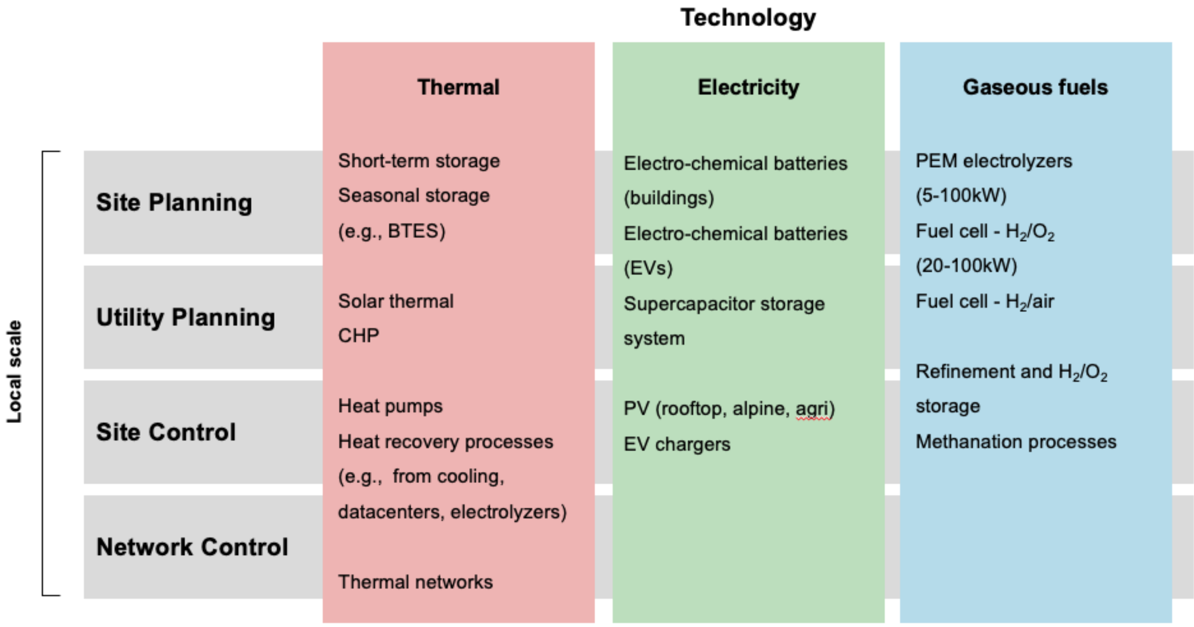

Figure 4: Map of technologies categorized in three pillars © PATHFNDR 2022

The sixth WP (WP6), assessing business opportunities and innovation strategies, identified five decarbonization strategies (i.e., energy efficiency, electrification, low-carbon fuels, CO2 removal and radical demand side changes) and analysed their strengths, weaknesses, and associated policy challenges. Eight technologies to enhance flexibility were also identified, including centralized options (i.e., transmission grid expansion, distribution grid expansion, hydropower, gas, power-to-x) and decentralized options (batteries, demand side management, renewables, co-generation).

The seventh WP (WP7), dealing with policies, has developed a framework to compare long-term policy strategies for deep decarbonization comparing Switzerland, EU, UK and Norway. The framework looks at policy rationale, targets, instruments, and direction as well as actors, and governance level.

The tenth WP (WP10), responsible for the integration and synthesis of the overall project results, has defined and described the concepts of flexibility and sector coupling, as well as their corresponding metrics to systematically evaluate the scenario results. In parallel, scenario dimensions and the corresponding variables were identified, as well as an approach to scenario building was developed. Finally, a pilot and demonstration (P&D) project on dynamic network tariffs was submitted and approved by the SFOE. The P&D will start in first quarter of 2023.

In terms of knowledge and technology transfer (KTT), internal and external communication and dissemination channels were established. Regular exchange meetings between the different WPs were set up to jointly define scenario dimensions, integrate the policy dimension, and identify the required input/output data. Also, monthly seminars were introduced to strengthen exchanges and collaboration among senior and junior researchers.

Figure 5: Annual PATHFNDR workshop 2022 © PATHFNDR 2022

The annual two-day PATHDNDR workshop with academic and industry partners was held to discuss the impact of import/export limitations, the role of hydrogen, regulations for flexibility use, and opportunities of sector coupling in the power sector (figure 5). Furthermore, meetings with cooperation partners (CPs) were conducted on the topic of multi-energy systems at local scale. Finally, in response to the energy supply crisis, an energy challenge initiative was launched to provide science-based evidence on energy markets, energy independency, seasonal heat storage, and hydro reserves.

2 Outputs of the reporting period

Peer-reviewed publications

Author(s), title, journal name, year	doi / link	Open access
Baader, F. J., Althaus, P., Bardow, A., & Dahmen, M. (2022). **Dynamic ramping for demand response of processes and energy systems based on exact linearization.** *Journal of Process Control*, *118*, 218-230.	**https://arxiv.org/pdf/2110.08137.pdf**	Open access guaranteed
Leenders, L., Hagedorn, D. F., Djelassi, H., Bardow, A., & Mitsos, A. (2023). **Bilevel optimization for joint scheduling of production and energy systems.** *Optimization and engineering*, *24*(1), 499-537.	**10.1007/s11081-021-09694-0**	Open access guaranteed
Reinert, C., Nolzen, N., Frohmann, J., Tillmanns, D. & Bardow, A. (2023). **Design of low-carbon multi-energy systems in the SecMOD framework by combining MILP optimization and life-cycle assessment**. *Computer & Chemical Engineering, 172*, 108176.	**10.1016/j.compchemeng.2023.108176**	Open access guaranteed
Baader, F. J., Althaus, P., Bardow, A., & Dahmen, M. (2023). **Demand response for flat nonlinear MIMO processes using dynamic ramping constraints.** *Computers & Chemical Engineering*, *172*, 108171.	**10.1016/j.compchemeng.2023.108171**	Open access guaranteed
Lienhard, N., Mutschler, R., Leenders, L., & Rüdisüli, M. (2023). **Concurrent deficit and surplus situations in the future renewable Swiss and European electricity system.** *Energy Strategy Reviews*, *46*, 101036.	**10.1016/j.esr.2022.101036**	Open access guaranteed
Rosa, L., Becattini, V., Gabrielli, P., Andreotti, A., & Mazzotti, M. (2022). **Carbon dioxide mineralization in recycled concrete aggregates can contribute immediately to carbon-neutrality.** *Resources, Conservation and Recycling*, *184*, 106436.	**10.1016/j.resconrec.2022.106436**	Open access guaranteed
Stankovski, A., Gjorgiev, B., & Sansavini, G. (2022). **Multi-zonal method for cascading failure analyses in large interconnected power systems.** *IET Generation, Transmission & Distribution*, *16*(20), 4040-4053.	**10.1049/gtd2.12565**	Open access guaranteed
Ohlendorf, N., Löhr, M., & Markard, J. (2023). **Actors in multi-sector transitions-discourse analysis on hydrogen in Germany.** *Environmental Innovation and Societal Transitions*, *47*, 100692.	**10.1016/j.eist.2023.100692**	Open access from 2024
Andersen, A. D., Markard, J., Bauknecht, D., & Korpås, M. (2023). **Architectural change in accelerating transitions: Actor preferences, system architectures, and flexibility technologies in the German energy transition.** *Energy Research & Social Science*, *97*, 102945.	**10.1016/j.erss.2023.102945**	Open access guaranteed

Markard, J., Isoaho, K., & Widdel, L. (2023). **Discourses around decline: Comparing the debates on coal phase-out in the UK, Germany and Finland.** *Technologies in Decline: Socio-technical approaches to discontinuation and destabilization.* 119-144.	**10.4324/9781003213642**	Open access guaranteed

Policy briefs, white papers

Author(s), title, channel or type of publication, year
Schlecht, I., Darudi, A., Hintermann, B., Schäfers, S. (2022). **Gas crisis: Tradable gas usage certificates to bring down price.** Policy brief. **https://www.zhaw.ch/storage/sml/institute-zentren/cee/PolicyBrief_GasPermits.pdf**
Schlecht, I., Savelsberg, J. (2022). **Wasserkraftreserve mittels handelbarer Verpflichtungen.** **https://www.zhaw.ch/de/sml/institute-zentren/cee/newsdetail/event-news/speicherreserve/**

Other non-peer-reviewed publications (working papers, press articles, etc.)

Author(s), title, channel or type of publication, year
Vivian, J., Heer, P., Fiorentini, M. (2023). **Optimal sizing and operation of long term ice thermal storage systems.** under review at *Applied Energy.*
Fochesato, M., Peter, C., Morandi, L. (2023). **Stochastic peak shaving for an EV charging station with a hydrogen based energy storage facility.** to be submitted to *IEEE Transactions on Smart Grid.*
Ehrhart, K.-M., Schlecht, I., Wang, R. (2022). **Price cap versus tariffs: The case of the EU-Russia gas market.** EconStor. **hdl.handle.net/10419/261834**
Ehrhart, K.-M., Schlecht, I. (2022). I**ntroducing a price cap on Russian gas: A game theoretic analysis**. EconStor. **hdl.handle.net/10419/261345**
Shu, D., Reinert, C., Mannhardt, J., Leenders, L., Lüthje, J. T., Mitsos, A., Bardow, A. (2023). **Bilevel Optimization of Energy System Transition Pathways considering Competition in Markets**. FOCAPO/CPC conference.
Baader. F., Bardow, A., Dahmen, M. (2023). **Heuristic Dynamic Ramping Constraints for Demand Response of Processes with Internal Dynamics.** FOCAPO/CPC conference.
Reinert, C., Nilges, B,, Baumgärtner, N., Bardow, A. (2023). **This is SpArta: Rigorous Optimization of Regionally Resolved Energy Systems by Spatial Aggregation and Decomposition.** arXiv:2302.05222.
Mayer, P., Leenders, L., Shu, D., Winter, B., Zibunas, C., Reinert, C., Bardow, A. (2022). **Transition Paths Towards a CO2-Based Chemical Industry Within a Sector-Coupled Energy System.** ESCPAE conference
Nolzen, N., Ganter, A., Baumgärtner, N., Leenders L., Bardow, A.. (2022). **Where to Market Flexibility? Optimal Participation of Industrial Energy Systems in Balancing-Power, Day-Ahead, and Continuous Intraday Electricity Markets.** arXiv:2212.12507.
Evrenosoglu, C.Y., Fuchs, A., Demiray, T. (2022). **Flexibilität: Warum, für wen und wie? - Flexibilität zwischen Netzebenen**, VSE Bulletin.
N.A. (2022). **Machine Learning für die Jagd nach Ölheizungen.** myScience / Schweizer Forschung/Innovation. 12.10.2022. N.A. (2022). **Machine Learning für die Jagd nach Ölheizungen.** innerschweizonline.ch / Innerschweiz Online. 12.10.2022. N.A. (2022). **Machine Learning für die Jagd nach Ölheizungen.** cetoday.ch / CE today Online. 13.10.2022.

N.A. (2022). **Machine Learning für die Jagd nach Ölheizungen.** netzwoche.ch / Netzwoche Online. 13.10.2022.
N.A. (2022). **Die Jagd nach Ölheizungen,** Surseer Woche.20.10.2022. N.A. (2022). **Jagd nach Ölheizungen.** Phase 5. 14.12.2022
Nussbaumer, L. (2022). **So wird im Kanton Luzern geheizt – und wie es ökologischer ginge.** zugerzeitung.ch / Zuger Zeitung Online. 29.10.2022.
Nussbaumer, L. (2022). **So wird im Kanton Luzern geheizt – und wie es ökologischer ginge**. urnerzeitung.ch / Urner Zeitung Online. 29.10.2022. Nussbaumer, L. (2022). **So wird im Kanton Luzern geheizt – und wie es ökologischer ginge.** bote.ch / Bote der Urschweiz Online. 29.10.2022.
Nussbaumer, L. (2022). **So heizen Luzern und die Schweiz.** Schweiz am Wochenende / Luzerner Zeitung. 29.10.2022.
Müller, L., Markard, J. (2022). **Net-zero policies: A procedure and four case studies.** EU-SPRI Conference June 1, Utrecht, conference paper.
Ruefenacht, L. A., Bardow, A., Schaffner, C., (2022). **Pfade in die klimaneutrale Energiezukunft**, Forum Raumentwicklung, Article.

Invited talks (scientific or broad audience)

Presenter(s), title, name of the event and location, year
Schlecht, I. (19.9.2022). **Handelbare Gasnutzungsrechte zur Senkung der europäischen Gaspreise.** on invitation, Energieökom:innen-Runde zur Energiekrise am Bundesministerium für Wirtschaft und Klimaschutz, Berlin. **https://twitter.com/BMWK_Econ/status/1572235906647556096**
Ingmar Schlecht, I. (10.11.2022). **Cap-and-trade markets to bring down gas prices in Europe.** Chief Economist Lunch, on invitation, DG ENER, European Commission, Brussels/virtual.
Garrison, J., Rüdisüli, M., Sanvito, F. (2023). **Model comparison between five different energy system models**. Presented at CROSS Final Conference: From SWEET CROSS to Co-evolution. **https://sweet-cross.ch/cross-to-co-evolution/**
Koirala, B. (1.12.2022). **Flexibility assessment of multi-energy districts, Technology Briefing: Photovoltaics – Technologies, integration and implications,** Empa, Dübendorf.
Koirala, B. (2022). **Prospects of the digital twin in planning urban energy systems**, BRENET status seminar, 7-8 September 2022, Aarau.
Koirala, B. (2022). **Digital twin of energy systems,** ERA-NET Digicities kick-off meeting, 24 May 2022, Lugano.
Fuchs, A., Evrenosoglu, C.Y. (2022). **Nutzung der dezentralen Flexibiltät zur Optimierung vom Verteilnetz mit WP, PV und Ladestationen,** VSE-Veranstaltung: Fachtagung Netzwirtschaft, November 23, 2022.
Demiray, T. (2022). **Die Rolle von Flexibilität, VSGS Veranstaltung: Garantieren Flexibilitäten die Versorgungssicherheit?**, November 8, 2022.
Demiray, T. (2022). **Die Bedeutung von Flexibilität und zunehmender Digitalisierung für die Energieversorgung im Jahr 2050**. Fachtagung NetzImpuls, March 23, 2022.
Markard, J. (2023). **Transition pathways to net-zero: Comparing different strategies**. Invited Talk, Tokyo University JP (online)
Markard, J. (2023). **Sustainability Transitions: Analyzing controversies in public discourses.** Invited Talk, Université de Montpellier FR, virtual.
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Brief description
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