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

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Executive summary

Switzerland's energy transition aims to achieve net-zero greenhouse gas emissions and a resilient, reliable energy system by 2050. This transformation requires changes like the electrification of the heating and transport sector, and the addition and integration of renewable energy sources via local-wide and system-wide flexibility. The PATHFNDR consortium, supported by the SWEET programme, supports these goals by conducting interdisciplinary research, collaborating with stakeholders from the public and private sectors, and testing innovative approaches in real-world settings.

PATHFNDR's overarching objective is to support Switzerland's energy system transition by enabling renewable energy integration, sector coupling, and flexibility. This is achieved through: (i) exploring future scenarios and transition pathways, (ii) developing infrastructure planning strategies at the local level, (iii) assessing key technologies, (iv) identifying business opportunities and implementation strategies, and (v) evaluating regulatory frameworks, market mechanisms, and social acceptance. The consortium's approach combines multi-scale energy system modelling, techno-economic studies, experimental validation, and policy analysis. Modelling work spans from integrated national and European energy systems down to local infrastructures. Experimental activities validate concepts in real-world settings, such as community-based smart heat pump control and dynamic network tariffs. Meanwhile, business and policy studies aim to align Swiss regulatory frameworks and market structures with emerging flexibility and sector coupling needs.

A key achievement was the identification of flexibility potential from electric vehicles and heat pumps. These technologies can contribute to balance supply and demand, reduce renewable curtailment, and lower system costs and electricity prices. Research highlights include the demonstrated value of smart electric vehicle charging and vehicle-to-grid technologies for grid stability and renewable integration. Heat pumps also show potential for shifting heating loads through building thermal inertia and coordinated community-level operation, as validated in the Nanoverbund pilot and demonstration project. Policy and market analyses further highlighted the need for updated tariffs, regulatory reforms, and consumer acceptance measures to fully unlock this flexibility potential. These findings were presented in a synthesis report. Additional achievements from this reporting period, along with future findings, will be synthesised in upcoming synthesis reports to provide consolidated insights.

Industry collaboration has been instrumental in bringing these concepts to application. Two key examples are the NeDeLa and the Nanoverbund pilot and demonstration projects. The NeDeLa project, developed in collaboration with Groupe E, implemented dynamic network tariffs and conducted field trials with residential customers, demonstrating how dynamic pricing can incentivize flexible electricity use and reduce peak demand. The Nanoverbund project, together with IWB, tested the automation system of the prosumer community with a shared thermal network, showing the potential to replace fossil fuel-based heating with renewable alternatives and energy flexibility. Both projects were awarded with the 2025 Watt d'Or energy prize recognizing their excellence in energy innovation. The engagement of policymakers is also central to PATHFNDR's strategy. In addition to targeted consultations, the first PATHFNDR conference brought together over 100 participants from government, academia, and industry to discuss the future of flexibility and sector coupling in Switzerland. These efforts ensure that research findings inform policymaking and market developments.

Looking ahead, PATHFNDR will continue to integrate and synthesise research findings across disciplines to deliver cohesive, evidence-based recommendations for policymakers and industry. This work ensures that scientific insights are translated into actionable strategies for Switzerland's energy transition.

Zusammenfassung

Die Schweizer Energiewende verfolgt das Ziel, bis 2050 Netto-Null-Treibhausgasemissionen zu erreichen und ein resilientes, zuverlässiges Energiesystem zu schaffen. Diese Transformation erfordert unter anderem die Elektrifizierung der Wärme- und Verkehrssektoren sowie den Ausbau und die Integration erneuerbarer Energiequellen durch Flexibilität auf lokaler und systemweiter Ebene. Das PATHFNDR-Konsortium, gefördert vom SWEET-Programms, unterstützt diese Ziele durch interdisziplinäre Forschung, Zusammenarbeit mit Akteuren aus dem öffentlichen und privaten Sektor sowie das Testen innovativer Ansätze in realen Anwendungskontexten.

Das übergeordnete Ziel von PATHFNDR ist es, die Schweizer Energiesystem-Transformation durch Integration erneuerbarer Energien, Sektorkopplung und Flexibilität zu unterstützen. Dies geschieht durch: (i) die Untersuchung von Zukunftsszenarien und Transformationspfaden, (ii) die Entwicklung von Infrastrukturplanungsstrategien auf lokaler Ebene, (iii) die Bewertung zentraler Technologien, (iv) die Identifikation von Geschäftsmodellen und Umsetzungsstrategien sowie (v) die Analyse regulatorischer Rahmenbedingungen, Marktmechanismen und gesellschaftlicher Akzeptanz. Der Ansatz des Konsortiums vereint multiskalige Energiesystemmodellierung, techno-ökonomische Analysen, experimentelle Validierung und Politikanalyse. Die Modellierungen reichen von integrierten nationalen und europäischen Energiesystemen bis hin zu lokalen Infrastrukturen. Experimentelle Aktivitäten validieren Konzepte unter realen Bedingungen, etwa die gemeinschaftsbasierte Steuerung von Wärmepumpen oder dynamische Netztarife. Parallel dazu zielen wirtschaftliche und politische Analysen darauf ab, die regulatorischen Rahmenbedingungen und Marktstrukturen der Schweiz an die wachsenden Anforderungen von Flexibilität und Sektorkopplung anzupassen.

Ein zentrales Ergebnis war die Identifikation des Flexibilitätspotenzials von Elektrofahrzeugen und Wärmepumpen. Diese Technologien können dazu beitragen, Angebot und Nachfrage im Stromsystem auszugleichen, Abregelungen erneuerbarer Energien zu reduzieren sowie Systemkosten und Strompreise zu senken. Die Forschungsergebnisse zeigen unter anderem den Mehrwert intelligenter Ladeinfrastrukturen sowie Vehicle-to-Grid-Technologien für Netzstabilität und Integration erneuerbarer Energien. Auch Wärmepumpen zeigen ein grosses Potenzial zur Lastverschiebung durch die thermische Trägheit von Gebäuden und eine koordinierte Steuerung auf Quartiersebene, wie im Pilot- und Demonstrationsprojekt Nanoverbund erfolgreich validiert wurde. Politikanalysen unterstreichen die Notwendigkeit neuer Tarifmodelle, regulatorischer Reformen und gesellschaftlicher Akzeptanzmassnahmen, um dieses Potenzial vollständig auszuschöpfen. Diese Ergebnisse wurden in einem Synthesebericht zusammengefasst. Weitere Erkenntnisse aus diesem Berichtsjahr sowie zukünftige Ergebnisse werden in kommenden Syntheseberichten integriert, um konsolidierte Handlungsempfehlungen abzuleiten.

Die Zusammenarbeit mit der Industrie war entscheidend, um diese Konzepte in die Praxis zu überführen. Zwei zentrale Beispiele dafür sind die Pilot- und Demonstrationsprojekte NeDeLa und Nanoverbund. Das NeDeLa-Projekt, in Zusammenarbeit mit Groupe E entwickelt, implementierte dynamische Netztarife und führte Feldversuche mit Haushaltskunden durch. Dabei wurde gezeigt, wie dynamische Preisgestaltung flexible Stromnutzung fördern und Lastspitzen reduzieren kann. Im Nanoverbund-Projekt, gemeinsam mit IWB realisiert, testete das Automatisierungssystem einer Prosumenten-Gemeinschaft mit einem gemeinsamen Wärmenetz. Ergebnisse zeigen das Potenzial, fossile Heizsysteme durch erneuerbare Alternativen zu ersetzen und gleichzeitig Energieflexibilität zu ermöglichen. Beide Projekte wurden mit dem Watt d'Or 2025 ausgezeichnet, der für herausragende Leistungen im Bereich Energieinnovation verliehen wird. Auch die Einbindung politischer Entscheidungsträger ist ein zentraler Bestandteil der PATHFNDR-Strategie. Neben gezielten Konsultationen brachte die erste PATHFNDR-Konferenz über 100 Vertreter*innen aus Politik, Wissenschaft und Industrie zusammen, um über die Zukunft von Flexibilität und Sektorkopplung in der Schweiz zu diskutieren. Diese Aktivitäten stellen sicher, dass Forschungsergebnisse in die politische Entscheidungsfindung und die Marktentwicklung einfliessen.

Mit Blick in die Zukunft wird PATHFNDR weiterhin disziplinübergreifend Forschungsergebnisse integrieren und synthetisieren, um kohärente, evidenzbasierte Empfehlungen für Entscheidungsträger in Politik und Industrie bereitzustellen. Damit wird sichergestellt, dass wissenschaftliche Erkenntnisse in umsetzbare Strategien für die Schweizer Energiewende überführt werden.

Résumé

La transition énergétique de la Suisse vise à atteindre la neutralité carbone et un système énergétique résilient et fiable d'ici 2050. Cette transformation nécessite, entre autres, l'électrification des secteurs du chauffage et des transports, ainsi que l'ajout et l'intégration de sources d'énergie renouvelable grâce à une flexibilité à l'échelle locale et nationale. Le consortium PATHFNDR, soutenu par le programme SWEET, soutient ces objectifs en menant des recherches interdisciplinaires, en collaborant avec des acteurs publics et privés, et en testant des approches innovantes dans des contextes réels.

L'objectif principal de PATHFNDR est d'accompagner la transition énergétique de la Suisse en facilitant l'intégration des énergies renouvelables, le couplage sectoriel et la flexibilité. Cela passe par : (i) l'exploration de scénarios futurs et de trajectoires de transition, (ii) le développement de stratégies de planification des infrastructures au niveau local, (iii) l'évaluation de technologies clés, (iv) l'identification d'opportunités commerciales et de stratégies de mise en œuvre, et (v) l'analyse des cadres réglementaires, des mécanismes de marché et de l'acceptation sociale. L'approche du consortium combine modélisation énergétique multi-échelle, études technico-économiques, validation expérimentale et analyse des politiques. La modélisation couvre les systèmes énergétiques nationaux et européens jusqu'aux infrastructures locales. Les activités expérimentales valident des concepts dans des environnements réels, tels que le contrôle intelligent des pompes à chaleur à l'échelle communautaire et les tarifs dynamiques. Parallèlement, les études commerciales et politiques visent à aligner les cadres réglementaires suisses et les structures de marché avec les besoins émergents en matière de flexibilité et de couplage sectoriel.

Une réalisation clé a été l'identification du potentiel de flexibilité des véhicules électriques et des pompes à chaleur. Ces technologies peuvent contribuer à équilibrer l'offre et la demande, à réduire les pertes liées à la surproduction des énergies renouvelables, et à diminuer les coûts du système ainsi que les prix de l'électricité. Les résultats notables incluent la valeur démontrée de la recharge intelligente des véhicules électriques et des technologies véhicule-réseau pour la stabilité du réseau et l'intégration des renouvelables. Les pompes à chaleur présentent également un potentiel pour décaler les moments de chauffage grâce à l'inertie thermique des bâtiments et à des opérations coordonnées à l'échelle communautaire, comme démontré dans le projet pilote Nanoverbund. Les analyses politiques et de marché ont également souligné la nécessité de réformes tarifaires, réglementaires, et de mesures d'acceptation par les consommateurs pour libérer pleinement ce potentiel de flexibilité. Ces résultats ont été présentés dans un rapport de synthèse. D'autres résultats obtenus pendant cette période de suivi, ainsi que les résultats futurs, seront intégrés dans les prochains rapports de synthèse afin de fournir des recommandations consolidées.

La collaboration avec l'industrie a joué un rôle essentiel dans la mise en application de ces concepts. Deux exemples clés sont les projets pilotes NeDeLa et Nanoverbund. Le projet NeDeLa, développé en collaboration avec Groupe E, a mis en œuvre des tarifs dynamiques et mené des tests sur le terrain avec des clients résidentiels, démontrant comment une tarification dynamique peut encourager une utilisation flexible de l'électricité et réduire les pics de demande. Le projet Nanoverbund, en collaboration avec IWB, a testé le système d'automatisation d'une communauté de prosommateurs dotée d'un réseau thermique partagé, démontrant le potentiel de remplacement du chauffage à base d'énergies fossiles par des alternatives renouvelables et une flexibilité énergétique accrue. Les deux projets ont été récompensés par le prix de l'énergie Watt d'Or 2025, saluant leur excellence en innovation énergétique. L'implication des décideurs politiques est également au cœur de la stratégie de PATHFNDR. Outre des consultations ciblées, la première conférence PATHFNDR a réuni plus de 100 participants issus du gouvernement, du monde académique et de l'industrie pour discuter de l'avenir de la flexibilité et du couplage sectoriel en Suisse. Ces efforts garantissent que les résultats de la recherche influencent les politiques publiques et les évolutions du marché.

À l’avenir, PATHFNDR continuera à intégrer et à synthétiser les résultats de recherche issus de différentes disciplines afin de fournir des recommandations cohérentes et fondées sur des données probantes à destination des décideurs publics et des acteurs industriels. Ce travail garantit que les connaissances scientifiques sont traduites en stratégies concrètes au service de la transition énergétique suisse.

Riassunto

La transizione energetica della Svizzera mira a raggiungere la neutralità climatica entro il 2050, costruendo un sistema energetico resiliente e affidabile. Questa trasformazione richiede l'elettrificazione dei settori del riscaldamento e dei trasporti, nonché l'integrazione di fonti rinnovabili attraverso soluzioni di flessibilità sia a livello locale che di sistema. Il consorzio PATHFNDR, sostenuto dal programma SWEET, sostiene questi obiettivi attraverso la ricerca interdisciplinare, la collaborazione con attori pubblici e privati e la sperimentazione di approcci innovativi in contesti reali.

L'obiettivo generale di PATHFNDR è supportare la transizione del sistema energetico svizzero abilitando l'integrazione delle energie rinnovabili, il sector coupling (accoppiamento settoriale) e la flessibilità. Questo viene realizzato tramite: (i) lo studio di scenari futuri e percorsi di transizione, (ii) lo sviluppo di strategie di pianificazione infrastrutturale a livello locale, (iii) la valutazione di tecnologie chiave, (iv) l'identificazione di opportunità di business e strategie di implementazione, e (v) l'analisi dei quadri normativi, dei meccanismi di mercato e dell'accettazione sociale. Il consorzio adotta un approccio che combina modellazione energetica multi-scala, analisi tecnico-economiche, validazione sperimentale e analisi delle politiche. La modellazione copre sistemi energetici a livello europeo, nazionale e locale. Le attività sperimentali includono test su soluzioni come il controllo intelligente delle pompe di calore e le tariffe dinamiche. Parallelamente, gli studi politici ed economici mirano ad allineare i quadri normativi svizzeri con le esigenze emergenti legate alla flessibilità e al sector coupling (accoppiamento settoriale).

Un risultato chiave è stata l'identificazione del potenziale di flessibilità offerto da veicoli elettrici e pompe di calore. Queste tecnologie possono contribuire all'equilibrio tra domanda e offerta, alla riduzione delle perdite di energie rinnovabili e alla diminuzione dei costi di sistema e dei prezzi dell'elettricità. Tra i risultati principali vi sono il valore dimostrato della ricarica intelligente dei veicoli elettrici e delle tecnologie vehicle-to-grid per la stabilità della rete e l'integrazione delle rinnovabili. Le pompe di calore mostrano inoltre un potenziale di spostamento dei carichi termici grazie all'inerzia termica degli edifici e al funzionamento coordinato a livello di comunità, come dimostrato nel progetto pilota Nanoverbund. Le analisi delle politiche e dei mercati evidenziano la necessità di riforme tariffarie, aggiornamenti normativi e misure per favorire l'accettazione da parte dei consumatori. I risultati sono stati presentati in un rapporto di sintesi. Ulteriori risultati di questo periodo, insieme a quelli futuri, saranno integrati nei prossimi rapporti di sintesi per offrire raccomandazioni consolidate.

La collaborazione con l'industria è stata fondamentale per l'applicazione pratica di questi concetti. Due esempi significativi sono i progetti pilota NeDeLa e Nanoverbund. Il progetto NeDeLa, sviluppato in collaborazione con Groupe E, ha introdotto tariffe dinamiche e testato sul campo comportamenti di consumo flessibile presso clienti residenziali, dimostrando come le tariffe dinamiche possano incoraggiare un utilizzo flessibile dell'elettricità e ridurre i picchi di domanda. Il progetto Nanoverbund, in collaborazione con IWB, ha testato il sistema di automazione di una comunità di prosumer con una rete termica condivisa, dimostrando il potenziale per sostituire il riscaldamento a combustibili fossili con alternative rinnovabili e soluzioni di flessibilità energetica. Entrambi i progetti sono stati premiati con il Watt d'Or 2025 per l'eccellenza nell'innovazione energetica. Anche il coinvolgimento dei decisori politici è al centro della strategia PATHFNDR. Oltre a consultazioni mirate, la prima conferenza PATHFNDR ha riunito oltre 100 partecipanti da enti governativi, accademia e industria per discutere il futuro della flessibilità e del sector coupling (accoppiamento settoriale) in Svizzera. Questi sforzi garantiscono che i risultati della ricerca informino le politiche pubbliche e lo sviluppo del mercato.

Guardando al futuro, PATHFNDR continuerà a integrare e sintetizzare i risultati della ricerca in raccomandazioni chiare e basate su evidenze per decisori pubblici e attori industriali, assicurando che le conoscenze scientifiche si traducano in strategie operative per la transizione energetica svizzera.

1 Work programme overview

Switzerland's energy transition envisions a net-zero greenhouse gas emissions target and a resilient, reliable energy system by 2050. Reaching this goal requires changes like the electrification of the heating and transport sector, as well as the addition and integration of renewable energy sources alongside demand-side flexibility across all parts of the energy system. Achieving this transformation in the Swiss context presents specific challenges: limited domestic renewable resources, a highly distributed infrastructures, regulatory complexity, and the need for broad public engagement.

The PATHFNDR consortium addresses these challenges by pursuing an energy system that is efficient, flexible, resilient, cost-competitive, and sustainable by 2050. Its main objective is to enable the integration of renewable energy by identifying flexibility options, advancing sector coupling solutions, and developing supportive business models, regulatory frameworks, and social acceptance measures. To achieve this, PATHFNDR is organized as an integrated, interdisciplinary "PATHFNDR machine" – a coordinated system where different disciplines (i.e., energy modelling, engineering, economics, social sciences) represent a vital component contributing to the shared goal (*Figure 1*).

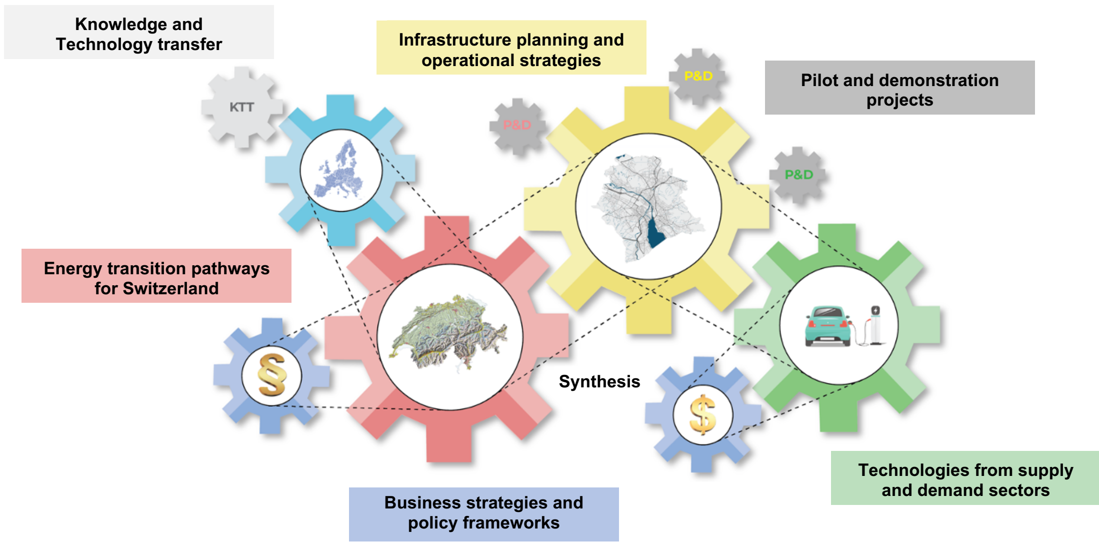

Figure 1: The "PATHFNDR machine" with the focus areas

The work programme is structured around the following focus areas: (i) Development of multi-scale **energy transition scenarios and pathways** for Switzerland, (ii) **Infrastructure planning and operational strategies** for distributed multi-energy systems, (iii) Assessment of key **flexibility-enabling technologies**, (iv) Exploration of **business models and innovation strategies**, (v) Evaluation of **policy and regulatory frameworks**, (vi) A **synthesis stream** to integrate findings into actionable, stakeholder-oriented recommendations, and (vii) **Pilot and demonstration projects** to test flexibility and sector coupling solutions.

The consortium is composed of eight leading research institutions – ETH Zurich, Empa, PSI, ZHAW, HSLU, UNIGE, EPFL, and TU Delft – and is supported by 26 cooperation partners from Swiss industry and associations. This diverse and interdisciplinary partnership bridges scientific and practical expertise across the energy sector and enables direct collaboration with stakeholders from the public and private sectors. Through pilot and demonstration projects (P+D), and targeted consultations, the consortium tests solutions in real-world contexts while ensuring that the perspectives of policymakers, industry, and citizens are considered into the research.

2 Progress of activities

PATHFNDR made substantial progress across its focus areas (described in section 1), with many activities already transitioning toward consolidating results as several work streams approach the end of their work.

(i) Development of multi-scale energy transition scenarios and pathways for Switzerland

At the national level, PATHFNDR advanced national and cross-border energy system modelling by soft-linking Nexus-e, Euro-Calliope, SecMOD to evaluate flexibility contributions of electric vehicles (EVs) and heat pumps (HPs) in a sector-coupled context. This integration provided consistent insights into flexibility potentials, which were consolidated in Synthesis Report 3 (Powell et al., 2025). In parallel, a methodology to assess system adequacy was developed and will be applied to the PATHFNDR energy scenarios to evaluate the role of flexibility in supporting system stability, particularly through demand-side management, storage, and generation amid rising renewables. Furthermore, the EXPANSE model was extended to include HPs alongside EVs, enabling high-resolution analysis on the municipal level (Wang et al., 2025).

(ii) Infrastructure planning and operational strategies for distributed multi-energy systems

At the local level, PATHFNDR developed and validated methods to optimize the use of flexibility resources in distribution networks. This included algorithms for integrating distributed flexibility into wholesale markets (Hübner & Hug, 2024; Hübner & Hug, 2025), and planning infrastructure upgrades using the Flexibility-Aware Distribution Planning method (Savvopoulos et al., 2024). The ReSim platform was expanded to assess real-world use cases (e.g., in the municipality of Losone). Preliminary results from these integrated models demonstrate the potential of coordinated flexibility strategies to defer grid reinforcements and reduce system costs while accounting for operational constraints and uncertainties.

(iii) Assessment of key flexibility-enabling technologies

Experimental work validated technologies for sector coupling and flexibility, including battery and hydrogen storage, large HPs, and integrated control strategies. Tests were conducted using demonstration facilities such as the EPFL Smart Gridmarco campus, and Empa NEST platform. Results include the co-optimization of hydrogen production with waste heat recovery (Vandenberghe et al., 2025), and the use of hydrogen storage for peak shaving (Fochesato et al., 2024). Further developments include a hybrid battery-hydrogen scheduling (Jacobs et al., 2024), privacy-preserving coordination of active distribution networks, and a predictive control approach for managing variable generation. These activities contribute to the ongoing work for Synthesis Report 4 on flexibility-enabling technologies and infrastructures.

(iv) Exploration of business models and innovation strategies

On the business and innovation side, PATHFNDR explored strategies for flexibility and sector coupling. Studies addressed the business case for vehicle-to-grid (V2G) in Switzerland (Andersen & Powell, 2025), stakeholder decision-making in EV charging infrastructure (Lerbinger et al., 2024), and consumer adoption patterns in EV ecosystems (Palmié et al., 2024). Additional work explored, policy coalitions of multiple stakeholders to support the development of renewable hydrogen (Löhr et al., 2024), and innovation monitoring using large language models (Toetzke, 2024). Findings on coordination strategies, profitability drivers, and barriers to market participation provided the foundation for policy-relevant insights and fed directly into the development of Synthesis Report 3 (Powell et al., 2025).

(v) Evaluation of policy and regulatory frameworks

PATHFNDR advanced its policy research by reviewing flexibility and sector coupling instruments in Switzerland and neighbouring countries (Mellot at el., 2025). Studies examined market mechanisms such as dynamic network tariffs and contracts for differences and assessed their impacts on flexibility and price stability (Winzer et al., 2024; Schlecht & Winzer, 2024). Public acceptance was evaluated through two informed citizen panels, which explored societal views on flexible EV charging, heating, DACCS, and hydrogen infrastructure. These insights contributed to actionable policy recommendations for sector coupling and flexibility, feeding into energy scenario work and informing Synthesis Report 3 (Powell et al., 2025).

(vi) Synthesis of results into stakeholder-oriented recommendations

The PATHFNDR consortium focused on its synthesis work to align interdisciplinary research with decision-making priorities, generating outputs designed to support policy and practice outcomes. Based on our prior studies that outlined the key role of EVs and HPs for the Swiss energy transition, Synthesis Report 3 outlines how flexibility from EVs and HPs can support Switzerland's energy transition (Powell et al., 2025). Work began on Synthesis Report 4, focusing on flexibility-enabling technologies and related infrastructures, selected and structured in close collaboration with researchers and industry partners. In parallel, Synthesis Report 5 was initiated to consolidate all findings into final statements and recommendations, structured around four thematic areas: energy systems, buildings and mobility, alternative fuels, and markets and policies. These synthesis reports serve as key knowledge transfer tools for decision-makers.

(vii) Pilot and demonstration projects to test flexibility and sector coupling solutions

Real-world application to test flexibility and sector coupling solutions was advanced through three P+D projects in partnership with industry stakeholders: The **NeDeLa project** implemented dynamic network tariffs with Groupe E and conducted field trials to assess customer response to dynamic tariffs. The **Nanoverbund project**, together with IWB, tested how coordinated, shared heat prosumer networks can replace fossil-based heating with renewable sources, showing high potential for national scalability. The **H_2-districts project**, in collaboration with Hälg Group, completed its pilot installation and began experimental runs and simulation studies to explore hydrogen's role in district energy hubs and peak shaving.

Stakeholder and public engagement

The PATHFNDR consortium intensified its stakeholder engagement activities to move beyond general dissemination and toward targeted, topic-specific consultation meetings and workshops. These efforts ensured that research outputs aligned with the needs of policymakers, and industry actors. Furthermore, the first **PATHFNDR Conference** brought together over 100 participants from research, government, and industry to discuss the role of flexibility and sector coupling in Switzerland's energy transition (*Figure 2*).

PATHFNDR continues to present research results through its **lunch talks**, which showcase published results to the public. Additionally, PATHFNDR maintains an active presence and disseminates the results and activities through its **website**, LinkedIn, **YouTube** channel and newsletter.

Figure 2: Impressions from the PATHFNDR conference in 2024.

3 Highlights of outputs

One of the most significant highlights of this reporting period is **the synthesis of research findings on** flexibility provision from **buildings and mobility**, specifically through EVs and HPs. The consolidated insights are presented in a synthesis report (Powell et al., 2025). A summary of the key findings (outputs) is provided below.

- EVs and HPs are both flexibility providers that help balance supply and demand, reduce renewable curtailment, and lower system costs, including costs for electricity generation and cost savings related to electricity imports and exports (*Figure 3*). However, large-scale electrification will stress distribution grids significantly if flexibility-aware planning and operation is not deployed.

- Smart charging (V1G) and vehicle-to-grid (V2G) technologies enable EVs to shift energy demand, helping to align consumption with solar generation and support grid stability. Workplace charging presents a major flexibility opportunity, and V1G and V2G could reduce PV curtailment by up to 2 MWh per workplace charging station annually by 2050 (Gschwendtner et al., 2023; Parajeles Herrera et al., 2024; Andersen et al., 2025).

- HPs can be controlled to avoid peak heating loads using thermal inertia of buildings. Controlled curtailments can last up to 10 hours without losing comfort, but uncoordinated curtailments risk rebound peaks (Meister, 2025). Community-level approaches, like the Nanoverbund pilot demonstration project, demonstrate how coordinating multiple buildings can reduce grid congestion and improve efficiency.

- Despite progress, Switzerland lacks consistent nationwide policies, such as a “right to charge” in multi-unit buildings. High infrastructure costs, outdated tariffs, and double taxation on discharged energy hinder broader flexibility adoption (Andersen et al., 2025). Local initiatives (e.g., in Basel and Bern) are testing policies to accelerate adoption.

- Dynamic pricing, hybrid tariffs, and more complex pricing structures like profile contracts can incentivize flexibility but require regulatory reform and consumer-friendly designs (Mellot et al., 2025; Winzer et al., 2024). Consumer acceptance is a key challenge, while 30% of Swiss consumers are willing to trade comfort for savings, 70% prefer solutions with no comfort impact (Winzer et al., 2024).

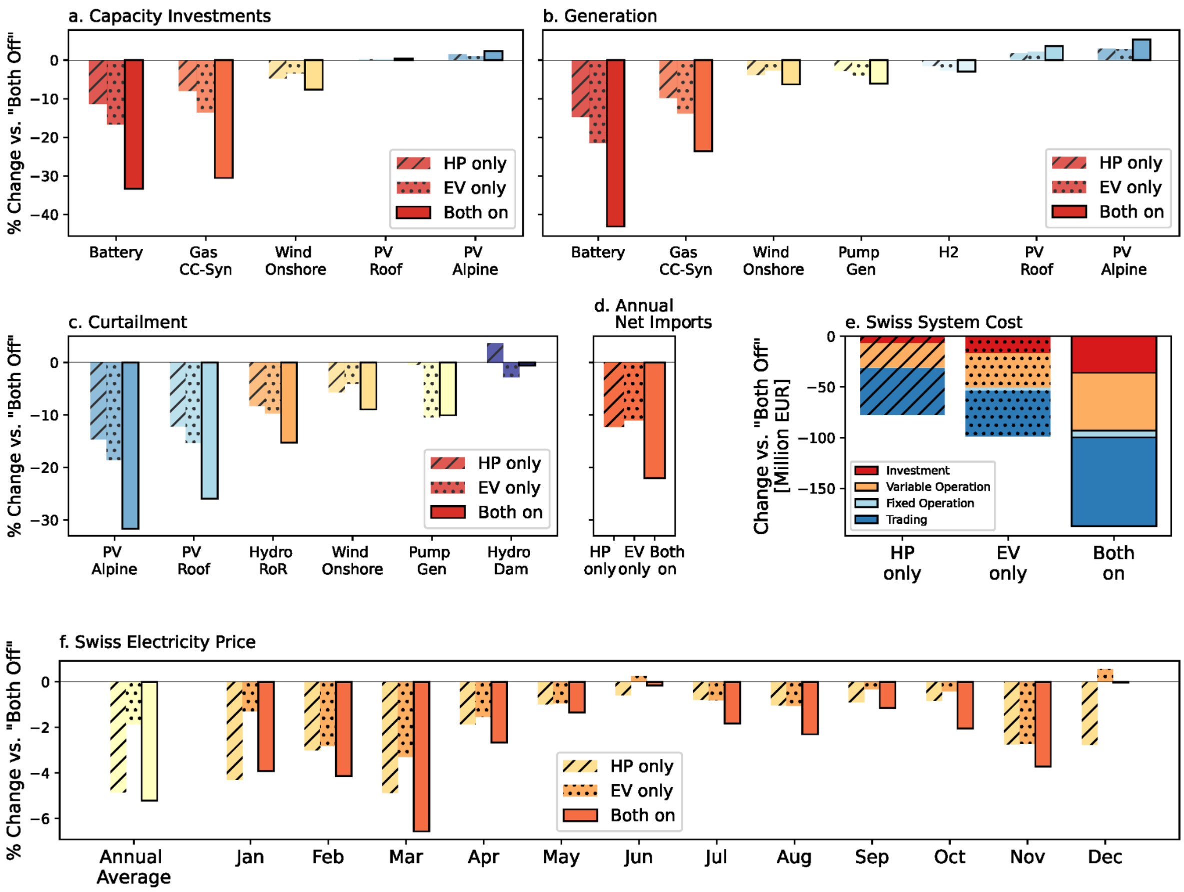

Figure 3: System-level comparison of scenarios with only EV flexibility (dots), only HP flexibility (slashes), or both (solid), relative to a baseline with no flexibility.

Furthermore, additional achievements from this reporting period are grouped into the following thematic areas: energy system, market and policy, and alternative fuels. These results, along with future findings, will be presented in upcoming synthesis reports to provide consolidated insights and actionable recommendations for decision-makers.

Energy system

- A study finds that Switzerland can meet the electricity demand increase while phasing out nuclear power by significant renewable capacity expansion by 2050. Winter shortages could be managed through energy imports and hydropower generation, complemented by measures such as hydrogen-based storage or expanded wind capacity (Akbari et al., 2024).

- A mix of rooftop PV, alpine PV, and wind power can significantly reduce system costs and winter electricity imports while maintaining low environmental impacts (Mellot et al., 2024).

- Switzerland's net-zero transition relies on coordinated electrification of transport and heating, with market integration and carbon capture and storage as critical enablers. Using machine learning on thousands of energy scenarios, the study highlights the need for cross-sectoral strategies and targeted investment in EVs and HPs (Baader et al., 2023).

- Industrial demand-side management (DSM) can reduce total system costs in a net-zero, sector coupled Swiss energy system by up to 4.4%, with thermal storage technologies capturing up to 61% of these savings. The findings highlight the value of industrial flexibility and the need for incentives to support thermal storage and DSM adoption (Mayer et al., 2024).

- Flexibility-aware planning enables DSOs to quantify the value of customer flexibility by comparing it to avoided grid investment costs. This approach supports smarter infrastructure decisions and helps design targeted mechanisms (e.g., direct load control) to activate flexibility and reduce system costs (Savvopoulos et al., 2024).

- Coordinated operation of active distribution networks with flexible energy resources (validated through real-world experiments) can optimize flexibility use while preserving data privacy. Policymakers are encouraged to promote balancing groups and energy communities to unlock system-wide flexibility (Jacobs et al., 2025).

Market and policy

- Effective auction design is essential to integrate distributed flexible resources (e.g., aggregators and storage systems) into day-ahead and intraday electricity markets. This work provides practical guidance for market designers and regulators to enhance participation and improve market efficiency (Hübner & Hug, 2024; Hübner & Hug, 2025).

Alternative fuels

- Concurrent optimization of hydrogen systems with waste heat recovery can reduce production costs by up to 18.9%, with electricity pricing, PV availability, and electrolyser efficiency identified as key cost drivers. The study recommends integrating waste heat recovery early in the design phase to maximize long-term savings for electrolysis (Vandenberghe et al., 2025).

- Hydrogen energy storage systems (HESS) can optimize the use of surplus renewable energy and reduce grid infrastructure needs. Experimental results show that HESS is technically a viable peak-shaving solution for local energy systems (Fochesato et al., 2024).

- Coordinated use of battery and hydrogen storage can enhance multi-day storage, peak shaving, and short-term balancing in energy systems. The study provides strategic insights for DSOs, TSOs, and balancing groups, while highlighting the need to address uncertainties in hydrogen storage costs due to limited real-world data (Jacobs et al., 2024).

Looking ahead, PATHFNDR will continue to integrate and synthesise research findings across disciplines to deliver cohesive, evidence-based recommendations for policymakers and industry. This work ensures that scientific insights are translated into actionable strategies for Switzerland’s energy transition.

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