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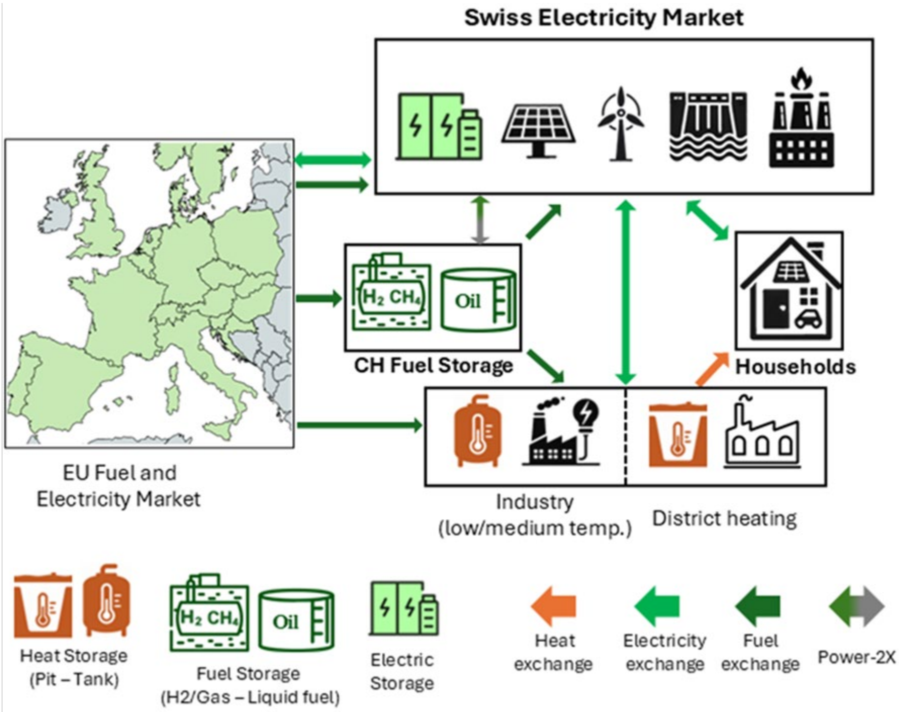
STORSUPPORT

Utility-scale storage in Switzerland: Needs assessment and support instruments



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

Summary

A renewable energy system dominated by solar and wind generation requires effective storage solutions to manage the variability of these resources. Switzerland's existing hydropower provides substantial electric storage capacity, yet the need for additional storage – and its optimal composition – remains uncertain. Given the limited potential to expand hydro storage, it is crucial to assess which alternative storage technologies (e.g., batteries, thermal storage, gas, or hydrogen) could be viable in the Swiss context. This project therefore addresses three central questions: How much additional storage will Switzerland require in a high-renewable future? What policy mechanisms can effectively support such investments? And how can auction designs be improved to allocate support contracts efficiently?

Since the beginning of the project, work has concentrated on two areas: storage needs (WP1) and auction design (WP3). For WP1, we advanced the numerical modelling framework by extending the representation of storage technologies, integrating multiple weather years to capture variability, and refining the profit structure of storage operation. These methodological improvements enhance the robustness of our assessment, and intermediate results have already been presented at several conferences. For WP3, we completed two major steps. First, a comprehensive study on the role of auctions in promoting renewable energy expansion. Second, a theoretical analysis comparing different auction formats, with particular attention to project realization. This work also proposes a new auction design and has been consolidated into a manuscript ready for submission to an international scientific journal.

Zusammenfassung

Ein erneuerbares Energiesystem, das stark von Solar- und Windenergie geprägt ist, erfordert wirksame Speicherlösungen, um die Variabilität dieser Ressourcen auszugleichen. Die bestehende Wasserkraft der Schweiz stellt zwar erhebliche Speicherkapazitäten bereit, dennoch bleibt der Bedarf an zusätzlichem Speicher – und dessen optimale Zusammensetzung – unsicher. Angesichts der begrenzten Möglichkeiten zum weiteren Ausbau der Wasserspeicherung ist es entscheidend zu prüfen, welche alternativen Speichertechnologien (wie Batterien, Wärmespeicher, Gas oder Wasserstoff) im schweizerischen Kontext tragfähig sein könnten. Das Projekt geht daher drei zentralen Fragen nach: Wie viel zusätzlicher Speicher wird die Schweiz in einem erneuerbaren Energiesystem der Zukunft benötigen? Welche politischen Instrumente können solche Investitionen wirksam unterstützen? Und wie lassen sich Auktionsdesigns verbessern, um Förderverträge effizient zu vergeben?

Seit Beginn des Projekts lag der Schwerpunkt der Arbeiten auf zwei Bereichen: dem Speicherbedarf (WP1) und dem Auktionsdesign (WP3). In WP1 wurde das numerische Modellierungsframework weiterentwickelt, indem die Abbildung der Speichertechnologien erweitert, mehrere Wetterjahre zur Erfassung der Variabilität integriert und die Erlösstruktur des Speicherbetriebs verfeinert wurden. Diese methodischen Verbesserungen erhöhen die Robustheit unserer Analysen, und Zwischenergebnisse wurden bereits auf mehreren Konferenzen vorgestellt. In WP3 wurden zwei wesentliche Arbeitsschritte abgeschlossen: Erstens eine umfassende Untersuchung zur Rolle von Auktionen bei der Förderung des Ausbaus erneuerbarer Energien, zweitens eine theoretische Analyse zum Vergleich verschiedener Auktionsformate mit besonderem Augenmerk auf die Realisierung von Projekten. Diese Arbeiten schlagen zudem ein neues Auktionsdesign vor und sind in einem Manuskript zusammengeführt, das zur Einreichung bei einer internationalen wissenschaftlichen Fachzeitschrift bereitsteht.

Résumé

Un système énergétique dominé par la production solaire et éolienne nécessite des solutions de stockage adaptées pour en gérer la variabilité. Bien que l'hydroélectricité existante en Suisse offre une

capacité de stockage substantielle, l'ampleur du besoin supplémentaire—ainsi que sa composition optimale—reste incertaine. Étant donné le potentiel limité d'expansion du stockage hydraulique, il est essentiel d'évaluer quelles autres technologies de stockage (p. ex. batteries, stockage thermique, gaz ou hydrogène) pourraient être pertinentes dans le contexte suisse. Le projet se penche ainsi sur trois questions principales : Quelle quantité de stockage supplémentaire sera nécessaire dans un système fortement renouvelable ? Quels instruments de politique publique peuvent soutenir efficacement ces investissements ? Et comment améliorer la conception des enchères afin d'attribuer les contrats de soutien de manière efficiente ?

Depuis son lancement, le projet se concentre sur deux axes : les besoins en stockage (WP1) et la conception des enchères (WP3). Dans le cadre du WP1, le modèle numérique a été enrichi par une représentation élargie des technologies de stockage, l'intégration de plusieurs années météorologiques pour mieux refléter la variabilité, ainsi que l'amélioration de la structure de rentabilité des opérations de stockage. Ces évolutions méthodologiques renforcent la robustesse de l'évaluation, et des résultats intermédiaires ont déjà été présentés lors de plusieurs conférences. Dans le cadre du WP3, deux étapes principales ont été réalisées : premièrement, une analyse approfondie du rôle des enchères dans le déploiement des énergies renouvelables. Deuxièmement, une étude théorique comparant différents formats d'enchères, avec une attention particulière à la réalisation effective des projets. Ce travail propose également une nouvelle approche de conception d'enchères et a été consolidé sous la forme d'un manuscrit prêt à être soumis à une revue scientifique internationale.

Contents

List of abbreviations

SFOE	Swiss Federal Office of Energy
FEM	Future Energy Markets model
NTC	Net Transfer Capacity
TYNDP	Ten-Year Network Development Plan
CfD	Contract for Difference
KIT	Karlsruhe Institute of Technology
ZHAW	Zürcher Hochschule für Angewandte Wissenschaften (Zurich University of Applied Sciences)
HSLU	Hochschule Luzern (Lucerne University of Applied Sciences and Arts)
PV	Photovoltaics

1 Introduction

1.1 Context and motivation

A renewable electricity system strongly based on solar and wind generation requires storage to balance the intermittency of these resources. Switzerland is highly interconnected with its neighbouring countries, yet the reliability of imports cannot be guaranteed. At the same time, Switzerland's existing hydropower offers substantial storage potential, but the extent of additional storage required remains uncertain. In this context, it is crucial to evaluate Switzerland's potential dependence on additional energy storage – both seasonal and diurnal – under various scenarios. Addressing this challenge requires comprehensive, fit-for-purpose numerical modelling that explicitly considers different storage technologies. Such an approach provides insights into the socially optimal amount of storage needed in Switzerland.

Once storage requirements are evaluated, policymakers may recognize the need to use market design instruments to incentivize adequate storage deployment and ensure sufficient capacity. Storage assets, characterized by high capital costs and low variable costs, are highly sensitive to capital expenditure, which is the main driver of overall costs. At the same time, storage revenues are exposed to significant risks because they depend on volatile power price spreads. This increases the cost of capital and may therefore result in deployment below the socio-economic optimum. Governments can cost-effectively support storage investment by sharing some of these risks, but doing so may weaken the short-term price signals that are crucial for efficient operation. Unlike support schemes for renewable energy, support instruments for storage have not yet been extensively studied. Traditional mechanisms such as feed-in tariffs or standard contracts for differences are not suitable, as they eliminate price-related incentives.

1.2 Project objectives

Our project addresses three critical aspects of energy storage in Switzerland: assessing the need for storage, designing suitable policy instruments to meet this need, and improving auction mechanisms to allocate support contracts efficiently.

Assess storage needs. To assess storage requirements, we have developed a fit-for-purpose modelling framework that combines several key elements. It incorporates multiple types of storage assets, including batteries, thermal storage, liquid fuels, gas, and hydrogen. It also accounts for demand-side flexibility, which competes with storage in providing system balancing. Furthermore, the model integrates different weather realizations, as storage needs depend both on renewable capacity factors and on weather-driven thermal demand. Finally, the framework explicitly simulates price fluctuations in spot markets, which are central to shaping the behaviour and profitability of storage technologies, and thereby their potential need for policy support.

Design storage support instruments. Once a need for storage is identified, support mechanisms can help ensure its deployment. Traditional instruments such as feed-in tariffs or standard contracts for difference are not suitable, as they remove market price incentives. Our aim is therefore to develop an innovative support contract that pursues a dual objective: reducing the cost of capital for storage assets while preserving undistorted incentives for their efficient operation. In other words, the mechanism should promote generation and consumption precisely in periods of high system value, while discouraging opportunistic behaviour in markets that could otherwise lead to inefficiencies. In designing such a scheme, we build on recent innovations in renewable support instruments, particularly financial contracts for difference applied to intermittent sources such as wind and photovoltaics.

Auction designs for investment in storage and PV. To ensure their effectiveness, auctions must be adapted to the specific national context, as factors such as market maturity, investor risk perceptions, and cost structures vary considerably between countries. Our project therefore seeks to propose auction designs tailored to the Swiss energy sector, with particular emphasis on avoiding pitfalls observed in previous international experiences.

2 Approach, method, results and discussion

2.1 Quantification of storage needs

Approach and method. Our study applies a numerical, techno-economic modelling approach to evaluate investment decisions, operational strategies, and market dynamics in Switzerland's future electricity and heating system. We use the *Future Energy Markets* (FEM) model – an integrated electricity-heat market model with hourly resolution – to optimise investments in generation, storage, and flexible demand for the target years 2035 and 2050.

FEM has been developed to capture both short-term balancing requirements (intra-day and intra-week) and long-term seasonal storage use. The model jointly optimises generation and storage while explicitly representing sector coupling between electricity and heat. By considering the interplay of investment costs, operational constraints, and market prices, FEM identifies both complementary and competing roles of generation and storage. A more detailed description of the model is provided in the Appendix.

Within this framework, our work during the current reporting period focused on expanding the scope of the FEM model and increasing its analytical robustness. Four main developments were undertaken:

- **Expanded storage representation –** The model now includes a broad portfolio of storage options, namely thermal storage, liquid fuel storage, gas storage, and hydrogen storage. These technologies differ in cost structure, efficiency, and discharge duration, meaning they can either compete with or complement one another. Including this diversity is essential for capturing realistic market dynamics and for identifying the most cost-effective mix of flexibility options.
- **Improved thermal demand modelling –** The representation of both household and district heating demand was refined to better estimate the role and value of thermal storage. Household thermal demand profiles and flexibility potentials were updated using data from HSLU, while district heating networks were introduced as a new component within FEM. This development is particularly important, as electricity and heat systems are expected to become increasingly interconnected through the widespread use of heat pumps. A more accurate heat demand model allows FEM to capture how heating needs vary across hours and seasons and how they interact with electricity consumption. Since thermal storage is directly linked to thermal demand, these refinements enable a more realistic optimisation of storage operation and investment, ensuring that capacity is sized and deployed in a way that reflects actual system needs and cost efficiency.
- **Multi-year weather coverage –** We incorporated multiple historical weather years to the analysis to make results more robust and less dependent on a single year's conditions. In addition to weather year 1995, we have updated our dataset with weather years 2008 and 2009. This extension ensures that results are not dependent on a single year's conditions. Because investment decisions for long-lived assets must be robust across different climatic futures, it is essential to test whether optimal technology mixes remain stable under varying renewable generation and demand conditions. Multi-year modelling therefore increases the resilience, economic viability, and relevance of investment strategies.
- **Refined price-fluctuation modelling –** Enhancements in the representation of market price formation improve how volatility and market dynamics are captured within the model. This allows for more accurate simulation of how different asset types – including storage, flexible generation, and cross-border exchanges – interact and influence market prices in Switzerland. As a result, both the operational behaviour and the profitability of storage technologies are now represented more realistically. This in turn enables a clearer assessment of whether specific storage technologies can recover their investment costs under prevailing market conditions or whether additional financial support mechanisms may be required.

As an example of the type of results generated with the improved FEM framework, we analysed investment decisions under different scenario assumptions. A key parameter in these scenarios is the net transfer capacity (NTC) between Switzerland and its neighbouring countries, since NTC levels strongly influence the results while remaining highly uncertain for the future. A major source of this uncertainty is the unresolved electricity agreement between Switzerland and the European Union. To reflect this, some scenarios assume that the agreement is accepted, others that it is rejected, while additional cases consider investment decisions that must be taken without knowing whether the agreement will ultimately be concluded. In parallel, we also examined scenarios in which the NTC varies. This allows us to systematically assess how different levels of cross-border capacity shape investment choices across technologies and to identify the sensitivity of optimal investments to external market integration.

Figure 1, for example, illustrates preliminary sensitivity results for 2050. The analysis considers scenarios in which net transfer capacities (NTCs) are gradually reduced from 100% of the values reported in the TYNDP 2022 down to 30%. The results indicate that thermal storage, primarily used for seasonal balancing, is only modestly affected by NTC reductions unless capacity is cut by half or more. A similar pattern is observed for heat generation technologies that supply these storages. By contrast, battery storage shows a markedly different behaviour: installed capacity initially declines as NTC levels decrease, reaching a minimum at around 60% of the original capacity, before rising again at lower NTC values. This non-linear relationship between NTC availability and battery investments is the subject of ongoing analysis.

In addition to the scenarios shown for 2050, a similar analysis is being conducted for 2035. Furthermore, additional scenarios are being developed that explicitly cover the cases in which the electricity agreement between Switzerland and the EU will be accepted, rejected, or modeled as a stochastic case that optimizes over the uncertainty of both outcomes.

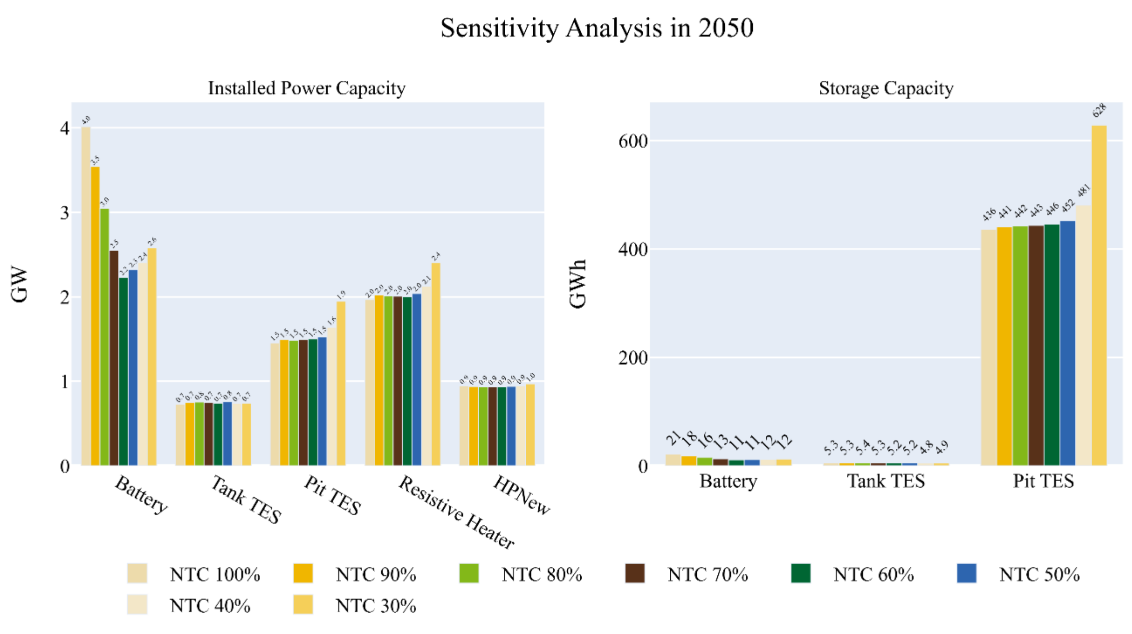

Figure 1: Effect of the NTC capacity on the investment of selected technologies.

2.2 Auction design

Approach and method. First, in a comprehensive study, we lay the theoretical foundations for auctions to promote the expansion of renewable energies and describe and evaluate various methods that have already been used and those that are conceivable for this purpose. These range from single-project auctions to multi-project, multi-attribute, and combinatorial auctions.

Second, we develop a theoretical model that compares two auction designs with a particular focus on non-realization risk: a two-sided contract for difference (CfD) and the market solution following a payment auction. In the market solution, electricity sales are unregulated. The winning bidder will participate in the electricity market without government hedging or support and can decide whether to equip themselves with privately negotiated hedges, such as PPA or OREC. In the payment auction, payments can occur in both directions, i.e., either a lump-sum subsidy from the auctioneer to the winning bidder or a payment from the winning bidder to the auctioneer after the realization decision. If some bidders are able to implement the project without support, the auction is won by the bidder who is willing to pay the highest amount to the auctioneer for the right to develop the project (as in the German auctions for non-centrally pre-investigated offshore wind sites since 2023). Conversely, if bidders need support, the bidder who demands the lowest lump-sum subsidy wins the auction. In both cases, electricity sales will be unregulated (market solution).

Bidders face the same uncertainty regarding both costs (modelled as a post-auction shock on top of private costs) and future revenues. At the time of the realization decision, cost uncertainty is resolved, while future revenues are known under the CfDs but remain uncertain after the payment auction. In addition, bidders' private costs in the payment auction differ from those in the CfD auction by a parameter that may vary across bidders.

Our findings reveal that differences between auction formats depend on bidders' risk preferences and challenge the conventional wisdom that CfDs necessarily reduce non-realization risk under risk aversion. Key findings include:

- Due to lower uncertainty of the future revenue, CfDs induce more aggressive bidding behaviour of risk-averse bidders and result in a higher non-realization risk than payment auctions.
- The advantage of the market solution over CfDs persists despite additional financing costs associated with the market solution and is further reinforced by the dispersion of these costs.
- If future revenue uncertainty is partially resolved during the implementation decision period, risk-averse bidders in the payment auction effectively "insure" against unfavourable belief updates by bidding more conservatively. This conservatism provides a buffer that protects the realization decision against moderate negative shocks after the auction.
- Requiring payments from bidders to the auctioneer before the implementation decision can increase the realization probability. However, this benefit must be weighed against potential higher financial costs of early payment and the risk of general non-participation.

With a focus on high project realization rates, which are essential for expanding renewable energy, we recommend using CfDs only when developers cannot implement their projects without support. Otherwise, implement a market solution with payments by the auction winner, if feasible. Because of information asymmetry, i.e., developers know best about the expected profitability of their planned project, both options should be offered to bidders, who decide competitively which option to implement. This promises efficient solutions with low subsidy costs or high revenues. The argument of information asymmetry also implies that developers know best whether they need support to implement their project or not. A misjudgement by the auctioneer – as recently observed in Denmark and the UK – can lead to undesirable outcomes such as a lack of participation and project delays. Therefore, based on our findings, the goal of a high project implementation rate should be pursued by leaving the decision between CfD and market solutions to the developers. We present an auction design that meets this requirement. It invites developers to participate and almost always selects the solution with the highest realization probability.

3 Conclusions and outlook

Based on the feedback received during presentations of the WP1 manuscript draft, we are preparing a manuscript that includes additional scenarios and extra analysis on the role of storage under limited electricity trade for Switzerland, contrasting the role of electric (battery) and thermal storage technologies in different scenarios. The accompanying dataset and the base model code will also be made publicly available in an open-source repository in Q1 2026. For WP3, a comprehensive work is carried out to improve understanding of the benefits and challenges of auctions for renewable energy support and to assist in selecting the most suitable procedure for a given application and specific national conditions. In addition, a manuscript on the comparison of auction procedures and a design proposal is prepared for submission to an international journal.

4 National and international cooperation

We collaborated with the Competence Center for Thermal Energy Storage of the Lucerne University of Applied Sciences (HSLU) on quantification of heating demand to better estimate the flexibility potentials in the heating sector. More concretely, the existing model has been further developed and refined in close collaboration with Philipp Schütz and Sarah Schneeberger, experts in thermal energy storage at the HSLU. Forecasts of future thermal demand from Swiss industry, district heating networks, and private households have been incorporated into the model to ensure their impact on the future Swiss electricity system is accurately represented. The know-how and data for these additions are based on the Competence Center for Thermal Energy Storage's latest research and publications.

5 Publications and other communications

On May 29th, 2025, David Holmer, member of our project team, presented and discussed preliminary results at the 21st International Conference on European Energy Markets (EEM) in Lisbon. He did so again on June 18th, 2025, at the 46th IAEE International Conference for energy solutions for a sustainable and inclusive future in Paris. A paper is in preparation about the interplay of NTC capacities and the investment in storage assets. The KIT project team plans to submit the paper comparing different auction procedures for supporting renewable energy to an international, peer-reviewed journal in 2025.

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7 Appendix

FEM model description

FEM calculates the economically optimal investments in storage and generation facilities individually for the target years 2035 and 2050. It optimizes their operation and the operation of existing technologies in the electricity and heat sectors represented by the model with an hourly resolution.

The model can be used to address various fields of application for storage facilities. These include, for example, intraday or intraweek balancing in the electricity system (solar peak storage, weekend and holiday effects), as well as seasonal storage use, such as storing surpluses in summer for use in winter and resilience against import restrictions.

The model does not specify any form of operation corresponding to one of the fields of application; instead, the operating schedules are derived in the model as a result of minimizing investment and operating costs through the technical and financial parameters of storage facilities, generation technologies, demand, and foreign trade. The optimization independently weighs up electricity and heat storage and generation, as they are considered simultaneously in the model.

Thanks to its stochastic objective function, which can consider multiple scenarios simultaneously with their assumed probabilities of occurrence, the model can be used for robust energy system planning. It identifies a combination of generation and storage technologies that performs efficiently across scenarios with different assumptions regarding their NTC. In this context, the definition of these scenarios—particularly the frequency and severity of low versus high NTC conditions—determines how often additional capacities are worth the investment. By optimizing across both scenarios with high and low net transfer capacities the model can capture the systemic value of each technology.

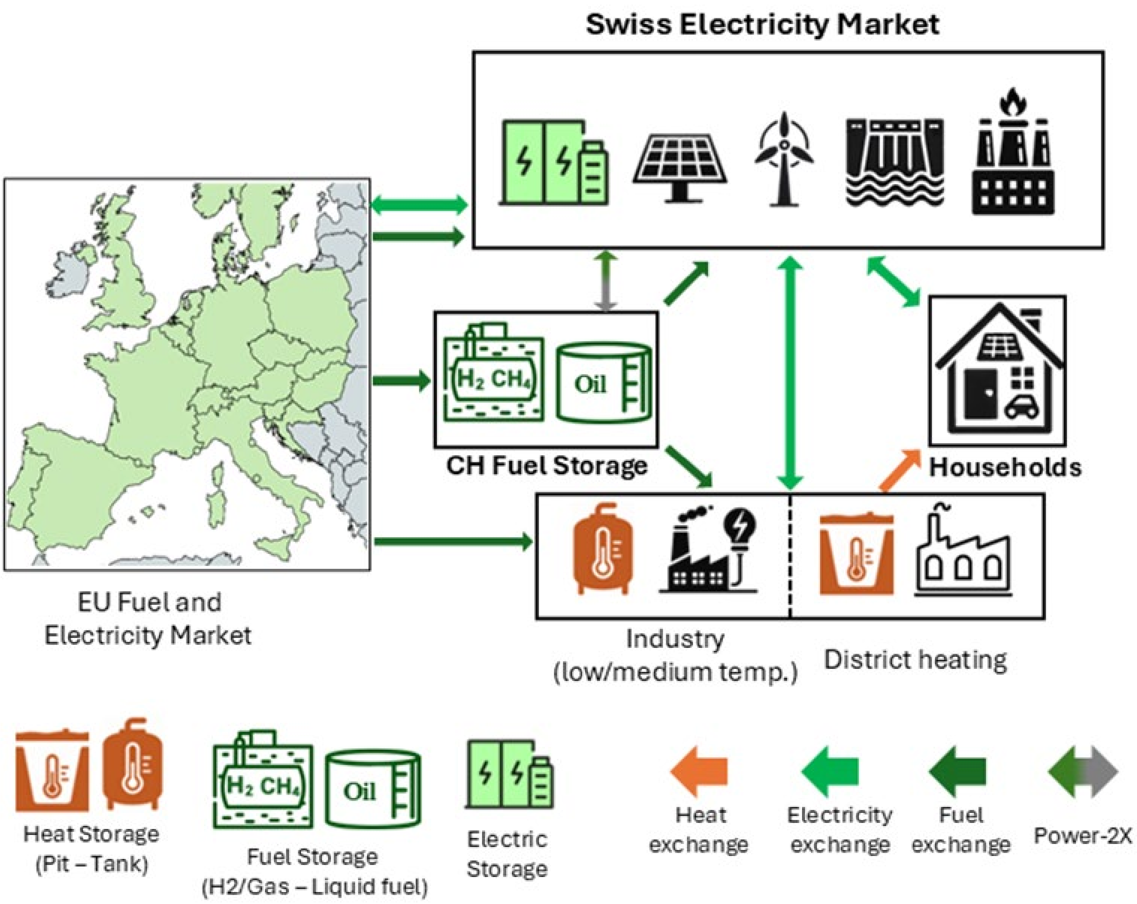

Figure 2: The Future Energy Market (FEM) Model

FEM is an extension of the Swissmod model mentioned in the references. Figure 2 provides a graphical illustration of the model's structure. At the core of the FEM model lies the Swiss electricity market, including renewable and conventional power generation as well as industrial and private electricity consumers. In addition to these, the model accounts for flexibility from private households through the use of heat pumps and electric vehicles. It also includes existing and future electricity-based district heating systems, along with the residential and industrial consumers they serve.

The FEM model is a techno-economic model developed to simulate investment decisions, deployment planning, and trading dynamics for the Swiss electricity and heating system. In addition to electricity and district heating generation, selected electricity consumers are also represented flexibly in the model, including electric mobility, the electricity consumption of heat pumps in buildings, and electrolysis.

District heating systems for buildings and industry in the low and medium temperature range—meaning temperatures below 200 degrees Celsius—are modeled in aggregated form. This includes investments and the operation of thermal storage facilities and heat generation plants. These areas of the heating sector are included because heat storage can be beneficial in the case of district heating for buildings and industry, or because they can act as implicit storage through their flexibility, as is the case with buildings equipped with heat pumps. These components are relevant for storage since they are connected to the electricity system via heat pumps, and electricity supply fluctuates significantly throughout the day and year. This makes storage particularly valuable in these areas.

Since most of the considered thermal plants operate with electricity, the thermal and the electric parts of the model are connected. By contrast, parts of the heating sector that produce heat solely through combustion—such as systems based on wood, gas, or oil—do not benefit economically from storage in typical years without import restrictions. The reason is that the prices of these fuels do not vary significantly over time, so heat storage offers no economic advantage. In a model like FEM, this means there is no economic incentive to include storage in these cases under normal conditions.

Combustion boilers—except those that are invested in for district heating generation within the model—solar thermal energy, and high-temperature heat are therefore excluded from the model. However, since these technologies do not create storage requirements in the modeled scenarios for the reasons described above, their exclusion has no impact on future results with respect to storage needs.

The model includes several energy storage technologies, such as electrical energy storage like large batteries, thermal storage such as earth basins or tank systems, and fuel storage for methane, hydrogen, or heating oil. Given the importance of electricity trading between Switzerland and its neighbors, the model also includes most EU countries and the trading relationships between them and Switzerland.

As already hinted, one of the major improvements of FEM within the work of STORSUPPORT is the model's expansion of the thermal sector. It includes two representative types of thermal storage: tank storage systems for compact medium-temperature applications and pit thermal storage systems for large-scale heat storage. Tank storage stands for solutions with high storage temperatures above 100 degrees Celsius and a high power-to-capacity ratio, making them particularly suitable for industrial applications or high-temperature district heating networks. Pit thermal storage, on the other hand, represents a cost-effective technology with a larger storage volume but a lower power-to-capacity ratio.

Other technologies, such as borehole thermal energy storage and aquifer thermal energy storage, are not explicitly considered in this study. This is due to the complexity involved in accurately modeling their behavior and the significant uncertainties and variations in their cost structures.

The detailed integration of thermal storage options—and more broadly, of heat consumers—is a distinctive feature of this model. By capturing their interactions with the electricity system, the model enables a more realistic and comprehensive analysis of future energy system configurations.