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Executive summary

The IEA ES TCP Task 35 dealt with the conceptualization and impact of energy storage implementation in sector coupling, thus providing a certain degree of flexibility to the latter (flexible sector coupling, FSC). The workload was distributed among four different Subtasks (ST). ST1 dealt with the definition of sectors and sector coupling as a whole, including an outlook on the regulatory framework and possible limitations. ST1 collected data from the other STs to produce a white paper with conclusions, outlook, and recommendations to stakeholders on the role of FSC in future energy systems. ST2 was responsible for identifying the most common FSC configurations existing at that time and providing recommendations on the most promising configurations given different applications. In ST3, important key-performance indicators (KPIs) to assess the performance of the different configurations on different levels (building, district, islands, and cities) were collected based on the data gathered in ST2. The KPIs further evaluated the most promising configurations identified in ST2 with a particular focus on the different scales mentioned. This served as a guideline to define boundary conditions for the assessment of systems on a national scale in ST4, where modeling activities of different scenarios in Germany in 2050 were carried out to estimate the benefits of utilizing energy storage within sectors to increase their flexibility.

Task 35 started on 1st June 2019 and terminated in 2023. 22 institutions from 13 countries actively participated in the Task and have contributed to deliver outstanding results. Additionally, two international organizations, namely the World Bank and the International Renewable Energy Agency (IRENA) were involved in the Task and grant its visibility worldwide.

Extremely relevant results were achieved within the framework of Task 35 activities. In ST1, the definition of sectors and the pathways connecting them through energy storage were clearly defined, thus leading to the identification of possible legal and regulatory bottlenecks. Opportunities for the integration of energy storage in flexible configurations were found, and recommendations were formulated to aid with the future integration of such systems in the energy landscape. A workshop with relevant stakeholders took place to communicate the most relevant results. In ST2 a clear overview of the storage technologies and sector coupling already available has been obtained, with a particular focus on higher TRLs, and gaps to address in future research have been identified. In ST3, this was addressed with a higher level of details with a look on "local" systems (households, districts, cities), and technical and regulatory barriers were identified. In ST4, the influence of energy storage on Germany in 2050 was modelled, and it clearly highlighted the potential of energy storage solutions in coupling different sectors both from a cost and from an energy demand perspective.

Zusammenfassung

Die IEA ES TCP Task 35 befasste sich mit der Konzeptualisierung und den Auswirkungen der Implementierung von Energiespeichern in der Sektorkopplung und bot so einen gewissen Grad an Flexibilität für letztere (Flexible Sector Coupling, FSC). Die Arbeitslast wurde auf vier verschiedene Subtasks (ST) verteilt. ST1 befasste sich mit der Definition von Sektoren und der Sektorkopplung insgesamt, einschließlich eines Ausblicks auf den regulatorischen Rahmen und mögliche Einschränkungen. ST1 sammelte Daten von den anderen Subtasks, um ein Whitepaper mit Schlussfolgerungen, Ausblicken und Empfehlungen an die Interessengruppen zur Rolle der FSC in zukünftigen Energiesystemen zu erstellen. ST2 war verantwortlich für die Identifizierung der zu diesem Zeitpunkt am häufigsten vorhandenen FSC-Konfigurationen und die Bereitstellung von Empfehlungen zu den vielversprechendsten Konfigurationen für verschiedene Anwendungen. In ST3 wurden wichtige Key Performance Indicators (KPIs) zur Bewertung der Leistung der verschiedenen Konfigurationen auf unterschiedlichen Ebenen (Gebäude, Stadtteil, Inseln und Städte) basierend auf den in ST2 gesammelten Daten erhoben. Die KPIs bewerteten die vielversprechendsten in ST2 identifizierten Konfigurationen weiter, wobei der Fokus besonders auf den erwähnten verschiedenen Maßstäben lag. Dies diente als Richtlinie zur Definition von Rahmenbedingungen für die Bewertung von Systemen auf nationaler Ebene in ST4, wo Modellierungsaktivitäten verschiedener Szenarien in Deutschland im Jahr 2050 durchgeführt wurden, um die Vorteile der Nutzung von Energiespeichern innerhalb der Sektoren zur Steigerung ihrer Flexibilität abzuschätzen.

Task 35 begann am 1. Juni 2019 und endete im Jahr 2023. 22 Institutionen aus 13 Ländern nahmen aktiv an der Task teil und haben dazu beigetragen, herausragende Ergebnisse zu liefern. Darüber hinaus waren zwei internationale Organisationen, nämlich die Weltbank und die Internationale Agentur für Erneuerbare Energien (IRENA), an der Task beteiligt und haben deren weltweite Sichtbarkeit gewährleistet.

Im Rahmen der Aktivitäten von Task 35 wurden äußerst relevante Ergebnisse erzielt. In ST1 wurden die Definition der Sektoren und die Wege, die sie durch Energiespeicher miteinander verbinden, klar definiert, was zur Identifizierung möglicher rechtlicher und regulatorischer Engpässe führte. Chancen für die Integration von Energiespeichern in flexible Konfigurationen wurden erkannt und Empfehlungen formuliert, um die zukünftige Integration solcher Systeme in die Energielandschaft zu unterstützen. Ein Workshop mit relevanten Interessengruppen fand statt, um die wichtigsten Ergebnisse zu kommunizieren. In ST2 wurde ein klarer Überblick über die bereits verfügbaren Speichertechnologien und Sektorkopplungen gewonnen, mit besonderem Fokus auf höhere TRLs, und es wurden Lücken identifiziert, die in zukünftiger Forschung angegangen werden müssen. In ST3 wurde dies mit einem höheren Detaillierungsgrad behandelt, mit einem Blick auf „lokale“ Systeme (Haushalte, Stadtteile, Städte), und technische sowie regulatorische Hürden wurden identifiziert. In ST4 wurde der Einfluss von Energiespeichern auf Deutschland im Jahr 2050 modelliert, und es wurde deutlich hervorgehoben, welches Potenzial Energiespeicherlösungen bei der Kopplung verschiedener Sektoren sowohl aus Kosten- als auch aus Energienachfrageperspektive haben.

Résumé exécutif

La tâche 35 de l'IEA ES TCP traitait de la conceptualisation et de l'impact de la mise en œuvre du stockage d'énergie dans le couplage sectoriel, offrant ainsi un certain degré de flexibilité à ce dernier (Flexible Sector Coupling, FSC). La charge de travail a été répartie entre quatre Subtasks (ST). La ST1 s'est occupée de la définition des secteurs et du couplage sectoriel dans son ensemble, y compris une perspective sur le cadre réglementaire et les limitations possibles. La ST1 a collecté des données des autres sous-tâches pour produire un livre blanc avec des conclusions, des perspectives et des recommandations aux parties prenantes sur le rôle du FSC dans les systèmes énergétiques futurs. La ST2 était responsable de l'identification des configurations FSC les plus courantes existant à l'époque et de la fourniture de recommandations sur les configurations les plus prometteuses pour différentes applications. Dans la ST3, des indicateurs clés de performance (ICP) importants pour évaluer les performances des différentes configurations à différents niveaux (bâtiment, quartier, îles et villes) ont été collectés sur la base des données recueillies dans la ST2. Les ICP ont ensuite évalué les configurations les plus prometteuses identifiées dans la ST2, avec un accent particulier sur les différentes échelles mentionnées. Cela a servi de guide pour définir les conditions limites pour l'évaluation des systèmes à l'échelle nationale dans la ST4, où des activités de modélisation de différents scénarios en Allemagne en 2050 ont été menées pour estimer les avantages de l'utilisation du stockage d'énergie au sein des secteurs afin d'augmenter leur flexibilité.

La tâche 35 a débuté le 1er juin 2019 et s'est terminée en 2023. 22 institutions de 13 pays ont activement participé à la tâche et ont contribué à fournir des résultats remarquables. De plus, deux organisations internationales, à savoir la Banque mondiale et l'Agence internationale pour les énergies renouvelables (IRENA), ont participé à la tâche et lui ont conféré une visibilité mondiale.

Des résultats extrêmement pertinents ont été obtenus dans le cadre des activités de la tâche 35. Dans la ST1, la définition des secteurs et les voies les reliant via le stockage d'énergie ont été clairement définies, ce qui a conduit à l'identification de possibles obstacles juridiques et réglementaires. Des opportunités pour l'intégration du stockage d'énergie dans des configurations flexibles ont été identifiées et des recommandations ont été formulées pour aider à l'intégration future de ces systèmes dans le paysage énergétique. Un atelier avec les parties prenantes concernées a eu lieu pour communiquer les résultats les plus pertinents. Dans la ST2, une vue d'ensemble claire des technologies de stockage et du couplage sectoriel déjà disponibles a été obtenue, avec un accent particulier sur les TRL élevés, et des lacunes à combler dans la recherche future ont été identifiées. Dans la ST3, cela a été abordé avec un niveau de détail plus élevé en se concentrant sur les systèmes « locaux » (ménages, quartiers, villes), et des barrières techniques et réglementaires ont été identifiées. Dans la ST4, l'influence du stockage d'énergie en Allemagne en 2050 a été modélisée, et le potentiel des solutions de stockage d'énergie pour coupler différents secteurs, tant du point de vue des coûts que de la demande énergétique, a été clairement mis en évidence.

Contents

1 Summary

1.1 Main goal, objectives and scope

In view of the recent energy crisis and of the upcoming energy policies, it is now clear that renewable electricity (RE) will constitute the main energy source in the energy systems of the future. Because RE relies on intermittent energy sources (e.g. wind, solar) it is important to ensure the highest flexibility in the grid. For this reason, distributing RE to other sectors, namely heating/cooling and the mobility sector, thus effectively achieving sector coupling, is of paramount importance, and the focus of the IEA ES TCP Task 35.

Figure 1 shows how the energy grid with sector coupling with different storage options could look like. The energy is either stored in its input form or transformed to another energy form (e.g. electricity to heat/cooled, electricity to synthetic fuel, Power-to-Gas or Power-to-Heat). By doing so, the different demand patterns of the "consuming" sectors thermal and mobility can help to match the volatile energy supply to a specific demand.

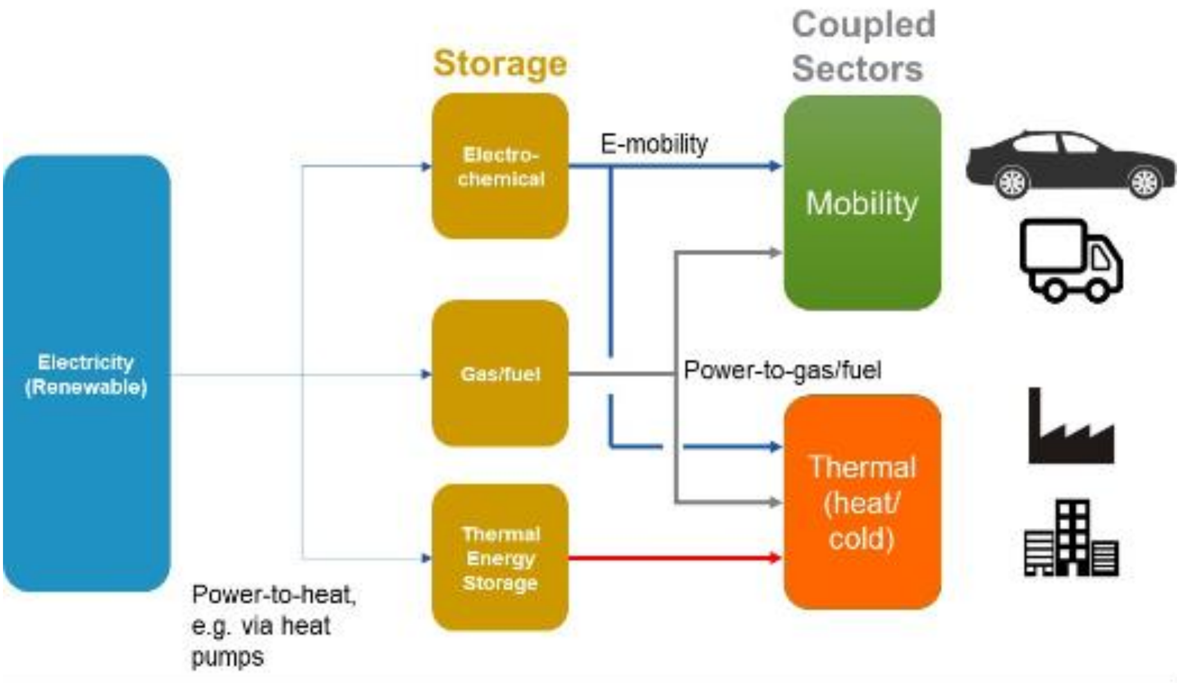


Figure 1. Conceptual overview of flexible sector coupling with different storage technologies

Based on this, the main goal, objectives and scope of Task 35 have been defined as follows:

- Goal: clarify the possibilities and the impact of energy storage implementation in sector coupling
- Objectives: the key objectives were defined as:
  - Compile a White Paper on "Flexible Conversion of Renewable Electricity to the Thermal and Mobility Sector by Energy Storage Implementation"
  - Identify non-technical barriers to energy storage implementation for Flexible Sector Coupling
  - Identify energy storage technologies for actual sector coupling applications (paths in the Figure 1) and their properties/requirements
  - Prioritizing most promising storage configurations for sector coupling applications

  - Assess technical and economic comparison to "no-storage" sector coupling scenarios
- Scope: the task focused only on options including energy storage, and did not consider power-to-X. Therefore, the following topics were covered in the task:
  - All energy storage technologies
  - All applications in the heating and cooling sector (buildings, DHW, process heat/cold in industry)
  - All applications in the mobility sector (private transport, public transport, freight traffic) and all propulsion technologies (EV, fuel cell, hydrogen etc.)

1.2 Subtask structure and work plan

Based on the goals defined above, the Annex was divided into four different subtasks. A summary of the main activities/goals within each subtask is reported in **Figure 2.**

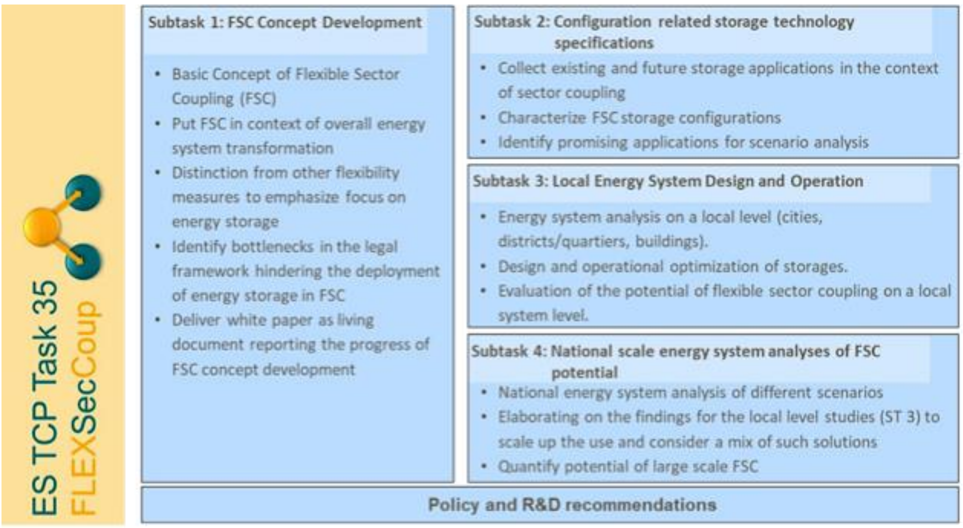


Figure 2. Definition of Task 35 four subtasks.

1.3 Overview of participants

A total of 22 institutions from 13 countries actively participated in the Task (Table 1) and have contributed outstanding results.

Table 1. List of Task 35 participants as of December 2021. Subtask leaders are highlighted in bold.

Country	**Institution**	**Representative (name)**
Austria	**AEE Institute for Sustainable Technologies** **Austrian Institute of Technology (AIT)** University of Innsbruck	**Wim Van Helden (ST2 leader)** **Gerhard Totschnig (ST3 leader)** Abdulrahman Dahash
Canada	Natural Resources Canada	Reda Djebbar
Denmark	**PlanEnergi**	**Rasmus Lund (ST4 leader)** Nikola Botzov Daniel Trier

France	INSA Lyon	Frederic Kuznik Kevyn Johannes
Germany	Forschungsstelle für Energiewirtschaft Fraunhofer IOSB-AST Fraunhofer UMSICHT Research Center Jülich **ZAE Bayern**	Andreas Zeislmair Peter Bretschneider Clemens Pollerberg Hendrik Wust **Andreas Hauer (Annex manager)** Anna Kummel Christoph Rathgeber
Italy	RSE Italy	Edoardo Corsetti Stefano Maran Federico Giudici Dario Siface
Korea	KIER	Sun-Hwa Yeon
Japan	Nagoya University HPTCJ Takasago	Masayao Okumiya Shuto Takayoshi Noboru Sue
Netherlands	ECN/TNO CE Delft	Herbert Zondag Joris Koornneef Thijs Scholten
Sweden	**KTH Royal Institute of Technology**	**Viktoria Martin (ST1 leader)**
Switzerland	Hochschule Luzern	Jörg Worlitschek Rebecca Ravotti Ueli Schilt Curtis Meister
Turkey	Cukurova Üniversitesi	Halime Paksoy
UK	Science & Innovation for Climate & Energy	Chloe Lianos

Apart from the official participating countries, two international organisations took part in Task 35:

- World Bank / Energy Storage Partnership
- International Renewable Energy Agency (IRENA)

1.4 Overview of expert meetings

A total of eight expert meetings and additional web conferences were organized. Table 2 lists the locations, dates, and number of meeting attendees.

Table 2: Details about the date and location of each expert meeting.

City	Country	Date	# Participants
Bad Tölz	Germany	16 – 18 October 2019	22
Web Conference	-	2 and 21 April 2020	42, 30
Web Conference	-	29 – 30 September 2020	51
Web Conference	-	1, 4, and 7 December 2020	17, 25, and 18
Web Conference	-	28 – 29 April 2021	32
Vienna (hybrid)	Austria	8 – 9 November 2021	17
Copenhagen (hybrid)	Denmark	26 – 27 April 2022	16
Milan (hybrid)	Italy	10 – 12 October 2022	14
Stuttgart (hybrid)	Germany	28 – 30 March 2023	13

1.5 Overview of deliverables

Table 3 shows the overview of both ongoing and concluded deliverables from Task 35.

Table 3: Overview of deliverables.

Deliverable	Subtask	Status
White paper	ST1	Drafting
Stakeholders workshop	ST1	Completed
Overview of technical examples	ST2	Completed
Overview of local systems examples	ST3	Completed
Germany 2050 model with scenarios	ST4	Completed
Final report	ST1,2,3,4	Drafting

2 Summary of Results

Considerable results have been achieved across all four subtasks. In the following pages, detailed results and deliverables for each subtask are presented.

2.1 Subtask 1 - Flexible Sector Coupling (FSC) Concept Development

In ST1, the flexible sector coupling (FSC) configuration and connections through different pathways were clearly defined with five possible pathways starting from RE via the three types of energy storage (thermal, gas/fuel, electrical) to the two consumption sectors (thermal, mobility) as highlighted in Figure 3.

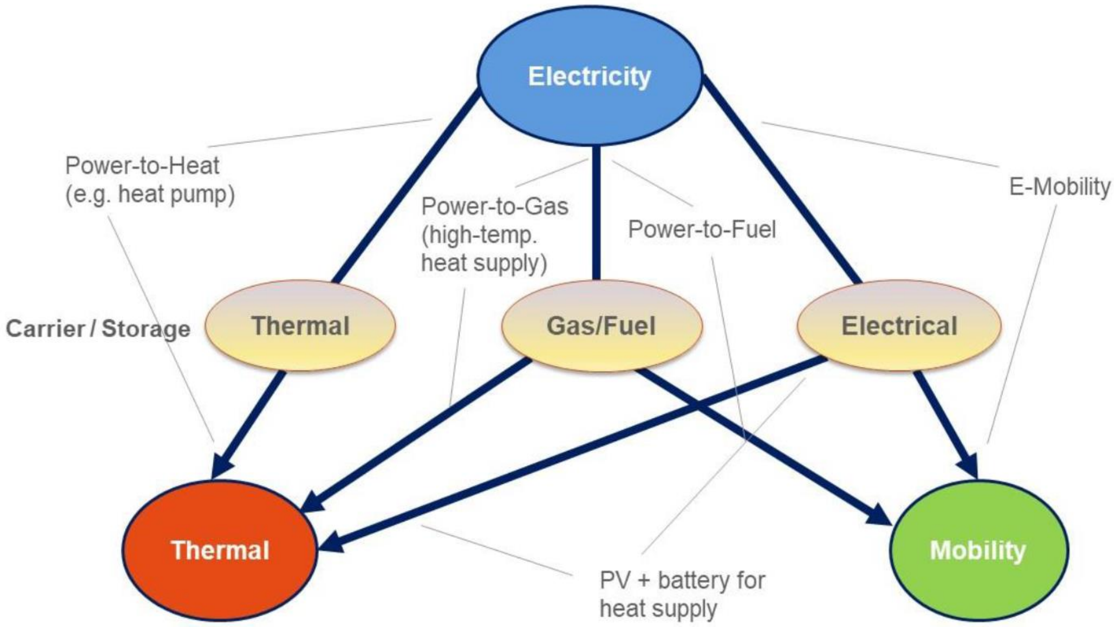


Figure 3. The refined concept of FSC and the pathways connecting different sectors and storage technologies.

The identification of the main pathways for flexibility allowed to identify both potential legal bottlenecks due to current taxation models that might become obsolete in a FSC configuration and opportunities for FSC in the current energy systems. In particular, the following opportunities were highlighted:

- FSC with storage enables Renewable Energy on Demand.
  - Opens up Renewable Energy (mainly renewable electricity) for other sectors – a larger market for renewable energy emerges.
- FSC with storage minimizes curtailment.
- FSC with storage allows for moving energy in time and space.
- FSC with storage minimizes the total system cost across the value chain.
  - Supports priority to demand-side solutions, whenever they are more cost-effective than investments in energy supply infrastructure.

Based on this, future recommendations aligning with current EU measures and with UN Sustainable Development Goals (SDG), especially SDG 7 “Affordable and Clean Energy” and SDG 12 “Responsible Consumption and Production”, were formulated as follows:

- Stable and integrated policy to support energy sector coupling, including energy storage options that provide flexibility.
  - Avoid multiple energy taxes across the value chain – energy carrier (e.g. electricity) taxed at the point of consumption.
  - Incentivize the minimization of curtailment of VRE, and rejection of industrial surplus heat.

    - Level taxation on fuels and electricity (natural gas vs electricity, fossil fuels for electricity generation vs for heat generation)

- Modernized market structures – energy storage working with price arbitrage, the foundation of a capacity market – a market for rapid ramping and rapid response.
- Enable a fair, “leveled” playing field for the technical and economic benefits and values energy storage solutions can provide.

In addition, a workshop involving key stakeholders was conducted at the Volta-X energy expo in Stuttgart in March 2023 to convey the most significant outcomes.

2.2 Subtask 2 - Configuration related storage technology specifications

In ST2 several examples on existing and upcoming storage configuration for all possible pathways identified in ST1 were collected from the experts and evaluated. In total, a collection of 30 FSC configuration examples was obtained. Of these, circa 40% are industrially proven and market available, while it is estimated the same fraction will come to the market in the next five years.

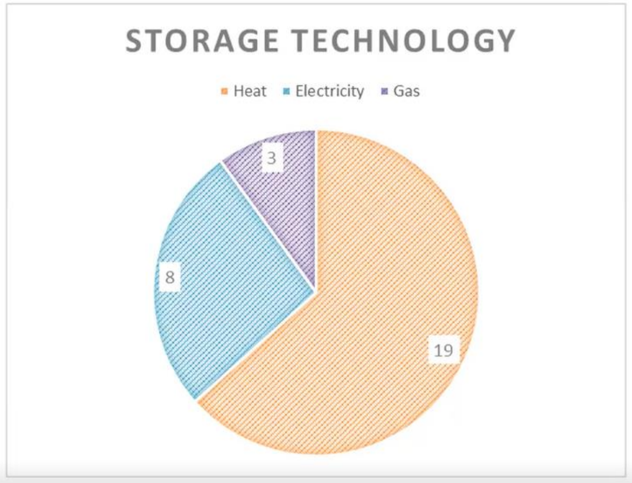


Figure 4. Overview of the storage technology type in the examples collected so far within ST2.

This allowed to gain a comprehensive overview of the technologies available and on those that might need further development in the near future as shown in Figure 4.

A very relevant example was that provided by the Living Lab Energy Campus presented in Figure 5.

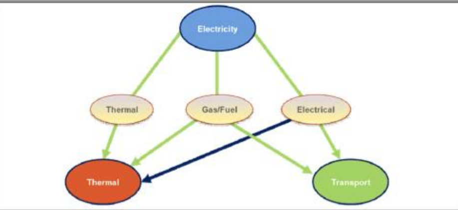
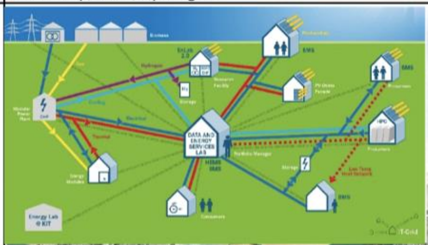
Example D:	Living Lab Energy Campus, Jülich		
Long Title:	Living Lab Energy Campus at Forschungszentrum Jülich	Storage Period:	seconds to seasonal
Application:	Highly integrated energy supply and storage system demonstrator on the campus; Possible application in urban districts for renewable energy long term storage and sector coupling	Status Technology:	7
Storage technology:	Li-Ion Batteries, Hydrogen Storage System (Electrolyzer, LOHC storage, Pressurized H2 storage, Fuel cell, CHP), DSM	Place, Country:	Jülich, Germany
Energy Source:	CHP, Solar, Wind	Capacity:	331.750 kWh
Energy Output:	electricity, heat, hydrogen	Power:	1.800 kW
Picture(s):	    		

Figure 5: FSC example for multiple pathways from renewable electricity to thermal and mobility demand sectors

This system includes a combined heat and power plant with hydrogen co-firing; lithium-ion batteries, storage and peak shaving unit; hydrogen infrastructure with electrolyzer, liquid organic hydrogen carriers storage, and fuel cell; waste-heat usage for low-temperature district heating network. The integration of battery and hydrogen electric vehicles is optional.

Another notable example of power-to-heat was that by Kraftblock, shown in Figure 6. In collaboration with Dutch energy supplier Eneco, Kraftblock is substituting gas with clean energy at a PepsiCo food production plant. Renewable electricity from Eneco is converted into high-temperature thermal energy storage by Kraftblock, which is then used to provide process heat for frying potato chips. The fossil-free system, utilizing thermal oil, replaces a gas-fired boiler to supply process heat.

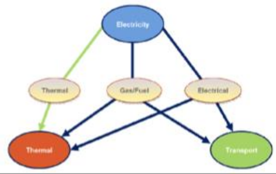
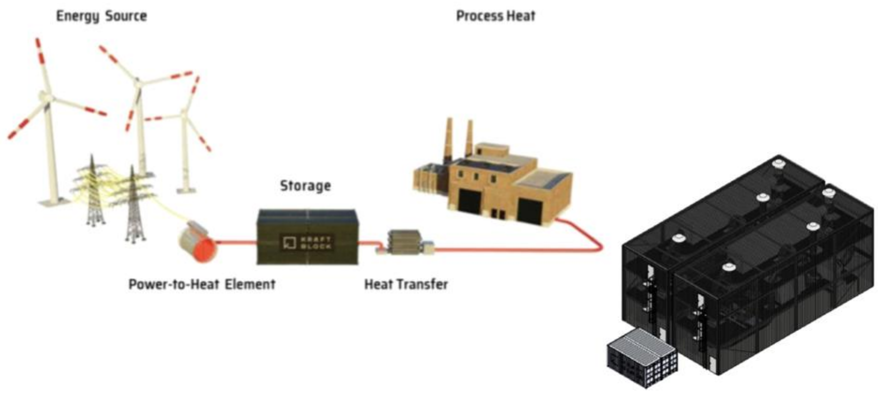
Example Power-to-heat	Kraftblock			
Long Title:	Net-Zero Heat System at PepsiCo food production	**Storage Period:**	hours - few days	
Application:	High-temperature sensible heat storage for process heat supply from renewable electricity	**Status Technology:**	6-8	
Storage technology:	Sensible solid heat storage at high temperatures (800 °C)	**Place, Country:**	The Netherlands	
Energy Source:	renewable electricity (wind)	**Capacity:**	70 000	kWh
Energy Output:	Process heat at about 300 °C	**Power:**	22	MW
Pictures:				

Figure 6: FSC example for power-to-heat applications at Kraftblock

HSLU provided two valuable examples for the power-to-heat pathway, namely the Heat4Cool demonstrator (https://www.heat4cool.eu) and the Ministor one (https://ministor.eu) (Figure 7 and 8). In both cases, power is transformed into heat to provide residential buildings with hot water.

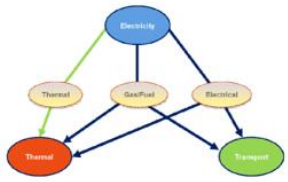
Example Power-to-heat	Heat 4 Cool			
Long Title:	Heat 4 Cool Demonstration: latent heat stores coupled to heat pump	**Storage Period:**	days	
Application:	Provision of space heating/cooling and domestic hot water	**Status Technology:**	Demo site (TRL 7)	
Storage technology:	Latent heat storage	**Place, Country:**	Chorzow (Poland), Sofia (Bulgaria), Valencia (Spain), Budapest (Hungary)	
Energy Source:	Electricity (solar and grid)	**Capacity:**	2.5	kWh
Energy Output:	Heat	**Power:**	~10	kW
Picture(s):				

Figure 7: FSC example for power-to-heat applications at the Heat4Cool demonstrator sites

Example Power-to-heat	**Minister**			
Long Title:	Compact residential storage system	**Storage Period:**	minutes/days/weeks	
Application:	Increased share of renewables and costs	**Status Technology:**	Demo sites (TRL 7)	
Storage technology:	Thermo-chemical, PCM	**Place, Country:**	Cork (Ireland), Santiago de compostela (Spain), Sopron (Hungary), Kimmeria (Greece)	
Energy Source:	Solar thermal, PV, Grid	**Capacity:**	182	kWh/m3
Energy Output:	Electricity, heat, cold	**Power:**	TBD	kW

Picture(s):

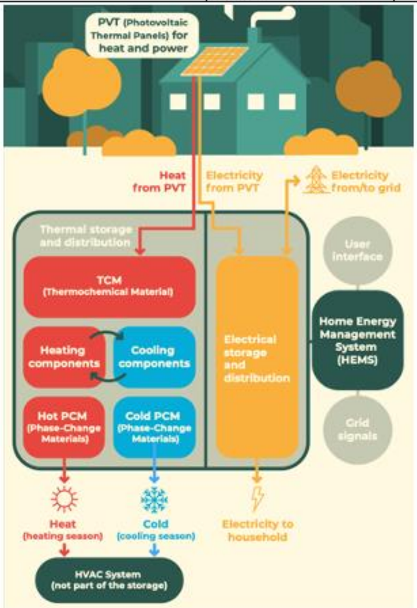


Figure 8: FSC example for power-to-heat applications at the Minister demonstrator sites

Through the examples presented, some remaining barriers for market integration were identified. These are mostly challenges in the system integration, including control integration and interface standardisation, regulatory barriers, non-flexible electricity tariffs, and upscaling/engineering issues.

2.3 Subtask 3 - Local Energy System Design and Operation

In ST3 based on the examples and data received in ST2, KPIs were defined in order to determine FSC configurations' efficiency and impact on different "local" scales (households, districts/hubs, cities).

The KPIs defined were:

- Cost reduction
- CO2 emissions reduction
- Renewables curtailment
- Degree of self-consumption
- Degree of reliability

Here, additional examples of multi-energy systems were provided by some of the participants including HSLU. In particular, the most relevant examples included:

- The first example showed a power-to-heat with a heat storage for heat networks in the Netherlands. Here, two techniques were explored, namely heat pumps and electric water heaters. Thermal storage options included tank storage (TTES), storage in an isolated ground pit (PTES), and high-temperature storage in an underground aquifer (HT-ATES) as outlined in Figure 9.

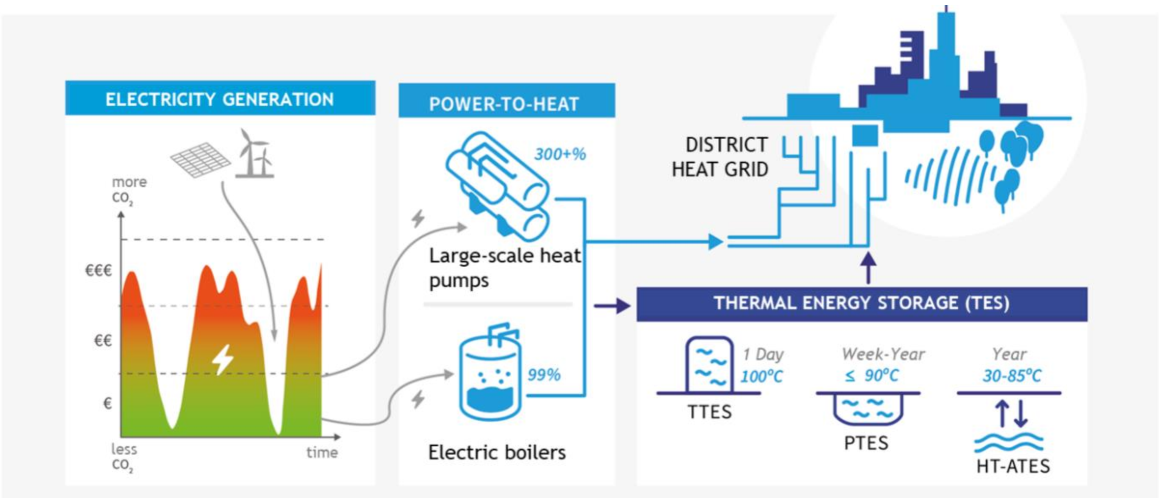


Figure 9: Illustration of the concept of power-to-heat combined with thermal energy storage for heat grids.

A business case was outlined, and the technical potential was determined. The impact on the electricity system was assessed through integrated modeling of electricity generation and sources in heat networks. Ultimately, technical and regulatory barriers were identified (Figure 10), and policy recommendations were formulated to facilitate the implementation of power-to-heat and thermal storage.

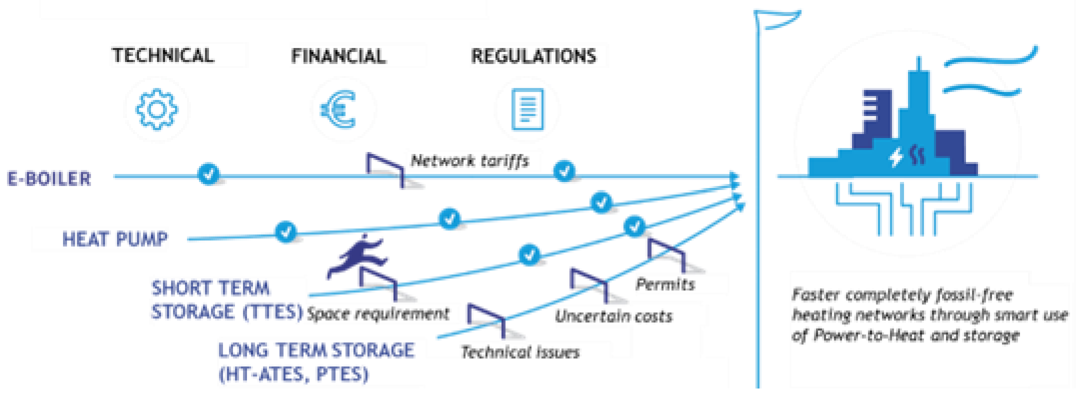


Figure 10: Technical, financial and regulatory barriers of the technologies involved

- A second study focused on cold storages integrated in a district cooling system in Sweden for power-to-cold configurations (Figure 11).

Figure 11: DC system of Norrenergi AB – the three cold production plants Sundbybergsverket, Frösundaverket (kylstation) and Solnaverket (where the existing cold storage is also located)

The study includes a case analysis of Norrenergi AB's district cooling system in Sweden, which serves Solna and Sundbyberg municipalities. The findings indicate that a combination of central and distributed CSs effectively facilitates FSC, offering competitive advantages compared to typical capacity investments like new chillers or pipes. Additionally, distributed TES were shown to also provide functional benefits to the network itself, in network configurations (as loops) which are more prone to differential pressure bottlenecks.

- In the example provided by HSLU, the effects of PV integration, fossil heater replacement, and thermal storage integration on the energy supply scenario of communities in Switzerland were evaluated. For this purpose, a model was deployed to represent the multi-energy system of the community. Simulations over one year of operation were carried out for different scenarios. Figure 12 shows the Multi-energy system model employed for a community considering the electricity and heating sectors including thermal storage.

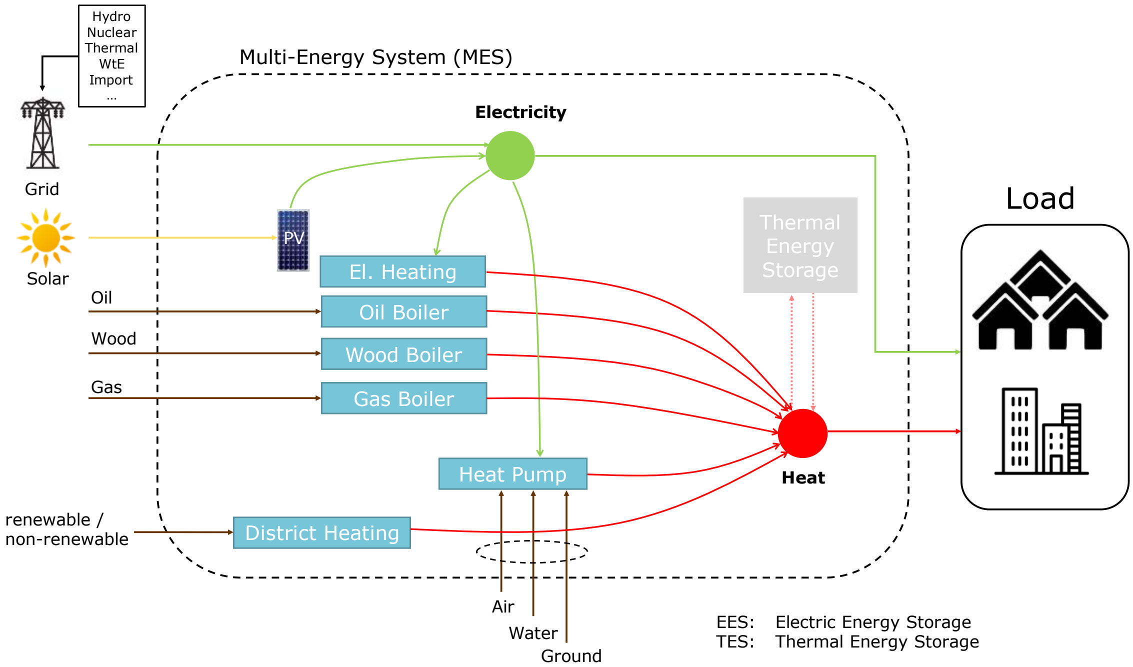


Figure 12: Multi-energy system model for a community considering the electricity and heating sectors including thermal storage.

The results presented demonstrated the impact of solar PV integration, fossil heater replacement, and thermal storage integration on the multi-energy system of a community. It was shown that integrating solar PV power alone led to limited benefits, as not all of the generated electricity could be utilized due to a supply/demand mismatch. The replacement of fossil heaters with heat pumps made use of some of the excess PV power through sector-coupling, as well as reduced carbon emissions linked to the burning of oil and gas. The implementation of thermal storage eliminated the need for solar PV export, as the heat supply could be shifted in time: the thermal storage was charged via heat pump during times of excess PV power availability. During times of high heat demand and low or no PV power availability, the thermal storage could be used to provide heat, reducing the requirement for heat pump operation. The increased use of locally generated solar PV power led to a reduction of cross-border imported electricity, which, in turn, resulted in a reduction in carbon-based emissions related to energy generation.

It is worth noting that this study only looked at the technical aspect of thermal storage and didn't consider costs associated with the design, installation, and operation of the systems.

The examples shown within the activities of ST3 meticulously illustrated the significance of sector coupling, particularly through the power-to-heat or power-to-cold pathways, in integrating renewable electricity from photovoltaic (PV) and wind sources.

The following key messages emerged:

- FSC enabled a more efficient utilization of installed PV/wind installations and mitigated curtailment.
- The inclusion of storage capacity within the FSC framework (with thermal energy storage for power-to-heat and power-to-cold in all studies) resulted in higher proportions of renewable energy within the system and a reduction in CO2 emissions.
- FSC contributed essential/additional flexibility to local multi energy systems (with high complexity), encompassing elements such as the electricity grid.
- The integration of installed storage capacity in conjunction with sector coupling, particularly power-to-heat and power-to-cold, led to decreased overall system costs.

2.4 Subtask 4 - National scale energy system analyses of FSC potential

In ST4, a national scale energy system analysis on the influence of FSC for Germany in 2050 was conducted. To model a decarbonized German energy system in 2050, a reference energy system based on the Heat Roadmap Europe project was implemented in the software EnergyPLAN. With a scenario analysis, the influence of installed energy storage capacity in five different applications (district heating, district cooling, individual heating, hydrogen, and electric vehicles) on the national energy system was investigated.

Given the boundary conditions and the scenario set, the model scope seen in Figure 13 was defined:

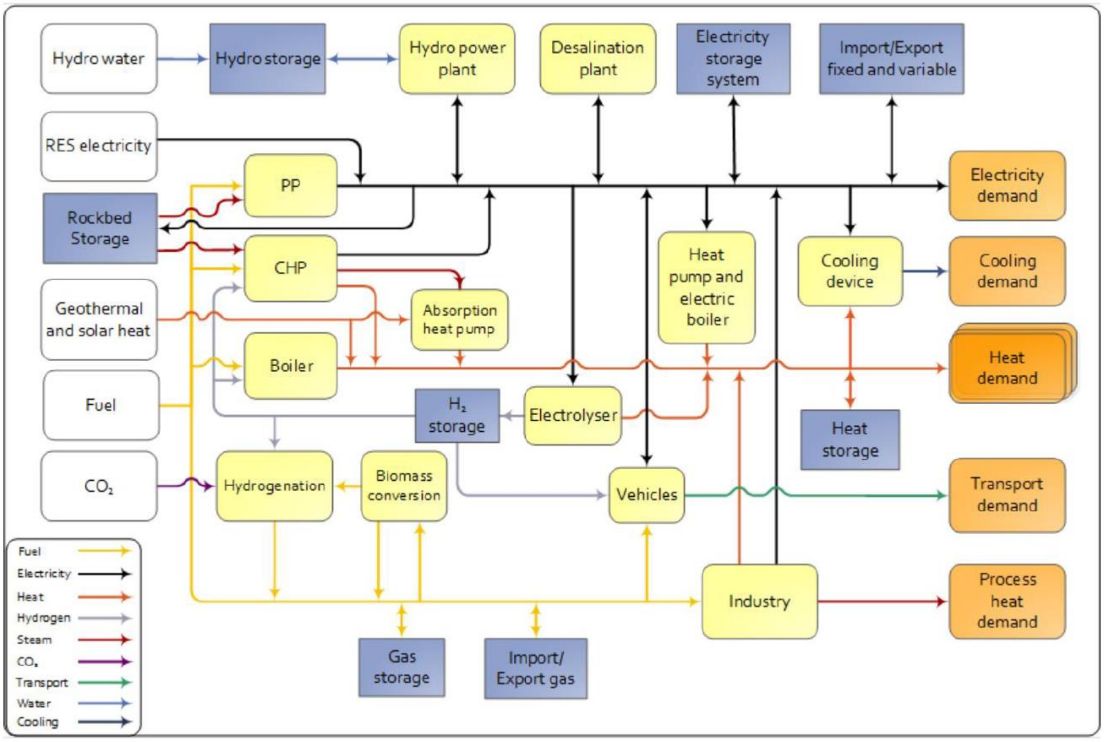


Figure 13: Model developed by PlanEnergi for the energy system analysis on the influence of FSC for Germany in 2050

The scenarios shown in Figure 14 were modelled:

Scenario	Name	Reference	Variation 1	Variation 2	Variation 3
1	DH Thermal storage	Reference	No storage	Double storage	
2	DH (no excess heat) Thermal storage	Reference (No excess heat)	No storage	Double storage	
3	Individual heat pumps Individual heat storage	Reference 1/10-day storage	No storage	1 day storage	
4	Individual electric heating Individual heat storage	Reference (electric heating) 1/10-day storage	No storage	1 day storage	
5	Hydrogen storage	Reference	~~No storage~~	Half storage	Double storage
6	District cooling Cold storage	Reference	No storage	Double storage	
7	Smart charge vehicles Battery storage	Reference 50% Smart Charge 50% Dump Charge	25% Smart Charge 75% Dump Charge	75% Smart Charge 25% Dump Charge	75% Smart Charge 25% Dump Charge + V2G
8	Electrolyser Hydrogen storage	Reference (double electrolyser cap.)	~~No storage~~	Half storage	Double storage

Figure 14: Overview of scenarios analysed in ST4 with the EnergyPLAN modelling tool for Germany 2050

The modelling activities showed that removing the district heating (DH) storage significantly increases both total costs and primary energy supply, primarily due to the reduced system flexibility. This limitation hinders intermittent production units from operating optimally under favorable conditions. Consequently, less efficient production units, such as boilers, play a more substantial role, leading to higher primary energy supply. Conversely, doubling the DH storage has the opposite effect, slightly reducing total costs and primary energy supply compared to the reference. A larger storage capacity allows for more flexible operation of intermittent DH production units, resulting in a more cost-effective and energy-efficient overall system. This was the most important result obtained, as it showed the vital role that energy storage will play to enable flexibility in future energy systems.

Additionally, the activities from ST4 brought to the following conclusions:

- Thermal energy storage in electrified district heating can reduce costs and improve system energy efficiency.
- The presence of excess heat in a central heating systems reduces the system costs but increases the necessity for a thermal storage in terms of energy efficiency.
- Heat production from individual heat pumps is considerably more expensive without thermal storage, due to the need for a larger production capacity.
- Cold storage for district cooling can reduce system costs and primary energy consumption.
- Hydrogen systems and storage play a central role in the system integration of fluctuating renewables as hydrogen can be used to cover demands directly or be converted to other fuels, and thereby creates FSC to both thermal and mobility demands simultaneously.
- A fully renewable based energy system without hydrogen storage needs significantly higher renewable energy production capacities, which increases costs considerably.
- Smart charging systems of battery-electric vehicles can generate better energy efficiency and lower total system costs.
- Battery-electric vehicles with a V2G option in addition to smart charge, can further reduce energy consumption and total costs.

3 Complementary activities at HSLU

HSLU contributed with own work and as well with bringing input from further activities in the Swiss research context. In particular, HSLU presented data and findings from the following studies and projects with a focus on the quantitative expectations on the amount of energy that can be supplied through energy storage integration:

- **Project SOTES (ongoing)**: Thermal Energy Storage - a new Approach of Constructive Technology Assessment (SOTES). A SNSF Sinergia project together with University of Berne (Political Science), HSLU CCTES, EMPA and OST (both technical). The project SOTES looks at seasonal thermal storage solutions and aims for pathways to overcome the current gap between the availability of technological solutions and their non-diffusion at the user side and look at the technology acceptance in more detail, with a particular focus on legal bottlenecks on a european level.
  The project is particularly relevant for ST1
- **Project QUBE (ongoing)**: Quartierbezogene erneuerbare Energien. An Innosuisse project of HSLU CCTES in collaboration with HSLU Social Science department together with the city and canton of Lucerne, the energy provider ewl and further regional institutions and companies in the energy sector. The project aims to promote and initiate cooperative energy production at neighborhood level. The aim is to design a socio-cultural approach to initialize and implement cooperative forms of renewable energy production and storage at neighborhood level. The realization and testing of the pilot project in the neighborhood should enable the applicability and scalability to other neighborhoods, communities or cities.
  The project is particularly relevant for ST1
- **Project TIKO (completed):** In this project, new procedures for the use/analysis of smart meter monitoring data were developed with partner company TIKO AG. Two main objectives were pursued: On the one hand, a method was developed to automatically differentiate between different operating states. On the other hand, a method for automatic, large-scale building characterisation and optimisation was developed, validated and evaluated by analysing field measurements of existing heat pumps.
  The project is particularly relevant for ST2 & ST3
- **Project GEAS (ongoing)**: “High-performance thermal insulation for STES” In this project with partner Swisspor AG a market-oriented and technically robust system is being developed that makes existing building structures usable as water storage up to 95°C by means of internal waterproof high-performance insulation.
  The project is particularly relevant for ST2 & ST3
- **Project HEAT4COOL (completed):** The H2020 project "Heat4Cool” investigated which renovation measures will make the building stock in Europe more energy-efficient. To this end, an optimisation tool was developed to find an optimal solution of measures to increase efficiency for given buildings and districts. In addition, new components for better utilisation of solar thermal systems and new processes for waste heat utilisation in building waste water were developed.
  The project is particularly relevant for ST2 & ST3
- **Project DeCarbCH (ongoing)**: “Decarbonization of Cooling and Heating in Switzerland”. The DeCarbCH project addresses the challenge of decarbonization of heating and cooling in Switzerland and prepares the grounds for negative CO2 emissions. The overall objective of the project (with the ultimate target of net zero emissions) is to speed up the implementation of renewables for heating and cooling in the residential sector as well as for the service and the industry sector. The DeCarbCH project focusses on three main

components, i.e. i) advanced renewable energy and transformation technologies, ii) thermal grids (for heating and cooling) and iii) energy storage.
The project is particularly relevant for ST4

- **Project EDGE (ongoing)**: "Enabling Decentralized renewable GEneration in the Swiss cities, midlands, and the Alps"
  The overall EDGE objective is to fast-track the growth of locally-sourced decentralized renewable energy in Switzerland through a regionalized analysis tailored to the Swiss cities, midlands, and the Alps. The pathways towards largely electrified and multi-carrier energy systems are examined by analyzing electricity, mobility, and heating sectors.
  The project is particularly relevant for ST4
- **Project SwissStore (completed)**: The SNSF Project of Uni Genf, Uni Basel and HSLU CCTES focuses on the role of storages in the Swiss Context introducing thermal aspects into national energy models. The project ended in early 2022 and has generated a sound modelling and framework basis for the study of storages in the energy system with a focus on the building sector introducing over 1000 building archetypes.
  The project is particularly relevant for ST4
- **PATHFNDR (ongoing)**: "PATHways to an efficient future energy system through Flexibility aND SectoR Coupling"
  The PATHFNDR project aims at solving the challenge on how to incorporate a much higher share of renewable energy sources into the energy system while striving to achieve a more efficient Swiss energy system with the goal to reach a net-zero greenhouse gas emission-society by 2050. To fulfill this goal, feasible pathways are studied in particular through enabling flexibility providers across various sectors, along different temporal and spatial scales ranging from the European perspective over the country level to municipalities and individual buildings and companies.
  The project is particularly relevant for all ST.

In addition, the HSLU spin-off company **COWA Thermal solutions AG** is currently in the process of entering the market with compact latent-heat storage solutions to increase the share of RE from solar (PV) in residential settings. Knowledge gained by the concept development and market entry was shared with the IEA network.

The following publications were of particular relevance to the FSC IEA annex 35:

- Gianfranco Guidati, Luca Baldini, Michel Haller, Jörg Worlitschek, AEE FESS Positionspapier: `Winterstrombedarf und saisonale Wärmespeicher – mit Sommerwärme Strom im Winter sparen', AEE Suisse, 2022;
  The White paper is available at:
  https://speicher.aeesuisse.ch/wp-content/uploads/sites/15/2022/05/FESS_Saisonale_Waermespeicher_Positionspaper_2205.pdf
  Further information around the white paper and its dissemination via other media can be found at www.hslu.ch/positionspapier.
- Berger, M.; Schroeteler, B.; Sperle, H.; Püntener, P.; Felder, T.; Worlitschek, J. (2022) Assessment of residential scale renewable heating solutions with thermal energy storages. Energy, 244,A, 1226198.
  Available at: https://www.sciencedirect.com/science/article/pii/S036054422102867X
- Villasmil, W.; Troxler, M.; Hendry, R.; Schuetz, P.; Worlitschek, J. (2021) Control strategies of solar heating systems coupled with seasonal thermal energy storage in self-sufficient buildings, J. En. Storage, 42, 103069
  Available at: https://www.sciencedirect.com/science/article/pii/S2352152X21007775
- Berger, M.; Worlitschek J. (2019) The link between climate and thermal energy demand on national level: A case study on Switzerland, En. And Build., 202, 109372
  Available at: https://www.sciencedirect.com/science/article/pii/S037877881931120X

Lastly, all official information and reports published by the IEA and the TCP on energy storage (ES) concerning Annex 35 can be found at the following link: https://iea-es.org/task-35/.

In addition, all final reports published by the IEA and the TCP on energy storage (ES) concerning other Annexes can be found at the following link: https://iea-es.org/publications/type/final-reports/.

4 Outlook

Currently, subtask leaders are drafting final reports concerning the activities conducted within their respective subtasks. These will contribute to both the white paper and the final report presented to the IEA executive committee (ExCo). Both the white paper and the final report are as well in the drafting phase, and are expected as early as Q1-Q2 2024.