



SWEET Call 1-2020: PATHFINDER

Deliverable report

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Internal project report

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Executive Summary

In this PATHFINDER deliverable, we investigate the potential for sector-coupling and flexibility in the net-zero Swiss energy system, focusing on the heat and industrial sectors. Given their substantial energy demands and potential for electrification, these sectors have been identified for their promising sector-coupling and flexibility potential. To holistically assess this potential, we develop a soft-link between three core models in the PATHFINDER project: Euro-Calliope, SecMOD, and Nexus-e. Each model contributes an essential component for our holistic analysis.

Our soft-link framework integrates electricity trade data from Euro-Calliope, sector-coupled electricity demands from SecMOD, and detailed electricity grid modeling from Nexus-e. Applying our framework to a reference scenario, we find that electrification dominates the decarbonization of civil and industrial low-temperature heat, with heat pumps and electric boilers supplying 100% of these heat demands. This electrification results in an additional 17.9 TWh/year of electricity demand, 23% higher than prior assumptions made by Nexus-e. Medium and high-temperature industrial heat demands are largely met by waste-to-energy and biomass. These energy carriers have a limited availability and competing uses across energy sectors, which we are able to capture with the SecMOD link in the soft-link framework. Therefore, by considering the sector-coupling perspective, our approach provides more realistic projections of the energy system's sector-coupled electricity demands.

From our reference scenario, we also identify significant short-term flexibility contributions from residential and low-temperature industrial heat: 70% of low-temperature industrial heat demand is temporally shifted to align with renewable electricity availability. Additionally, electricity trade emerges as a major long-duration flexibility source, reinforcing the importance of considering the cross-border electricity flows in our soft-link.

Overall, this deliverable establishes a comprehensive framework for holistically assessing the role of sector-coupling and flexibility in the net-zero Swiss energy system. We test this framework on a reference scenario, showing the strengths of our approach and identifying key contributions from the civil heat and industrial sectors to sector-coupling and flexibility for Switzerland.

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1 Goal & Scope definition

The overarching goal of this deliverable is to assess the potential of sector-coupling and flexibility considering the sectors heating and industry in Switzerland on a national and cantonal level. In this Chapter, we outline our deliverable goals and define the scope of our analysis. In Section 1.1, we introduce the necessary background for motivating our deliverable goal. In Section 1.2, we introduce our methodological approach for assessing the potential of sector-coupling and flexibility from the heating and industry sectors.

1.1 Background

Here, we introduce the necessary background for motivating our deliverable goal. Section 1.1.1 introduces the importance of sector-coupling and flexibility for the Swiss energy system, setting the context for Work Package 1 (WP1) and our deliverable. Section 1.1.2 discusses the relevance of the heating and industry sectors regarding sector-coupling and flexibility. Section 1.1.3 describes the modeling tools used for our methodology.

1.1.1 Sector-coupling and flexibility

Switzerland has pledged to reach net-zero greenhouse gas emissions by 2050 (Federal Council, 2021). In order for Switzerland to reach this target, emissions from all energy sectors must be abated. Electrification can play an important role in sectoral emissions abatement by shifting energetic reliance from fossil-based resources to renewables. For instance, transitioning the heat and transportation sectors to heat pumps and battery electric vehicles reduces reliance on conventional fossil-based technologies. This increased reliance on the electricity sector is an example of sector-coupling, where energy sectors become interconnected to support the integration of renewables (Ramsebner et al., 2021). Sector-coupling can play a significant role in the future Swiss net-zero emission energy system.

As sector-coupling increases, the increased electricity demand requires an expansion of the electricity sector, which involves careful infrastructure planning. Furthermore, as the electricity sector integrates more renewables, their variable nature requires the sector-coupled energy system to also increase flexibility. Flexibility refers to the ability of an energy system to manage the variability and uncertainty that renewables introduce into the system on different time scales to reliably supply all sectoral energy demands (Taibi et al., 2018). Flexibility can be obtained from dispatchable energy suppliers, demand response from energy consumers, energy conversion (i.e. sector-coupling), energy storage, and energy trade (Bardow et al., 2023).

The aim of WP1 in the SWEET PATHFINDER project is to develop potential designs for an efficient, flexible, resilient, cost-competitive, and sustainable future Swiss energy system, with an emphasis on

a broad range of flexibility and sector-coupling strategies. In this deliverable 1.2.1, we assess the potential of sector-coupling and flexibility considering the sectors heating and industry at a national and cantonal level. The role of sector-coupling and flexibility for the transportation sector is considered in deliverable 1.2.2.

1.1.2 The Swiss heating and industry sectors

The Swiss heating and industry sectors are significant contributors to the country's emissions. Together, they comprised 45% of the country's emissions in 2022, with 22% coming from space heating and hot water supply for residential and commercial buildings (FOEN, 2024a) and 23% coming from industry (FOEN, 2024b). Regarding heating of buildings, currently more than 50% of space heating and more than 40% of hot water are supplied via fossil fuels (heating oil or gas) (Federal Statistical Office, 2024). Swiss cantons are increasingly setting mandates for the phase-out of fossil-based heating systems in exchange for electricity-powered heat pumps. Zurich, Basel, and Geneva have already banned the installation of new fossil fuel-based heating systems for new buildings (Torné and Trutnevyte, 2024). While this push for sector-coupling of the heat sector will reduce reliance on fossil fuels, it will require a non-trivial expansion of the electric grid. In fact, projections expect heat pumps to account for 44% of the increase in electricity demand between 2019 and 2050 (Bundesamt für Energie, 2020b). This increased electricity demand through sector-coupling can potentially help with renewables penetration.

In addition to enhancing renewables penetration, heating of residential and commercial buildings has the potential to provide flexibility to renewables-dominated energy systems. By making use of the thermal inertia of buildings, heat supply can be shifted to better follow the availability of renewables as long as building temperatures stay within a comfort range. Rinaldi et al. (2021, 2022) show that flexible heat pump operation contributes to an increase in photovoltaic deployment for the Swiss residential sector by 2050. Ultimately, the heating sector merits careful consideration in the Swiss sector-coupled energy system transition due to its potential role in both sector-coupling and flexibility.

Regarding the Swiss industry sector, emissions are mainly attributed to fossil fuel combustion to fulfill its energy demands. Swiss industry requires 6 TWh/year of electricity and 20 TWh/yr of heat (Mayer et al., 2024), at various temperature levels. Lower temperatures can be directly electrified with heat pumps or electric boilers. Higher temperatures, however, cannot be so easily electrified. Emissions abatement of industrial high-temperature heat requires more electricity-intensive or capital-intensive solutions such as power-to-X (gas or hydrogen) for combustion, carbon capture and storage, or high-temperature resistance heaters (Leicher et al., 2024). Combustion of biomass is also an option for supplying high-temperature industrial heat, although biomass is a limited resource with many competing uses and may not be fully available for the industry sector (Gerssen-Gondelach et al., 2014). Hence, the emission abatement strategies chosen for industrial energy demands can also have a large impact on the electric grid.

At the same time, the industry sector can provide flexibility to a renewables-dominated energy system in numerous ways. One way is through demand-side management (DSM), where industrial energy consumption profiles are altered to follow the availability of renewables (Meyabadi and Deihimi, 2017). Implementing this flexibility from an industry perspective can be challenging due to reliability concerns. However, the industry sector is a good candidate for DSM from an energy system perspective due to its large energy demands, its potential for shifting production over longer time horizons, thus

providing longer duration flexibility, and the avoidance of behavior changes from individuals (Zhang and Grossmann, 2016, Williams et al., 2023). We explore the potential of industrial DSM for the Swiss sector-coupled energy system in Section 3.3.

A specific and readily available way that the industry sector can provide flexibility is through thermal energy storage (TES), which allows for the temporal shifting of industrial heat supply. If heat supply is electrified, i.e., through heat pumps or electric boilers, TES can allow industrial heat supply to follow the availability of renewables. TES can have round-trip efficiencies greater than 95% for heat recovery (Murakoshi and Fushimi, 2022a). Furthermore, TES technologies are significantly cheaper than batteries (Victoria et al., 2019). Hence, TES is an efficient and inexpensive way to implement flexibility at industrial sites. In our evaluation of industrial DSM for the Swiss sector-coupled energy system¹ (Mayer et al., 2024), we benchmark the energy system benefits obtained from TES to those obtained from industrial DSM.

Overall, the Swiss heat and industry sectors are key components of the energy system's transition to net-zero emissions. They are both expected to play a significant role in sector-coupling and flexibility as the electricity sector evolves to incorporate increasing renewables. To assess this potential role, as is the objective of this deliverable, we need models that capture the sector-coupling and flexibility potentials of the heat and industry sectors while maintaining a detailed view of a renewables-dominated electricity sector. Several models are available within the PATHFNDP project, each contributing a piece of the required modeling capabilities. These models are described in the following section (Section 1.1.3).

1.1.3 Models available for our deliverable goals: Euro-Calliope, SecMOD, & Nexus-e

A suite of models are available within the PATHFNDP project to help reach our deliverable goals: Euro-Calliope, SecMOD, and Nexus-e. Each model has its own scope and strengths, which are all needed to properly evaluate the roles of flexibility and sector-coupling for Switzerland.

At the broadest level, Euro-Calliope considers the entire European sector-coupled energy system (Pickering et al., 2022). Euro-Calliope minimizes the costs of the European energy system, determining the cost-optimal investment and operational decisions for each European country, including Switzerland, subject to emission constraints. Euro-Calliope provides insights regarding electricity trade between Switzerland and its surrounding countries. Electricity trade is particularly important for Switzerland, which has a significant seasonal imbalance of renewable electricity production and consumption between summer and winter (Mellot et al., 2024): Switzerland is expected to import around 9 TWh of electricity in the winter months in 2050, nearly 20% of the total electricity consumed during the season (Bundesamt für Energie, 2020a), which raises concerns around secure electricity supply for the future Swiss energy system. Therefore, electricity trade is an important component in our modeling scope.

However, Euro-Calliope represents Switzerland with a single node, hence prohibiting the evaluation of sector-coupling and flexibility at a cantonal level. Additionally, the lack of spatial resolution overlooks the critical spatial dimension of renewable resource availability (Pfenninger et al., 2014). Considering this spatial dimension is necessary for resolving the Swiss electricity grid—the central pillar for effective sector-coupling.

¹<https://doi.org/10.3389/fenrg.2024.1443506>

At a more spatially detailed level, SecMOD considers the Swiss sector-coupled energy system with spatial resolution (Mayer et al., 2024) (cf. Chapter 2). SecMOD minimizes the costs of the Swiss energy system, determining the cost-optimal investment and operational decisions for each Swiss canton subject to national emission constraints. However, the current version of SecMOD does not consider Switzerland's neighboring countries in its system boundaries, neglecting the critical component of electricity trade. Additionally, SecMOD models a simplified electricity grid with a DC-power-flow implementation and a central planner approach. DC-power-flow models simplify the representation of the electric grid via linearization of the active power flow equations (Dvijotham and Molzahn, 2016). While this approach significantly reduces computational complexity, it disregards transmission losses and reactive power flows, potentially leading to inaccuracies on the order of 5% (Van den Bergh et al., 2014).

In both Calliope and SecMOD, a central planner approach assumes that all investment and operational decisions are made by a single entity, neglecting the potentially conflicting interests of individual stakeholders in the decision-making process (Shu et al., 2024). Specifically, the SecMOD model of Switzerland assumes that all investment and operational decisions are centrally made considering a single objective for all of Switzerland, disregarding the priorities and objectives of regional/individual decision-makers responsible for deploying renewable energy sources. A central planner approach can drastically affect the spatial distribution of renewable energy deployment (Shu et al., 2024).

At the most granular level, Nexus-e focuses on modeling the Swiss electricity sector in great detail by combining modules that consider: centralized investment decisions (Centiv), distributed investment decisions (Distiv), grid security (Cascades), and market (eMark) and economic (GemEI) drivers. Nexus-e consists of a soft-link between the different modules to resolve a highly informed future net-zero emission Swiss electricity sector (Gjorgiev et al., 2022). Besides considering many more dimensions necessary for electricity sector planning than SecMOD, the Nexus-e modules are formulated as mixed integer linear programs (MILP), as opposed to SecMOD, which is formulated as a linear program (LP). The MILP formulation captures more realistic discrete investment decisions and a more accurate representation of operational behavior, such as ramping limits.

While Nexus-e models the electricity sector in great detail, it does not model any additional sectors, such as heat and industry. Rather, Nexus-e relies on exogenous projections of their future electricity demands. Additionally, while Nexus-e does consider Switzerland's neighboring countries in the system boundaries, it does not resolve their installed capacities of electricity-producing technologies but rather relies on exogenous data for these capacities. The initial idea of this deliverable had, therefore, been to generate this input data for Nexus-e in static form. However, over the course of the project, a tighter model integration seems promising and achievable.

In summary, neither Euro-Calliope, SecMOD, nor Nexus-e are sufficient in isolation to adequately evaluate the role of flexibility and sector-coupling from the heat and industry sectors at the national and cantonal levels for Switzerland. Therefore, in this deliverable, we create a soft-link between all three models, passing the critical information between them to harness their individual strengths. Through our soft-link, we ultimately make the heat and industry sector electricity demands available for Nexus-e to evaluate their impact on the electricity sector, the backbone of the Swiss sector-coupled energy system.

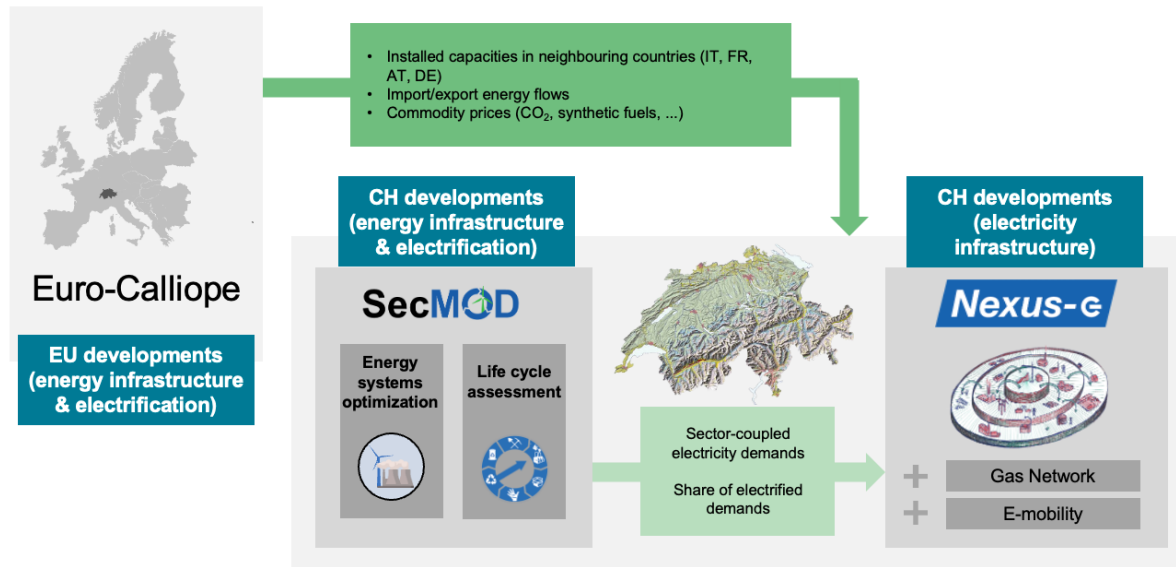


Figure 1.1: Schematic of soft-link between Euro-Calliope, SecMOD, and Nexus-e.

1.2 Softlinking Euro-Calliope, SecMOD, & Nexus-e

Through our soft-link approach, each model provides a piece of the necessary information to holistically evaluate the role of flexibility and sector-coupling from the heat and industry sectors for Switzerland (cf. Figure 1.1): First, Euro-Calliope optimizes the European sector-coupled energy system for a net-zero scenario in 2050. These results provide the hourly electricity flows between Switzerland and its four neighboring countries: Germany, France, Italy, and Austria. The electricity flows are then sent to SecMOD. The Euro-Calliope results also provide the installed capacities of electricity-generating technologies in Switzerland's neighboring countries and the hourly commodity prices (i.e. synthetic fuels, CO₂). These installed capacities and hourly prices are sent to Nexus-e.

The flows from Euro-Calliope sent to SecMOD are separated into exports and imports. The exports are exogenously provided as additional electricity demands that the Swiss energy system must fulfill. The imports are exogenously provided as a cost-free electricity supply option that the Swiss energy system can choose to utilize but is not required to. SecMOD then optimizes the spatially and time resolved sector-coupled Swiss energy system for a net-zero scenario in 2050 (Section 2).

In SecMOD, we include the residential heat sector, comprised of space and warm water demands for private households and the commercial sector. We represent the industry sector by including its electricity and process heat demands at three temperature levels (Section 2.2), as the industrial energy demands are the biggest contributor to the sector's emissions for Switzerland (Section 1.1.2). We also include the private mobility sector, as modeled by Mayer et al. (2024). However, as the focus of this deliverable is on the heat and industry sectors, we do not go into detail as to how the mobility sector is modeled.

The SecMOD optimization results yield the sector-coupled electricity demands for residential heating, industrial heating, and mobility. These demands are sent to Nexus-e which already considers the industrial electricity demands in their base load profiles. The sector-coupled electricity demands for mobility are used to scale the detailed e-mobility profiles provided by the work done in Deliverable 1.2.2 by sending the share of electrified mobility to Nexus-e.

Finally, Nexus-e combines their base electricity demand profiles with the sector-coupled electricity demands from SecMOD and with the neighboring country electricity-generation capacities from Euro-Calliope to model the Swiss electricity sector in great detail. With the detailed Nexus-e view, we can accurately represent flexibility strategies for the residential and industrial heating sectors, and understand the implications of these sector-coupled demands on the Swiss electricity grid.

1.3 Reference scenario description

To evaluate the capabilities of our soft-link, we rely on a reference scenario that represents a technologically advanced and highly market-integrated future Swiss energy system. This reference scenario assumes a shared carbon responsibility between Switzerland and Europe, allowing Switzerland to offset its residual emissions abroad and thus increase its domestic emissions target. Still, we assume an emission target of -1.6 Mt for Switzerland, reflecting the need to offset 30 % of the country's current aviation emissions domestically (Bundesamt für Statistik (BFS), 2024). With this target, we implicitly assume that by 2050, 70 % of aviation fuel will be produced from renewable sources.

The scenario also assumes high market integration with the European energy system and with world trade. This assumption involves unrestricted electricity trade with the neighboring countries and a restriction of 866.7 kton/year of synthetic fuel imports taken from Marcucci et al. (2022) under their high market integration scenario (Section 2.4).

Additionally, the scenario adopts a high-tech perspective, incorporating progressive assumptions on innovative technologies and flexibility options. Specifically, the scenario allows for the deployment of flexible heat pumps and battery electric vehicles, which enhance flexibility in both the heating and transport sectors.

Overall, the reference scenario corresponds to the abroad-high-progressive scenario described in more detail in PATHFND's synthesis report II (Sanvito et al., 2024). This scenario definition is based on and aligned with the pre-existing CROSS scenario document (Marcucci et al., 2022). By applying the soft-link to this reference scenario, SecMOD assesses the decarbonization of the Swiss heating and industrial sectors, while providing their sector-coupled electricity demands for Nexus-e.

2 The Swiss sector-coupled energy system model in SecMOD

In this chapter, we present the Swiss sector-coupled energy system model SecMOD used for our analysis. Our model includes both time and spatial resolution. For the time resolution, we consider hourly data for every hour of the year. For the spatial resolution, we consider 162 nodes: 154 nodes are located within Switzerland, while additional 8 nodes represent Switzerland's four neighboring countries. Based on these nodes, our model represents Switzerland's high-voltage grid, including connections to the neighboring countries.

In this chapter, we focus on our modeling assumptions for the Swiss residential (Section 2.1) and industrial heating (Section 2.2) sectors as these sectors are the focus of this deliverable. We also present our biomass and waste assumptions (Section 2.4) since these resources are an important component available for the Swiss heating sector. Finally, we present our modeling assumptions for carbon capture and storage (Section 2.5), a key technology for achieving the net-zero emissions target. The remainder of the modeling details concerning the other energy sectors can be found in the Supplementary Information of Mayer et al. (2024).

2.1 Residential heat sector

The residential heat demand covered by our model comprises the space heating and warm water demands of private households and the commercial sector, provided by the CROSS Scenarios and Drivers Definition (CROSS, 2022). The total residential heat demand for Switzerland in 2050 is projected to be 66.3 TWh, with 44.6 TWh coming from private households and 21.7 TWh coming from the commercial sector.

To spatially and timewise distribute this yearly demand, we first model a spatial resolution based on cantonal heating demand shares and population distribution of the communes (Section 2.1.1). Then, we create an hourly demand profile over the year (Section 2.1.2). In Section 2.1.3, we describe the technologies available to produce residential heat. Finally, in Section 2.1.4 we describe our modeling of flexibility for residential heat.

2.1.1 Spatial resolution of residential heat demand

The residential heat demand from private households is spatially distributed based on the cantonal heating demand shares and the population distribution of the communes within the cantons. First, we derive the heat demand of private households in each canton, Q_q^{ph} , by multiplying the national yearly private household demand, $Q^{ph} = 44.6$, with the cantonal heating demand shares, f_q^{hd} , given by the Hotmaps Project (Pezzutto and Zambotti, 2018, 2019) (Eq. 2.1).

$$Q_q^{ph} = f_q^{hd} \cdot Q^{ph}, \forall q \in \mathcal{Q} \quad (2.1)$$

The cantonal heating demand shares represent the share of private heat demand in each canton, q , from the national demand in 2012. We assume that the cantonal shares remained constant in the last decade and that they will stay constant through 2050 as a conservative assumption.

After allocating the private household demand to individual cantons, we divide the demands between the communes, Q_m^{ph} . Each commune, m , gets a share of its cantonal demand that is proportional to the population, p , of the commune (Eq. 2.2).

$$Q_m^{ph} = \frac{p_m}{p_q} \cdot Q_q^{ph}, \forall m \in \mathcal{M}_q, \forall q \in \mathcal{Q} \quad (2.2)$$

The national yearly residential heat demand from the commercial sector, $Q^{co} = 21.7$, is spatially distributed based on the population of each commune, p_m relative to the total Swiss population, p_{CH} (Eq. 2.3). The spatial distribution of the Swiss residential heat demand is shown in Figure 2.1.

$$Q_m^{co} = \frac{p_m}{p_{CH}} \cdot Q^{co}, \forall m \in \mathcal{M}_q \quad (2.3)$$

Finally, we redistribute the commune-level residential heat demands into our model's 162 nodes based on spatial proximity.

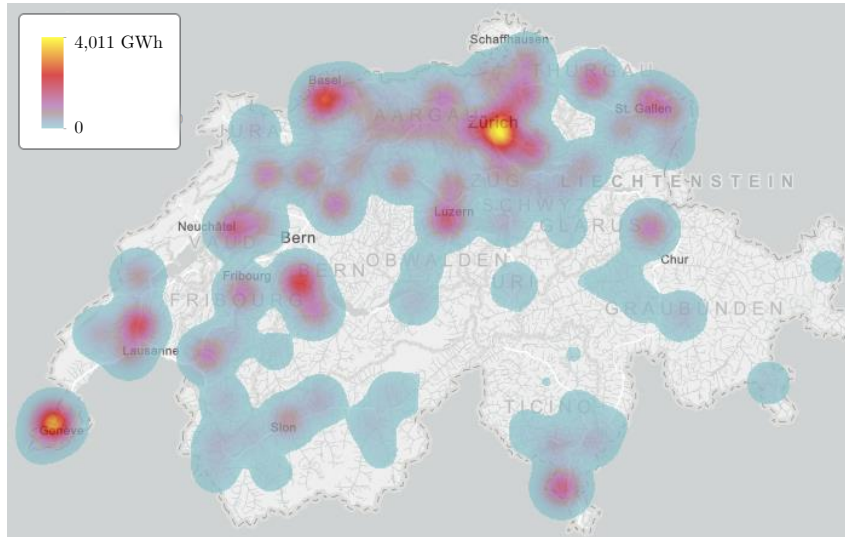


Figure 2.1: Spatial distribution of the yearly Swiss residential heat demand in 2050.

2.1.2 Time resolution of residential heat demand

To represent the private household residential heat demand in time, we use the approach of Baumgärtner et al. (2021). This approach is also known as the "Heating Degree Method" as recommended by

the SIA 380/1 standard (SIA, 2016). We model the temporal profile of this heat demand using the hourly outdoor temperature of Switzerland (Renewables.ninja, 2021, Gelaro and McCarty, 2017) as follows:

- 1) Days are assumed to have a heating demand only if the average daily outside temperature is below 12°C (Swiss Federal Office of Energy (SFOE), 2020). Otherwise, the heat demand of the entire day is assumed zero.
- 2) For days that have a heat demand, the hourly demand is proportional to the normalized temperature difference between the target indoor temperature of 20°C, T^i , (Swiss Federal Office of Energy (SFOE), 2020) and the outdoor temperature, T_t^o . This temperature difference is normalized by the sum of the temperature difference for the entire year. Outdoor temperatures are taken from Renewables.ninja (2021), Gelaro and McCarty (2017) for the year 2019. As a conservative estimate, we neglect the effects of climate change on heating demand.
- 3) To get the private household residential heat demand of a Swiss commune m at an hour t , $Q_{m,t}^{ph}$, we multiply the temperature factor described above with the yearly private heat demand of the commune, Q_m^{ph} (Eq. 2.4).

$$Q_{m,t}^{ph} = \frac{\max\{0, (T^i - T_t^o)\}}{\sum_t (T^i - T_t^o)} \cdot Q_m^{ph}, \forall m \in \mathcal{M}_q, t \in \mathcal{T}. \quad (2.4)$$

Regarding the temporal residential heat demands, which comprise both space heating and hot water, for the commercial sector, $Q_{m,t}^{co}$, we assume that they stay constant for every hour (Eq. 2.5).

$$Q_{m,t}^{co} = \frac{Q_m^{co}}{8760}, \forall m \in \mathcal{M}_q \quad (2.5)$$

The total residential heat demand for each commune at each time step is then calculated as the sum of the private household demand, $Q_{m,t}^{ph}$, and the commercial demand, $Q_{m,t}^{co}$ (Eq. 2.6).

$$Q_{m,t}^{res} = Q_{m,t}^{ph} + Q_{m,t}^{co}, \forall m \in \mathcal{M}_q, t \in \mathcal{T} \quad (2.6)$$

2.1.3 Residential heat provision technologies

To produce residential heat, we consider ground-source heat pumps, electric boilers, gas boilers, gas combined heat and power (CHP), hydrogen boilers, heat from waste incineration, and heat from burning of wood. Thus, while we do not explicitly model district heating, we implicitly account for it by including technologies that could be used in district heating networks. We also consider the option to retrofit buildings with thermal insulation to overall decrease the heat demand by 13.3 TWh/a (Marcucci et al., 2021b). The resource availabilities for waste and wood are documented in Section 2.4. The techno-economic parameters for the considered technologies are found in Tables 2.1 and 2.2.

Table 2.1: Costs and lifetimes of residential heat production technologies for the year 2050 used in our Swiss energy system model. CHP: combined heat and power, CCS: carbon capture & storage.

Technology	CAPEX [EUR/kW]	Maintenance [EUR/(kW·a)]	Cost sources	Lifetime [years]
electric boiler	238	4.75	Brauner (2019)	20 (Henning and Sauer, 2015)
thermal insulation	2369	0.00	Baumgärtner et al. (2021)	50 (Baumgärtner et al., 2021)
heat pump (ground)	3000	20.21	NERA Economic Consulting (2009), Moret (2017a)	20 (Henning and Sauer, 2015)
natural gas boiler	152	4.57	Moret (2017b,a)	20 (Baumgärtner et al., 2021)
natural gas CHP	660.7	17	Panos et al. (2023)	25 (SFOE, 2022)
hydrogen boiler	38	0.38	Panos et al. (2023)	25 (SFOE, 2022)
oil boiler	137	8.2	Moret (2017b,a)	20 (Baumgärtner et al., 2021)
waste CHP with CCS (electricity-driven)	4454	44.5	Gjorgiev et al. (2022), Panos et al. (2023)	20 (Gjorgiev et al., 2022)
waste CHP with CCS (heat-driven)	5934	154	Panos et al. (2023)	25 (SFOE, 2022)
wood CHP	1793	153.8	Panos et al. (2023)	25 (SFOE, 2022)
wood boiler	443	15.5	Guidati et al. (2021)	17 (Guidati et al., 2021)

Table 2.2: Energy and material flows of residential heat production technologies used in our Swiss energy system model for the year 2050.

Technology	Flows	Unit	Source
electric boiler	electricity	-1 MWh	Baumgärtner et al. (2021)
	residential heat	0.99 MWh	
heat pump (ground)	electricity	-1 MWh	Conservative assumption after CROSS alignment
	residential heat	4 MWh	
natural gas boiler	natural gas	-1.05 MWh	Baumgärtner et al. (2021)
	residential heat	1 MWh	
natural gas CHP	natural gas	-2.18 MWh	SFOE (2022)
	residential heat	0.76 MWh	
	electricity	1 MWh	
hydrogen boiler	hydrogen	-0.04 tonne	Panos et al. (2023)
	residential heat	1 MWh	
oil boiler	oil	-1.05 MWh	Baumgärtner et al. (2021)
	residential heat	1 MWh	
waste CHP with CCS (electricity-driven)	waste	-5.88 MWh	Own calculation assuming $\eta_{\text{tot}} = 0.5$ with η_{el} based on Marcucci et al. (2021a)
	residential heat	1.94 MWh	
	electricity	1 MWh	
waste CHP with CCS (heat-driven)	waste	-8.4 MWh	SFOE (2022)
	residential heat	5.57 MWh	
	electricity	1 MWh	
wood CHP	wood	-5.56 MWh	Moret (2017b)
	residential heat	2.94 MWh	
	electricity	1 MWh	
wood boiler	wood	-1.18 MWh	Guidati et al. (2021)
	residential heat	1 MWh	

2.1.4 Modeling residential heat flexibility

Shifting heat demand leverages the thermal inertia of buildings without additional storage costs, enabling pre-heating during off-peak hours when renewable electricity is abundant. However, shifting may reduce comfort and depends on user acceptance. We assume a maximum shift of up to three hours in the reference scenario according to discussion within the PATHFINDER project (Sanvito et al., 2024).

Residential heat demand can be reduced through thermal insulation. The remaining demand can be supplied by the following categories: (1) Power-to-Heat, (2) Heat from CHPs fired by waste, hydrogen, gas, or wood, and (3) Heat from boilers fired by waste, hydrogen, gas, or wood. To account for the decentralized nature of the residential heating sector, SecMOD introduces a must-run formulation for heating technologies. In this approach, the aggregated residential heating demand at each node must be met proportionally to the installed capacities of heating technologies.

Here, the must-run formulation ensures installed capacities operate proportionally within each category (Göke et al., 2023). Heat demand flexibility is implemented for technologies listed as categories (1) and (2) above by introducing virtual energy storages, enabling demand shifts to align with renewable availability or optimize CHP operation. Flexibility is limited to three-hour shifts and cannot extend beyond the typical days used in SecMOD. Consequently, we neglect thermal energy storage as a seasonal flexibility option in the residential heating sector. However, our implementation allows shifting heat demand to earlier time steps (i.e., "precharging" buildings) as well as to later time steps. Category (3) (and thermal insulation) remain inflexible due to continuous fuel availability.

Eqs. 2.7 to 2.10 formalize the implementation of residential heat demand flexibility and must-run constraints in our model. Note that we only present the key constraints for modeling heat demand flexibility in combination with the must-run constraint, while referring to Kotzur et al. (2018) for the general method and the complete set of constraints used to model seasonal storage.

Eq. 2.7 defines the capacity share ϕ_{cat} , for each heat production category, cat , calculated as the sum of all capacities in the category divided by the overall maximum demand $Q^{\text{dem,max}}$:

$$\phi_{\text{cat}} = \frac{\sum_{p \in P_{\text{cat}}} Q_p^{\text{nom}}}{Q^{\text{dem,max}}}, \forall \text{ cat} \in \text{CAT} \quad (2.7)$$

Eq. 2.8 ensures that heat production satisfies demand and incorporates flexibility via the virtual energy storage. The equation is split into the fixed heating share from the must-run condition (a) and the flexibility part with the virtual energy storage (b):

$$\sum_{p \in P_{\text{cat}}} Q_{p, c, t, n} = \underbrace{\phi_{\text{cat}} \cdot Q_{c, t, n}^{\text{dem}}}_{(a)} + \underbrace{\delta_{\text{flex}} \cdot (Q_{\text{cat}, c, t, n}^{\text{in, VES}} - Q_{\text{cat}, c, t, n}^{\text{out, VES}})}_{(b)}, \forall \text{ cat} \in \text{CAT}, c \in C, t \in T, n \in N. \quad (2.8)$$

Note that we use typical days within SecMOD, while relying on the method proposed by Kotzur et al. (2018) to model seasonal storage. Thus, Eq. 2.8 is formulated for all clusters $c \in C$, time steps $t \in T$ and nodes $n \in N$. However, we ensure that no heat is shifted beyond the respective typical day.

Eq. 2.9 limits the state of charge (SOC) of the virtual energy storage to cover heat demand for at most the defined flexibility duration ($\Delta t_{\text{flex}} = 3\text{h}$):

$$\text{SOC}_{\text{cat}, c, t, n}^{\text{VES}} \leq \frac{Q_{c, t-1, n}^{\text{dem}} + Q_{c, t, n}^{\text{dem}} + Q_{c, t+1, n}^{\text{dem}}}{3h} \cdot \Delta t_{\text{flex}} \cdot \phi_{\text{cat}}, \forall \text{ cat} \in \text{CAT}, c \in C, t \in T, n \in N. \quad (2.9)$$

Finally, Eq. 2.10 excludes flexibility for Category (3) technologies (e.g., wood, waste boilers), which have time-independent availability. The corresponding virtual energy storage inflows ($Q_{(3), c, t, n}^{\text{in, VES}}$) and outflows ($Q_{(3), c, t, n}^{\text{out, VES}}$) are set to zero:

$$Q_{(3), c, t, n}^{\text{in, VES}} = Q_{(3), c, t, n}^{\text{out, VES}} = 0, \forall c \in C, t \in T, n \in N. \quad (2.10)$$

Eqs. 2.7 to 2.10 do not explicitly consider the reduced heat demand from thermal insulation, as this may lead to numerical instabilities due to over-determination. Yet, the heat demand reduction by thermal insulation is implicitly given.

The concept of modeling heat demand flexibility is extended to both the electricity and transportation sectors. In the electricity sector, we assume a maximum energy shift of 3 GWh and a peak power shift of up to 1 GW according to discussion within the PATHFNDR project (Sanvito et al., 2024). In the transportation sector, mobility demands can be freely shifted within a typical day without constraints on virtual storage. Note that this is an optimistic assumption for shifting mobility demands. However, mobility is analyzed in detailed by other partners in the PATHFNDR project and also a central part of the current synthesis report III.

2.2 Industrial sector

Our model includes industrial energy demands comprising electricity and heat at three temperature levels. We use an industrial electricity demand of 6 TWh/a (Swiss Federal Office of Energy (SFOE), Prognos AG, TEP Energy GmbH, INFRAS AG, 2020) and a heat demand of 19.5 TWh/a (Marcucci et al., 2021a) projected in 2050. The heat demand refers to process heat and is split into three temperature levels (Table 2.3) (Swiss Federal Office of Energy (SFOE), Prognos AG, TEP Energy GmbH, INFRAS AG, 2020). We assume that the energy demands stay constant for every hour of the year. The industrial electricity demands are added to the exogenous electricity sector demand described in the supplementary information of Mayer et al. (2024). We spatially distribute the demands based on existing industrial facilities (Section 2.2.1). Particularly, the high-temperature heat is relevant for a limited set of industrial sites, emphasizing the importance of accurately representing the spatial distribution of these facilities. For industrial flexibility, we consider thermal energy storage for low and medium temperature heat (Section 2.2.3).

Table 2.3: Yearly energy demands of Swiss industry included in our Swiss energy system model for the year 2050.

	Temperature Range [°C]	Value [TWh/a]
electricity	–	6
low temperature heat	< 200	6.6
medium temperature heat	200 - 800	7.9
high temperature heat	> 800	5.0

Section 2.2.1 describes the spatial distribution of the industrial energy demands. Section 2.2.2

describes the technologies available to supply industrial heat. Finally, section 2.2.3 describes our modeling approach of flexibility for industrial heat.

2.2.1 Spatial resolution of industrial heat demand

For the spatial distribution of industrial heat demand, we utilize spatial data from the SFOE, which provides the locations of individual industrial sites, j , in Switzerland, along with each site's process heat demand and its associated industrial sector, i (Swiss Federal Office of Energy (SFOE), Verband Fernwärme Schweiz (VFS), 2013, ESRI Inc. - Environmental Systems Research Institute). Using this spatial data, we calculate a demand factor f_j for each site, representing its share of the total heat demand within its respective industrial sector. This factor is calculated as the ratio of the site's heat demand Q_j to the total heat demand of the entire industrial sector Q_i (Eq. 2.11).

$$f_j = \frac{Q_j}{Q_i}, \quad \forall j \in \mathcal{J}_i, i \in \mathcal{I} \quad (2.11)$$

We then use the breakdown of the industrial heat consumption by industrial sector, i , and by temperature level, tl , (Table 2.4) provided by Prognos AG to determine the heat demand at each temperature level for the individual sites, $Q_{j,tl}$ (Eq. 2.12).

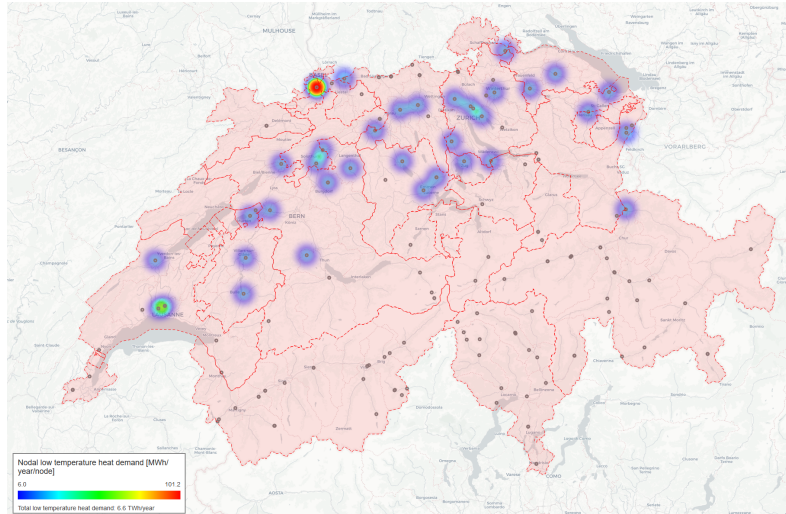
$$Q_{j,tl} = Q^{CH} \cdot f_{i,tl} \cdot f_j, \quad \forall j \in \mathcal{J}_i, i \in \mathcal{I}, tl \in TL \quad (2.12)$$

In Eq. 2.12, Q^{CH} corresponds to the total annual Swiss industrial heat demand of 19.5 TWh/a and $f_{i,tl}$ corresponds to the share of the total industrial heat demand by sector and temperature level found in Table 2.4.

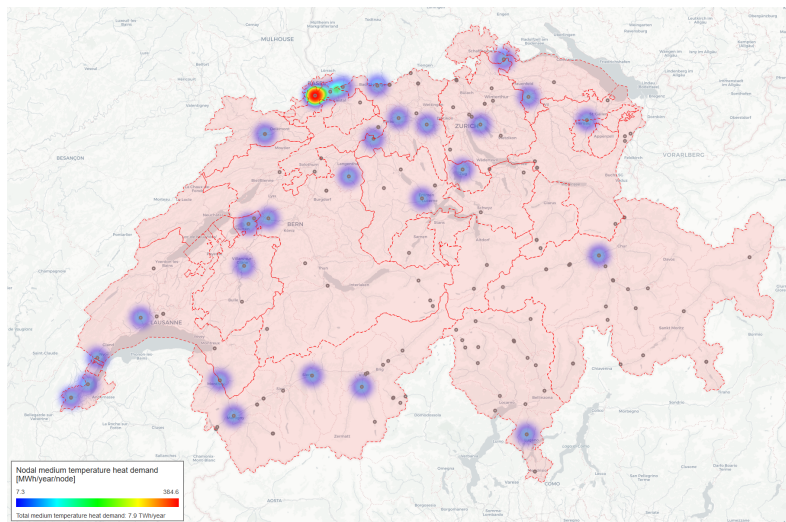
Finally, the site-level demands are assigned to the closest node within our modelled spatial grid. Figure 2.2 shows the resulting spatial distribution for the industrial heat demands of our three temperature levels.

Table 2.4: Industrial process heat demand shares for Switzerland for different industrial sectors and temperature levels (Prognos AG).

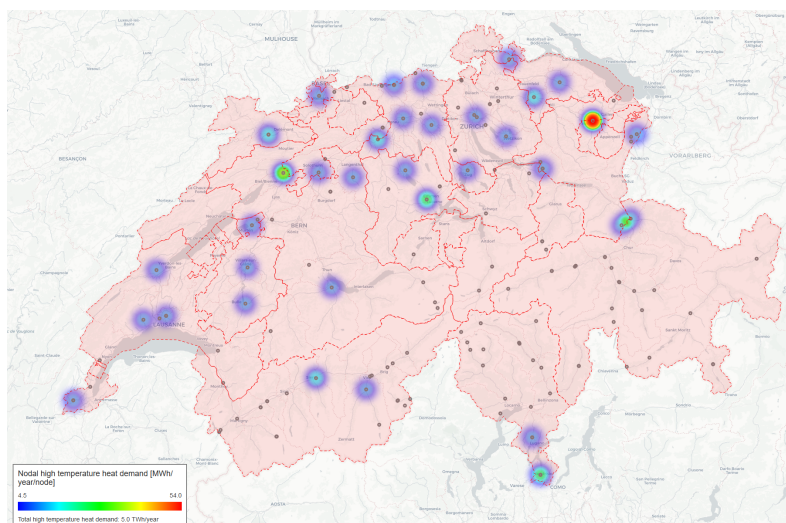
Industrial sector i	<200 °C	200-800 °C	>800 °C
Food	13.4%	0.0%	0.0%
Paper	8.4%	0.0%	0.0%
Chemical/Pharmaceutical	0.0%	32.0%	0.0%
Mineral	0.0%	1.6%	16.2%
Metal	0.0%	3.4%	8.3%
Electronics/Mechanical	1.1%	0.6%	1.1%
Others	10.7%	3.1%	0.0%



(a) Spatial distribution of Switzerland's yearly low-temperature heat demand (6.6 TWh/a).



(b) Spatial distribution of Switzerland's yearly medium-temperature heat demand (7.9 TWh/a).



(c) Spatial distribution of Switzerland's yearly high-temperature heat demand (5.0 TWh/a).

Figure 2.2: Spatial distribution of Switzerland's industrial heat demand across the three temperature levels.

2.2.2 Industrial heat production technologies

To produce industrial heat, we consider ground-source heat pumps, electric boilers, natural gas boilers, natural gas combined heat and power (CHP), hydrogen boilers, heat from waste incineration, and heat from burning of wood. Different technologies are available for producing heat at the various required temperature levels (Table 2.3). The resource availabilities for waste and wood are documented in Section 2.4. The techno-economic parameters for the considered technologies are found in Tables 2.5 and 2.6.

2.2.3 Industrial heat flexibility

Industrial heat flexibility is implemented via thermal energy storage (TES) for low-temperature (LT) and medium-temperature (MT) heat. TES can be implemented for all heat-requiring processes, making it an accessible industrial flexibility option. In a deep-dive analysis on this topic, available TES technology is shown to be a promising flexibility option for industry (Mayer et al., 2024), capturing up to 61% of the maximum system cost reductions that could be obtained from industrial demand-side management. This deep-dive study is available open source¹.

Our TES technologies include water tanks, steam accumulators, packed beds, molten salts, and phase change materials. The techno-economic parameters for these technologies are shown in Table 2.7.

Table 2.7: Techno-economic parameters for thermal energy storage (TES) technologies included in our Swiss energy system model.

Technology	Temp. Level	Efficiency [%]	Invest. Cost [k€/MWh]	Fixed O&M Cost [k€/MWh]	Lifetime [years]
water tank	LT ^a	0.9 ^b	10 ^a	0.15 ^c	30 ^b
steam accumulator	LT ^d	0.95 ^e	114 ^d	4.1 ^f	25 ^e
packed bed	MT ^b	0.9 ^g	13.15 ^b	4.1 ^f	13 ^b
molten salt	MT ^b	0.95 ^g	10.52 ^a	8.2 ^f	30 ^b
phase change material	MT ^b	0.95 ^b	70.16 ^b	4.1 ^f	21 ^b

^aIRENA (2013)

^bIRENA (2020)

^cPetkov and Gabrielli (2020)

^dAl Kindi et al. (2022)

^eMurakoshi and Fushimi (2022b)

^fGautam et al. (2022)

^gStrasser and Selvam (2014)

2.3 Limitations of our residential heat and industrial sector modeling

While our modeling assumptions regarding the residential heat and industrial sectors provide a strong basis for assessing the potential of sector-coupling and flexibility from these sectors in Switzerland,

¹<https://doi.org/10.3389/fenrg.2024.1443506>

Table 2.5: Costs and lifetimes of industrial heat production technologies for the year 2050 used in our Swiss energy system model. CHP: combined heat and power, CCS: carbon capture & storage, LT: low temperature, MT: medium temperature, HT: high temperature. Temperature ranges can be found in Table 2.3.

Temp. Level	Technology	CAPEX [EUR/kW]	Maintenance [EUR/(kW-a)]	Cost sources	Lifetime [years]
LT/MT	electric boiler	238	4.75	Brauner (2019)	20 (Henning and Sauer, 2015)
LT	heat pump (ground)	472	20.21	Moret (2017b,a)	20 (Henning and Sauer, 2015)
LT/MT/HT	natural gas boiler	56.5	1.13	Moret (2017b,a)	20 (Baumgärtner et al., 2021)
LT	natural gas CHP	660.7	17	Panos et al. (2023)	25 (SFOE, 2022)
LT/MT/HT	hydrogen boiler	38	0.38	Panos et al. (2023)	25 (SFOE, 2022)
LT/MT/HT	waste (with CCS)	4454	44.5	Gjorgiev et al. (2022), Panos et al. (2023)	20 (Gjorgiev et al., 2022)
LT	waste CHP (with CCS)	5934	154	Panos et al. (2023)	25 (SFOE, 2022)
LT	wood boiler CHP	1793	154	Panos et al. (2023)	25 (SFOE, 2022)
LT/MT/HT	wood boiler	443	15.5	Guidati et al. (2021)	17 (Guidati et al., 2021)

Table 2.6: Energy and material flows of industrial heat production technologies used in our Swiss energy system model for the year 2050.

Temp. level	Technology	Flows	Unit	Source
LT/MT	electric boiler	electricity	-1 MWh	Baumgärtner et al. (2021)
		heat	0.99 MWh	
LT	heat pump (ground)	electricity	-1 MWh	Deutz and Bardow (2021)
		heat	2.51 MWh	
LT/MT/HT	natural gas boiler	natural gas	-1.05 MWh	Baumgärtner et al. (2021)
		heat	1 MWh	
LT	natural gas CHP	natural gas	-2.18 MWh	SFOE (2022)
		heat	0.76 MWh	
		electricity	1 MWh	
LT/MT/HT	hydrogen boiler	hydrogen	-0.04 tonne	Panos et al. (2023)
		heat	1 MWh	
LT/MT/HT	waste CHP with CCS (electricity-driven)	waste	-5.88 MWh	Own calculation assuming $\eta_{\text{tot}} = 0.5$ with η_{el} based on Marcucci et al. (2021a)
		heat	1.94 MWh	
		electricity	1 MWh	
LT	waste CHP with CCS (heat-driven)	waste	-8.4 MWh	SFOE (2022)
		heat	5.57 MWh	
		electricity	1 MWh	
LT	wood CHP	wood	-5.56 MWh	Moret (2017b)
		heat	2.94 MWh	
		electricity	1 MWh	
LT/MT/HT	wood boiler	wood	-1.16 MWh	Guidati et al. (2021)
		heat	1 MWh	

there are some limitations that we list here and that could be addressed in future work. The limitations include the following points:

- **Spatial distribution of residential heat demand:** We assume the same cantonal heat demand shares as in 2012 (Section 2.1.1). However, these shares can change, particularly due to decreasing heat demand in the Swiss alpine regions (Berger and Worlitschek, 2019).
- **Temporal distribution of residential heat demand:** For our time-wise distribution of the residential heat demand, we use the "heating degree method" from the SIA 380/1 standard (SIA, 2016) with a target indoor temperature of 20°C (Section 2.1.2), as commonly used for modeling heat demands in national energy system models. However, the target indoor temperature is debated and higher target temperatures could lead to higher heat demands.
- **Commercial building heat demand:** We assume a constant hourly space heating and hot water demand throughout the year. However, this demand would likely have a weekly profile with lower demands on weekends.
- **Heat pump modeling:** We model only ground-source heat pumps for residential and industrial heat provision, assuming conservative efficiencies and neglecting time-dependent COPs. Additionally, we do not impose any limitations on their installation, despite studies indicating potential constraints on heat extraction at the national level (Bundesamt für Energie, 2020b). Due to the lack of spatially resolved data, we neglect these limitations, which may lead to an overestimation of their potential. Future work could extend the model to include air-source heat pumps with time-dependent COPs and integrate spatial constraints on ground-source heat extraction.
- **District heating:** We do not explicitly model district heating but implicitly consider it by including technologies such as CHPs and hydrogen boilers. Future work could refine our model and explicitly model district heating networks, including, amongst other things, distribution losses and nodal potentials.
- **Heat flexibility from the residential heat sector:** We assume that the hourly heat demand can only be shifted by three hours and cannot extend beyond the typical days used in SecMOD. Consequently, we neglect thermal energy storage as a seasonal flexibility option in the residential heating sector. Furthermore, we assume that all residential heat is available for flexibility provision, which may be an optimistic assumption.

2.4 Biomass, Waste, and Synthetic Fuels

2.4.1 Resource availabilities and Costs

We consider domestic biomass and waste resources in our model, constraining their annual availability (Table 2.8). Biomass sources include wood, animal manure, green waste, and sewage sludge. To align with Swiss regulations, we assume that waste must be utilized within Switzerland and that its emissions must be captured.

For synthetic fuels (synfuels), we incorporate technologies for producing e-hydrogen, e-methane, and e-diesel. Additionally, we allow synfuel imports, capped at 866.7 kt/a based on the import

Table 2.8: Annual Swiss biomass and waste availabilities and costs

Product	Availability [TWh/a]	Availability Source	Cost [€/kWh]	Cost Source
Wood	17.2	Guidati et al. (2021)	0.03	Guidati et al. (2021)
Animal manure	7.3	Marcucci et al. (2022), Guidati et al. (2021)	0.004	Guidati et al. (2021)
Green waste	3.3	Marcucci et al. (2022)	0.011	Guidati et al. (2021)
Sewage sludge	1.7	Guidati et al. (2021)	0.014	Guidati et al. (2021)
Waste	11.8 ^a	Marcucci et al. (2022)	0	

^aBottom-up calculation from 4 Mt CO₂ emissions

values reported by Marcucci et al. (2022) for hydrogen and synthetic e-fuel imports under the high market integration scenario. We assume an import cost of 6 k€/t (Marcucci et al., 2022), applying a €:CHF conversion factor of 1.1125. All synfuels are assumed to be imported as hydrogen, which can subsequently be used for a wide range of application, such as electricity generation via fuel cells, heat production via hydrogen boilers, and mobility via fuel cell vehicles. Furthermore, we assume no emissions associated with synfuel imports.

2.4.2 Biomass and waste conversion technologies

In addition to their potential for directly generating residential and industrial heat (Tables 2.2 and 2.6), the biomass and waste resources can be converted to useful energy carriers across the energy system (Table 2.9). Biomass can be converted to biogas, methane, diesel, hydrogen, and combined heat and power (CHP). Waste can be utilized for residential and industrial heat production (Tables 2.2 and 2.6) as well as for electricity generation through incineration.

Table 2.10: Costs and lifetimes of biomass and waste conversion technologies for the year 2050 used in our Swiss energy system model. WW: wastewater treatment, CHP: combined heat and power.

Technology	CAPEX [EUR/kW]	Maintenance [EUR/(kW·a)]	Cost sources	Lifetime [years]
anaerobic digestion (for CHP)	1596	132.1	Panos et al. (2023)	25 Guidati et al. (2021)
anaerobic digestion (for biogas)	947	84.3	Guidati et al. (2021)	25 Guidati et al. (2021)
anaerobic digestion (WW treatment)	947	84.3	Guidati et al. (2021)	25 Guidati et al. (2021)
fischer tropsch	1757	32.2	Guidati et al. (2021)	15 Guidati et al. (2021)
gasification (for methane)	2634	133.9	Guidati et al. (2021)	25 Guidati et al. (2021)
gasification (for H ₂)	59769	5976.9	Panos et al. (2023)	25 ^a
hydrothermal gasification (for methane)	1528	106.1	Guidati et al. (2021)	15 Guidati et al. (2021)
hydrothermal gasification (for CHP)	5744	287.2	Guidati et al. (2021)	15 Guidati et al. (2021)
methanation	702	91.7	Guidati et al. (2021)	20 Guidati et al. (2021)
pyrolysis	2314	115.7	Guidati et al. (2021)	25 Guidati et al. (2021)
waste incineration	7361	1104	Panos et al. (2023)	25 ^b

^aassume same lifetime as hydrogen boiler (Table 2.5)

^bassume same lifetime as waste CHP (Table 2.5)

Table 2.9: Conversion technologies for biomass and waste in addition to the heat generation technologies found in Tables 2.2 and 2.6. WW: wastewater treatment, CHP: combined heat and power.

Technology	Feedstock options	Flows	Source
anaerobic digestion (for CHP)	animal manure green waste sewage sludge	feedstock -7.72 MWh electricity 1 MWh LT heat 1.12 MWh	Guidati et al. (2021)
anaerobic digestion (for biogas)	animal manure green waste	feedstock -3.33 MWh biogas 1 MWh	Guidati et al. (2021)
anaerobic digestion (for biogas, WW treatment)	sewage sludge	feedstock -1.85 MWh biogas 1 MWh	Guidati et al. (2021)
fischer tropesch	wood	feedstock -22.59 MWh electricity -0.73 MWh LT heat 3.95 MWh diesel 1 m ³	Guidati et al. (2021)
gasification (for methane)	wood	feedstock -1.4 MWh methane 1 MWh HT heat 0.32 MWh	Guidati et al. (2021)
gasification (for H ₂)	wood	feedstock -54.64 MWh hydrogen 1 tonne	Panos et al. (2023)
hydrothermal gasification (for methane)	animal manure green waste sewage sludge	feedstock -2.36 MWh methane 1 MWh electricity 0.09 MWh	Guidati et al. (2021)
hydrothermal gasification (for CHP)	animal manure green waste sewage sludge	feedstock -3.93 MWh HT heat 1.32 MWh electricity 1 MWh	Guidati et al. (2021)
methanation	biogas	feedstock -1-19 MWh electricity -0.02 MWh methane 1 MWh LT heat 0.10 MWh MT heat 0.09 MWh	Guidati et al. (2021)
pyrolysis	wood	feedstock -15.03 MWh electricity 0.24 MWh diesel 1 m ³	Guidati et al. (2021)
waste incineration	waste	feedstock -6.25 MWh electricity 1 MWh	Panos et al. (2023)

2.4.3 Emissions from biomass and waste

Emissions from biomass and partly waste (37 % from Marcucci et al. (2022)) are assumed to be biogenic, meaning that the emissions are offset by carbon absorbed by the biomass throughout the carbon life cycle. This circularity results in net-zero emissions from biomass and 37% of waste use in the energy system. Coupling these biogenic emissions with carbon capture and storage (CCS) results in net-negative emissions for the energy system (cf. Section 2.5).

In the model, waste utilization is mandatory to comply with future regulations, which require both the complete utilization of waste and the capture of its emissions. All technologies that use waste for heat or electricity therefore include CCS infrastructure, making these technologies carbon-negative due to the capture of the 37% biogenic carbon. Since waste must be utilized, it is considered a cost-free resource, making its use for heat and electricity an attractive option for offsetting energy system emissions.

Wood-consuming technologies for heat, CHP, and hydrogen production (Tables 2.2, 2.6, and 2.9) can be equipped with CCS infrastructure (Section 2.5) to achieve net-negative emissions. Alternatively, if CCS is not applied, their biogenic emissions are released, resulting in net-zero emissions.

Other biomass-converting technologies (Table 2.9) yield net-zero emissions when producing heat, electricity, or biogas. However, when producing biodiesel or biomethane —both products which can be mixed with fossil-based equivalents—the biomass-converting technologies generate negative emissions within the modeled energy system, effectively offsetting downstream emissions from the combustion of these carbon-containing products in other sectors.

2.5 Carbon capture and storage

We include two technologies for capturing CO₂: direct air capture (DAC) and point source capture from wood-consuming technologies (Table 2.11). Waste-consuming technologies are automatically equipped with CCS infrastructure (Section 2.4.3). The CO₂-capturing technologies offset emissions within the energy system, helping achieve the net-zero emissions target. We do not consider costs associated with the CO₂ transport and storage. However, as these costs affect both CO₂-capturing technologies equally, their omission does not affect the cost-optimal technology selection between these two options. We note that as a limitation, omitting these transport and storage costs may make CCS overly favorable vs. other emissions mitigation strategies such as power-to-X.

The techno-economic parameters for our CO₂-capturing technologies are reported in Tables 2.12 and 2.13.

Table 2.11: List of wood-consuming technologies that can be retrofitted with point source CO₂ capture.

Technology	Product
wood boiler CHP	residential heat
wood boiler	residential heat
wood boiler CHP	LT heat
wood boiler	LT/MT/HT heat
gasification	H ₂

Table 2.12: Energy requirements and emissions uptake of our CO₂-capturing technologies.

Technology	Emissions [tonne CO ₂]	Flows [MWh]	Source
Direct air capture	-0.987	electricity	-0.5 Deutz and Bardow (2021)
		LT heat	-1.5
Point source capture	-0.9	electricity	-0.1 SFOE (2022)
		LT heat	-1

Table 2.13: Costs and lifetimes of our CO₂-capturing technologies for the year 2050 used in our Swiss energy system model.

Technology	CAPEX [EUR/(kg/hr)]	OPEX [EUR/kg]	Cost source	Lifetime [years]	Lifetime source
Direct air capture	11,230.7	0.058	Sievert et al. (2024)	30	Deutz and Bardow (2021)
Point source capture	1,618	0	SFOE (2022)	25	SFOE (2022)

3 PATHFINDER reference scenario results

Here, we present the SecMOD results from our reference scenario (Section 1.3). We focus on the resulting Swiss energy system configuration for 2050 (Section 3.1), presenting the resulting CO₂ balance and electricity production mix. We then present the results of the heat and industry sectors, with a focus on the electrified demands that are sent to Nexus-e (Section 3.2). We present the flexibility options for the resulting Swiss energy system (Section 3.3), differentiating between short-term and long-term flexibility options. Finally, we discuss the strengths and weaknesses of the soft-link approach (Section 3.4).

3.1 Swiss energy system configuration

The sector-coupled energy system model SecMOD assesses the decarbonization of the Swiss energy system. The results highlight the contributions of various technologies and resources to achieving a net-zero emissions target and ensuring a balanced energy supply and demand.

CO₂ Emissions in the 2050 reference scenario

The Swiss energy system reaches the imposed -1.6 Mt CO₂ emissions target (Section 1.3) in 2050 by balancing positive and negative emissions. The -1.6 Mt CO₂ emissions target accounts for the need to offset 30 % of the current Swiss aviation emissions domestically, assuming that 70 % of aviation fuel is renewable by 2050 (Bundesamt für Statistik (BFS), 2024). Figure 3.1 illustrates the CO₂ emissions balance across different technologies and resources in the reference scenario. The emissions balance is mainly achieved through:

- Pyrolysis, producing biodiesel from biomass. This biomass-based diesel production offsets emissions from diesel cars, achieving net-zero emissions in the mobility sector.
- Gasification of animal manure, sludge, and green waste, primarily supplying biogas for flexible electricity production in combined-cycle gas turbines. Thus, these turbines are mostly run on biogas (83 %), with the remaining 17 % of the required natural gas coming from imports of 1.7 TWh_{th}. Thus, the overall electricity production from combined-cycle gas turbines results in roughly 0.2 Mt positive emissions.
- Capturing waste emissions is required. Thus, waste CCS for high- and medium-temperature heating applications result in negative emissions of 1.1 Mt.
- Direct air capture provides 0.7 Mt of negative emissions to achieve the required negative emissions of -1.6 Mt CO₂.

Our results are in line with other studies projecting the transition to a net-zero Switzerland, such as the Energy Perspectives 2050+ (Bundesamt für Energie, 2020b). In this report, they show that the

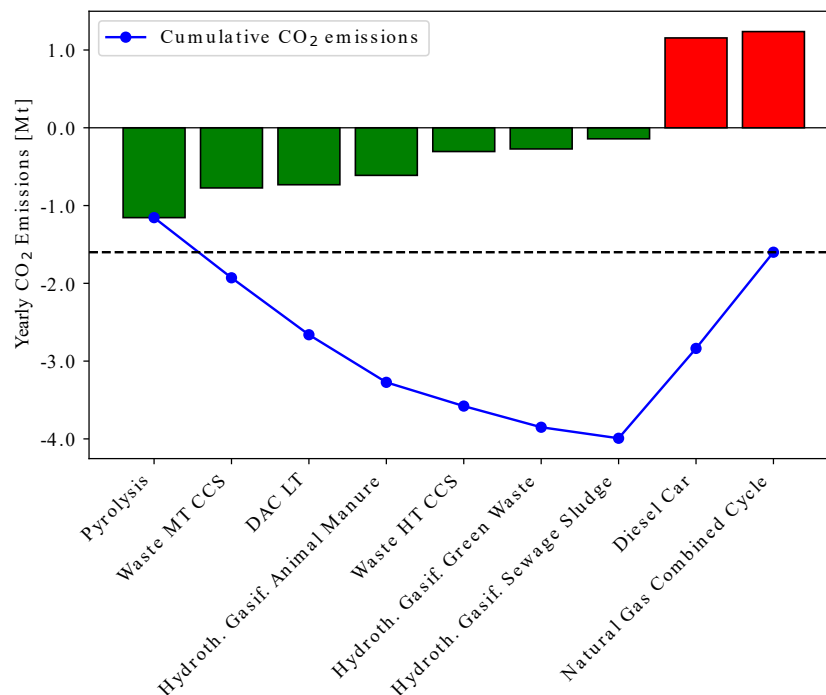


Figure 3.1: Yearly positive and negative CO₂ emissions in the reference scenario in 2050 for the installed technologies. The cumulative CO₂ emissions sum up the respective contributions of each technology.

net-zero target will mainly be achieved by reducing emissions of the mobility and residential heating sectors together with CCS, mirroring our resulting emissions balance.

Electricity Production and Consumption

Switzerland's electricity system in 2050 is shaped by a sector-coupled demand profile, renewable-dominated supply, and flexible storage solutions (Figure 3.2).

- Consumption:** Beyond the base electricity demand of 44 TWh, additional sector-coupled loads contribute significantly: Battery electric vehicles add 10 TWh, residential heat pumps and electric boilers 14.9 TWh, industrial heat pumps and electric boilers 3.0 TWh, and direct air capture 0.8 TWh. Overall, the Swiss electricity consumption is 78.4 TWh.
- Production:** Renewable sources dominate electricity generation, with photovoltaics supplying 38.3 TWh and hydropower 36.4 TWh. Waste-to-energy contributes 2.0 TWh while also supplying heat for industrial processes. Natural gas combined cycle plants provide 3.7 TWh, primarily as a flexibility option.
- Storage & Flexibility:** Strong seasonal variations characterize the electricity system (Figure 3.6). In winter, low photovoltaic output and reduced hydropower necessitate high electricity imports. Conversely, summer features surplus photovoltaic generation, leading to significant exports. To balance these fluctuations, the system employs power-to-hydrogen-to-power, natural gas combined cycles, and hydro and battery storage. Additionally, the heating and mobility sectors enhance short-term flexibility (see Section 3.3).

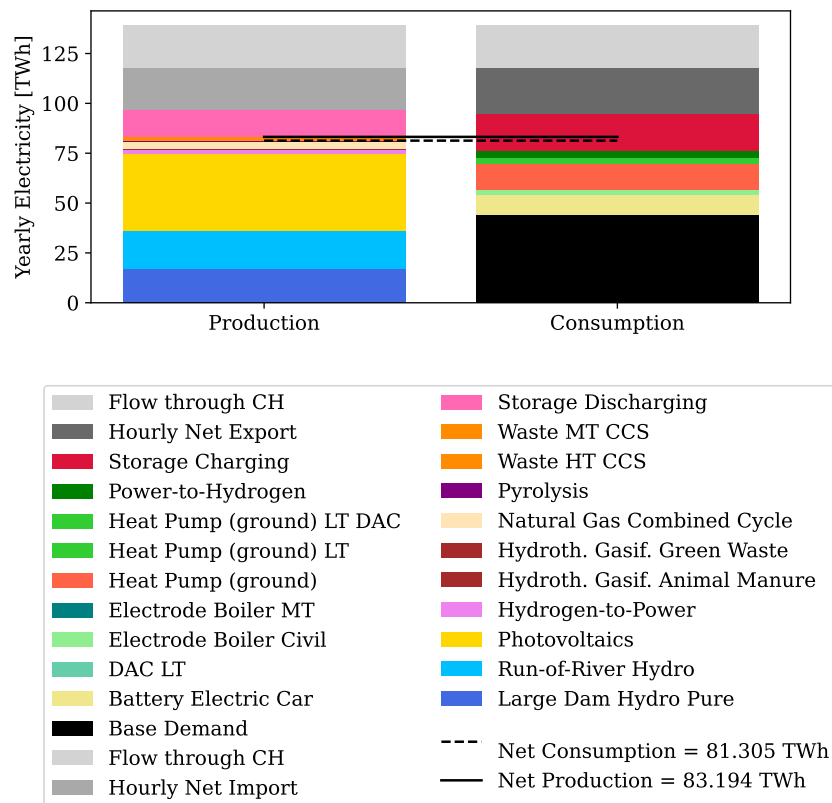


Figure 3.2: Yearly aggregate electricity production and consumption in the reference scenario in 2050.

The results of the energy system optimization model are highly dependent on the input data and assumptions used. To ensure consistency and comparability, SecMOD participated in the SWEET-CROSS project, which compares different energy system models of Switzerland across various scenarios (SWEET-CROSS, 2024). Through this collaboration, many model parameters were aligned and updated. Consequently, the results for electricity production and consumption are well in line with other models, with most reporting a domestic electricity production and consumption between 70 and 80 TWh.

3.2 Sector-coupled demands

SecMOD models the residential and industrial heating sectors and the mobility sector to provide the sector-coupled electricity demands for Nexus-e. By including these sectors into the optimization model, SecMOD captures trade-offs between technologies that either increase electricity demand or rely on alternative energy sources. The relative contributions of these technologies to each sector are shown in Figure 3.3.

The residential and low-temperature heating sectors are fully electrified. The residential heat demand (66.3 TWh_{th}/a) is reduced by 13.3 TWh_{th}/a by fully exploiting the potential for energetic rehabilitation. The remaining residential heat demand is primarily met by ground-source heat pumps (96 %), supplemented by electric boilers (4 %) to cover peak loads. The industrial low-temperature heat

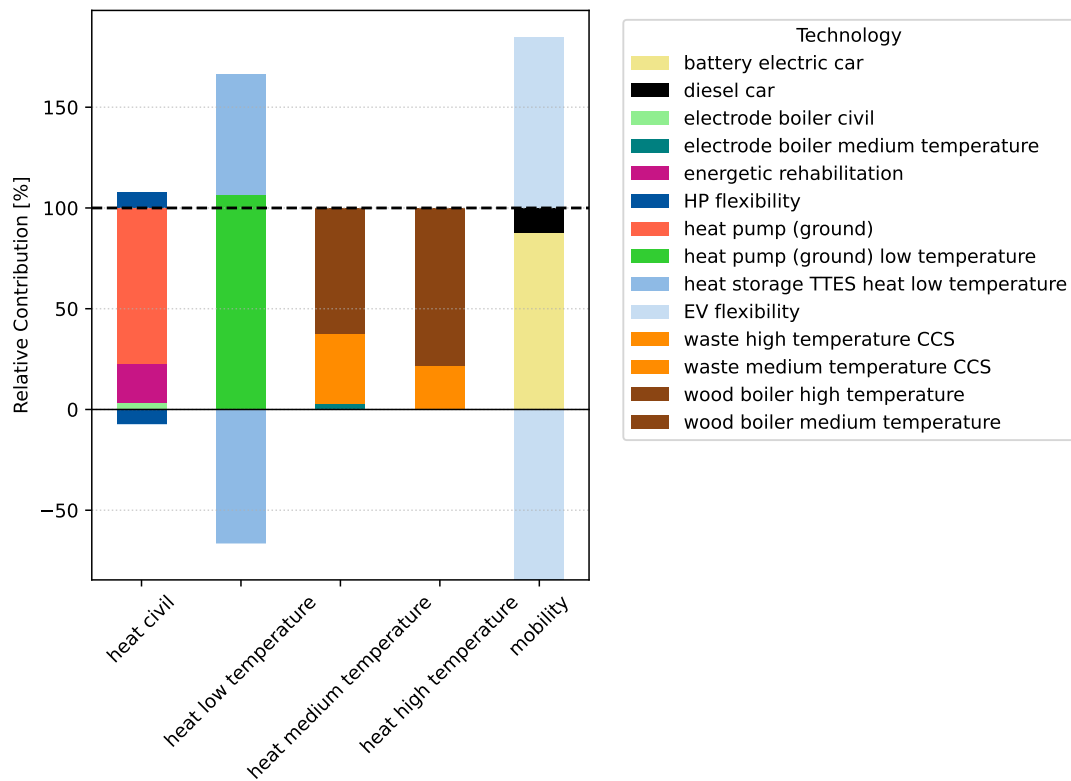


Figure 3.3: Relative contribution of conversion technologies to the residential heating sector (demand: 66.3 TWh_{th}/a), low-temperature heating sector (demand: 6.6 TWh_{th}/a), medium-temperature heating sector (demand: 7.9 TWh_{th}/a), high-temperature heating sector (demand: 5.0 TWh_{th}/a), and mobility sector (demand: 67.1 Mio. vkm/a). The contribution of each technology is referenced to the demand in its respective sector.

demand (6.6 TWh_{th}/a) is also fully electrified by ground-source heat pumps. This sector deploys thermal energy storage to shift substantial amounts of heat over time. However, this shifting results in energy losses of 6 %, requiring additional low-temperature heat supply. Overall, the residential and low-temperature heating sectors contribute substantial flexibility to the energy system (see Section 3.3).

Medium- and high-temperature heat is primarily supplied by a mix of waste-to-energy plants and biomass, with biomass preferentially allocated to higher temperature levels: the medium-temperature level is supplied by 62 % biomass and 38 % waste, while the high-temperature level has an allocation of 78 % biomass and 20.5 % waste and 1.5 % electricity by electric boilers. Both sectors achieve net-zero emissions, as carbon capture is required for waste incineration.

The mobility sector is largely electrified, with electric vehicles accounting for an additional sector-coupled electricity demand of 10 TWh/a. However, 12 % of mobility demand is still met by diesel vehicles running on biodiesel produced via pyrolysis. Both the mobility and industrial heating sectors fully utilize the available biomass potential of 17.2 TWh_{wood}/a.

Overall, the reference scenario optimizes a total electricity supply of 17.9 TWh_{el}/a for heating demands and 10 TWh_{el}/a for mobility demands. These sector-coupled electricity demands serve as input to Nexus-e. The reference scenario highlights the importance of biomass, waste, and electricity for the

decarbonization of residential and industrial heating, as well as the transportation sector, illustrating how sector coupling extends beyond electricity to include multiple energy carriers.

3.3 Flexibility options

Due to its strong reliance on photovoltaics and hydropower for electricity production in a net-zero scenario (Figure 3.2), Switzerland requires flexibility at various timescales in order to manage the variable availability of these renewable electricity sources. Short-duration flexibility is needed to balance the day-night fluctuations of photovoltaics. Long-duration flexibility is needed to balance the seasonality associated with both photovoltaics and hydropower.

Short-duration flexibility

For short-duration flexibility, the Swiss energy system uses flexibility from building inertia (Figure 3.4), mobility (Figure 3.5), and industrial low-temperature (LT) heat storage to balance the day-night renewables variability. For residential heating flexibility, the allowed demand shift is limited to three hours (Section 2.1.4). This modeling assumption therefore limits the renewables variability that flexibility from building inertia can absorb. However, we still see a shift in residential heat production within the allowable two hours to make use of renewables availability. For mobility, the demand shift is limited to 24 hours. Thus, we see a clear shift to over-production via battery electric vehicles during daytime hours such that the nighttime demands are also satisfied. Finally, low-temperature heat storage serves as a strong short-duration flexibility option. Despite the smaller absolute heat demand from the low-temperature heat sector than for residential heat (6.6 TWh_{th}/a vs. 66.3 TWh_{th}/a), 67% of this demand is shifted in time to provide short-duration flexibility to the energy system. In addition to these flexibility options, the system also uses Li-ion batteries for short-duration flexibility, investing in 10 GWh of storage capacity.

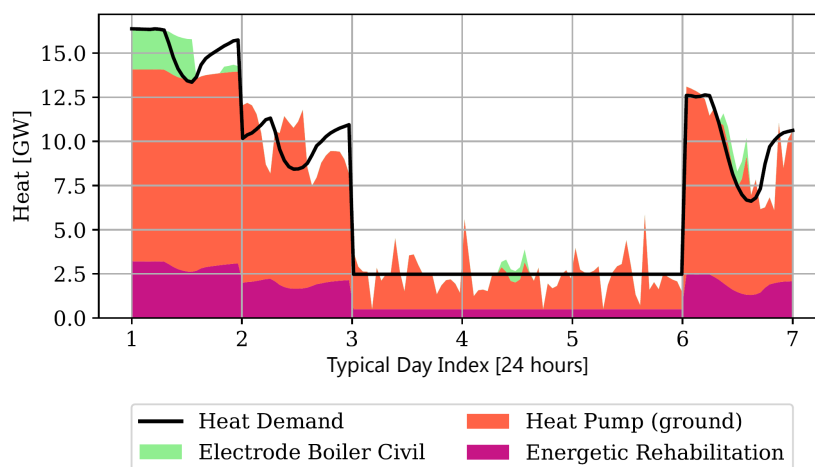


Figure 3.4: Residential heat demand profiles (black line) vs. heat production (colored area) for the seven typical days of our Swiss energy system model.

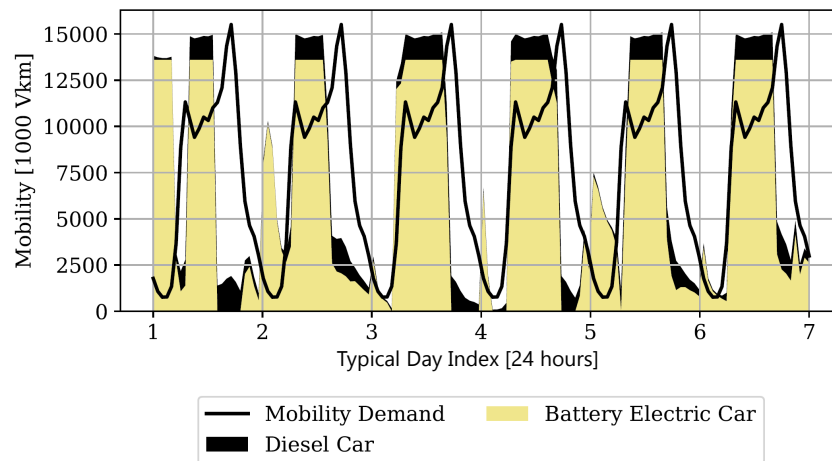


Figure 3.5: Mobility demand profiles (black line) vs. its provision (colored area) for the seven typical days of our Swiss energy system model.

Long-duration flexibility

The main long-duration flexibility option employed by the energy system is electricity trade (Figure 3.6). The Swiss energy system imports 43.3 TWh of electricity throughout the year, with 70 % imported during the winter months. Similarly, the system exports 44.6 TWh of electricity throughout the year, with 58 % exported during the summer months. This temporal distribution of imports and exports serves as a valuable seasonal flexibility option to the energy system. Additionally, the energy system uses pumped hydro storage and power-to-hydrogen as seasonal flexibility options, storing 7.3 TWh of electricity in pumped hydro reservoirs and 0.74 TWh of newly built hydrogen in lined rock caverns for dispatching during the winter months.

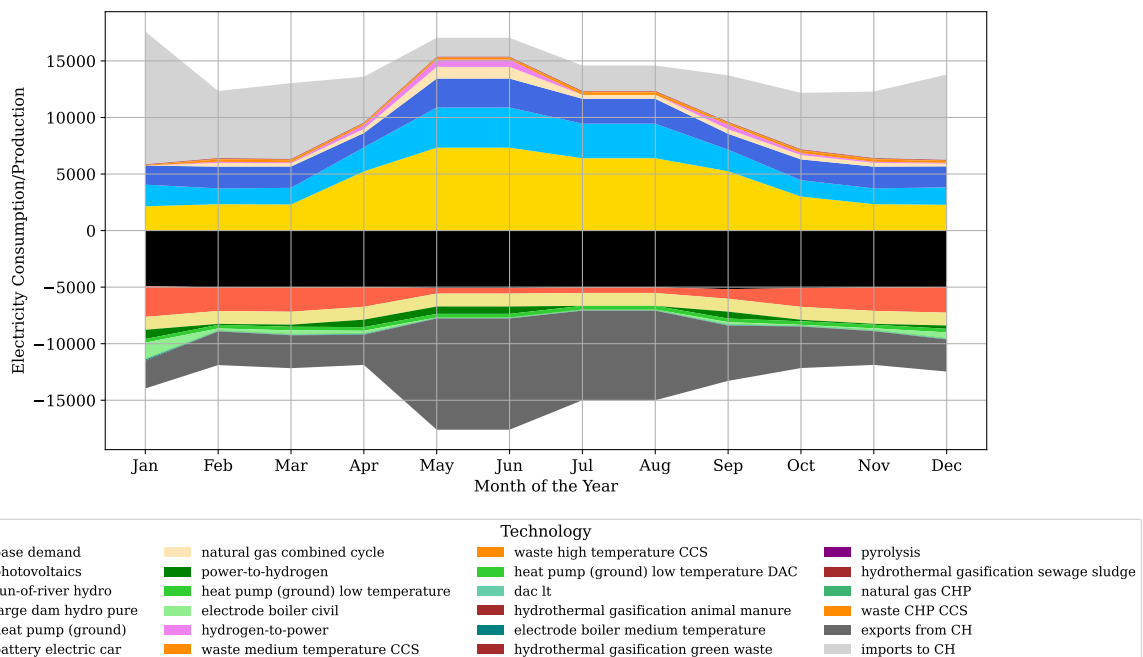


Figure 3.6: Monthly average electricity production and consumption in the reference scenario in 2050.

Industrial demand-side management as a flexibility option

In a separate study that forms part of the PATHFNDR project, we investigate the potential flexibility provision from industrial demand-side management (DSM) in the net-zero Swiss sector-coupled energy system (Mayer et al., 2024). We consider three different configurations of the future Swiss energy system, varying the alternative flexibility options to industrial DSM. We calculate the maximum system cost reductions that industrial DSM can provide for these three configurations. As a concrete DSM measure, we evaluate the flexibility potential from thermal energy storage and benchmark this potential against that of industrial DSM.

We find that industrial DSM can decrease the total system costs between 2% to 4.4%. The cost decrease depends on the alternative flexibility options for the energy system, particularly over seasonal time horizons. The 2% cost reduction corresponds to a configuration with inexpensive alternative seasonal flexibility options. Conversely, the 4.4% corresponds to a configuration with expensive alternative seasonal flexibility options. Therefore, the value of flexibility provision from industrial DSM must be evaluated within the context of the overall energy system. Policymakers should holistically assess Switzerland's flexibility options before prioritizing industrial DSM measures.

This deliverable makes an important contribution towards expanding policymakers' ability to assess Swiss energy system flexibility options beyond those considered in the industrial DSM study. The study was carried out solely with SecMOD without considering electricity trade or a detailed electricity grid, thus limiting the flexibility options considered in the study. With our soft-link approach, policymakers have the ability to more holistically consider the flexibility options for the Swiss energy system in order to make better-informed policy decisions.

When considering thermal energy storage as a concrete DSM measure, we find that thermal energy storage can capture between 28% and 61% of the maximum cost reductions from industrial DSM. This potential makes thermal energy storage a promising and accessible flexibility measure for the energy system. This finding is reemphasized within this deliverable, showing the strong potential of LT thermal energy storage for flexibility provision.

3.4 Discussion on the soft-link

Our approach leverages the complementary strengths of SecMOD and Nexus-e through a soft-linking framework. SecMOD excels in modeling multi-sector energy systems, particularly electricity, heating, and mobility, allowing for an integrated sector-coupling perspective. However, its representation of the electricity sector is simplified, using a DC load flow model and aggregated technology definitions. In contrast, Nexus-e provides a highly detailed electricity system representation, including an AC power flow model, individual power plant and storage unit modeling, and co-optimization of centralized and distributed investments. However, it does not endogenously model heating or mobility sectors, relying on externally defined demand projections, which neglect key trade-offs in the decarbonization of these sectors. Notably, the soft-linking approach adjusts the demand from electric vehicles in Nexus-e by scaling it down by 43 % while increasing the electrified heating demand by 23 %. By soft-linking the two frameworks, our method enhances system-wide analysis, combining SecMOD's multi-sector optimization with Nexus-e's detailed electricity system representation. This integration ensures a more holistic assessment of the Swiss energy system transition.

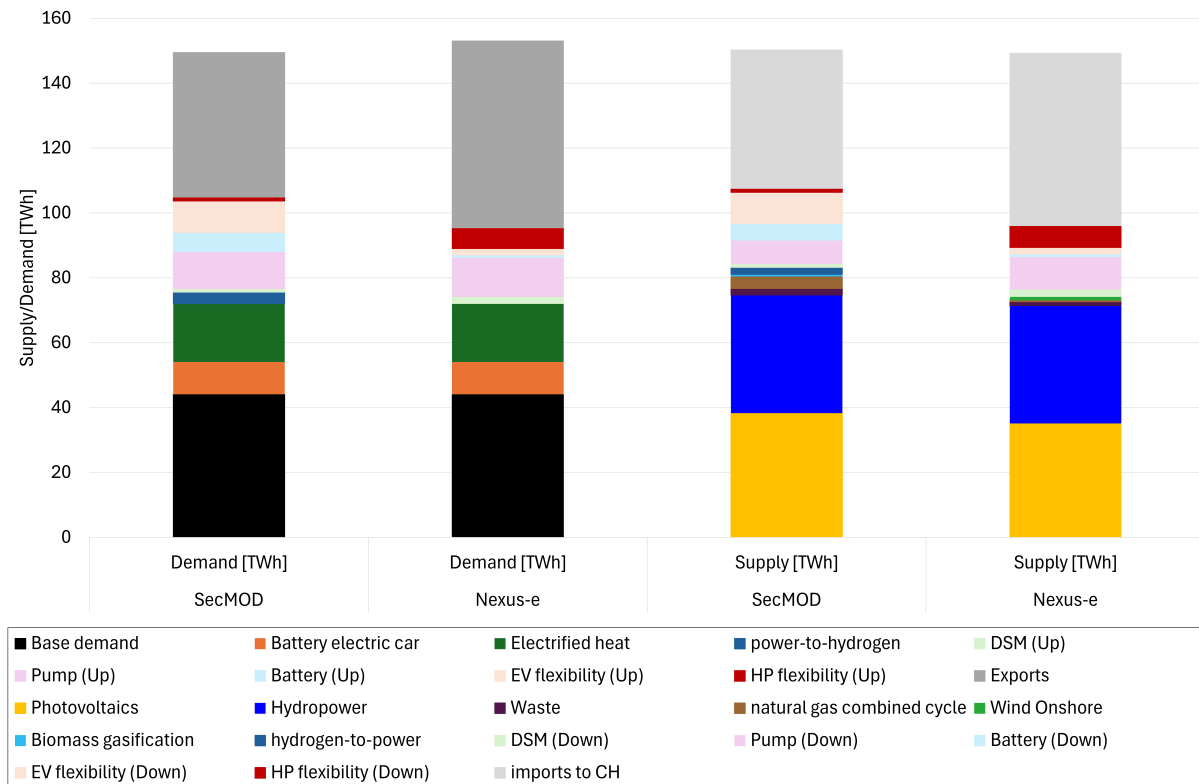


Figure 3.7: Electricity demand and supply modeled by SecMOD and Nexus-e in the reference scenario.

A crucial aspect of achieving meaningful results with soft-linking is the alignment of input data across both models. Thus, a significant portion of the modeling work in WP1 was dedicated to harmonizing key assumptions for technologies such as heat pumps, battery electric vehicles, direct air capture, point-source carbon capture, and renewables in terms of costs and efficiencies. Both SecMOD and Nexus-e were part of the CROSS model intercomparison study (SWEET-CROSS, 2024), further ensuring consistency. As a result, both models exhibit reasonable alignment in electricity supply and demand (Fig. 3.7, bold colors).

However, notable differences remain in their treatment of flexibility options (Fig. 3.7, light colors): Nexus-e can leverage electricity imports and exports with neighboring countries, whereas SecMOD's cross-border electricity flows are fixed at levels predefined by Euro-Calliope. Consequently, SecMOD additionally relies on power-to-hydrogen-to-power as a seasonal flexibility option. While both models use demand-side management, pumped hydro storage, and batteries for short-term flexibility, SecMOD makes greater use of EV flexibility, whereas Nexus-e relies more heavily on heat pump flexibility.

During the development of our soft-link approach, we also developed and implemented a bidirectional link between the models, where Nexus-e's optimized electricity sector capacities were fed back into SecMOD. However, this approach substantially increased computational complexity while having little effect on the sector-coupled demands generated by SecMOD. As a result, the bidirectional link was not further pursued, as the drawbacks outweighed the benefits.

Overall, our soft-linking approach enables Nexus-e to account for sector-coupled electricity demands

from heating and industry, as well as their associated decarbonization trade-offs, thereby allowing a more holistic assessment of the Swiss energy transition.

4 Conclusions & Outlook

In this deliverable, we investigate the potential for sector-coupling and flexibility from the heat and industrial sectors in the net-zero Swiss energy system. Both sectors have been identified as having large potential contributions to sector-coupling and flexibility due to their significant energy demands and the possibility for their electrification. To investigate this potential, we develop a soft-link between three core models in the PATHFINDER project: Euro-Calliope, SecMOD, and Nexus-e. Each of these models contributes a piece of the necessary information to holistically evaluate the role of flexibility and sector-coupling from the heat and industry sectors for Switzerland. We apply our soft-link to a reference scenario for a net-zero Switzerland, serving as a proof-of-concept and showcasing the strength of our approach.

From Euro-Calliope, we obtain the electricity trade between Switzerland and its neighboring countries, a crucial component of the Swiss energy system. With SecMOD, we optimize the Swiss sector-coupled energy system under a net-zero emissions constraint, obtaining the sector-coupled electricity demands from the heat and industry sectors. We also evaluate the potential flexibility provision from the civil and industrial heat sectors, addressing a key part of our deliverable goal. Finally, the sector-coupled electricity demands are sent to Nexus-e, which models the Swiss electricity grid in great detail. This detailed view is important since the electricity sector forms the backbone of a net-zero sector-coupled energy system.

From our proof-of-concept reference scenario, we find that the Swiss energy system heavily relies on electrified technologies, waste, and biomass to fulfill the demands of the residential heat and industrial sectors. For civil heat, 100% of the demand after thermal efficiency improvements is supplied via heat pumps and electrode boilers. For industrial heat, 100% of the low-temperature demand is also supplied via heat pumps. These electrified technologies lead to an additional sector-coupled electricity demand of 17.9 TWh_{el}/a, which is 23% more than the original exogenous sector-coupled electricity demands that Nexus-e considered for heating. The medium and high temperature industrial heat demands are primarily supplied by a mix of waste-to-energy plants and biomass. The remaining biomass is used to produce biodiesel for the mobility sector and methane for flexible electricity production. Our soft-link approach allows us to consider the limited availability of the various energy carriers and the competing uses for these energy carriers across the energy sectors, yielding more realistic projections of the energy system's sector-coupled electricity demands.

Regarding flexibility from the heat and industrial sectors, we find that both civil and low-temperature industrial heat provide valuable short-duration flexibility by shifting production to hours with higher renewables availability. Nearly 70% of the low-temperature industrial heat demand is temporally shifted to manage renewables volatility: a finding that is possible due to consideration of the sector-coupled energy system in our soft-link approach and in line with our recent paper (Mayer et al., 2024). Furthermore, we find that electricity trade is a major source of long-duration flexibility for the Swiss energy system, another finding made possible by our soft-link approach that considers Switzerland's neighboring countries.

Through our approach presented in this deliverable, we have developed a framework for holistically assessing the role of flexibility and sector-coupling in the net-zero Swiss energy system. We have applied the framework to a reference scenario, obtaining insights regarding flexibility and sector-coupling from the civil heat and industrial sectors. As a next step, we plan to expand the analysis to fully investigate the role of flexibility from the civil heat and mobility sectors. We will evaluate the eight PATHFNDR scenarios (Figure 4.1) varying the market integration and the allowed flexibility from heat pumps and battery electric vehicles to fully understand the role of these flexibility options for Switzerland.

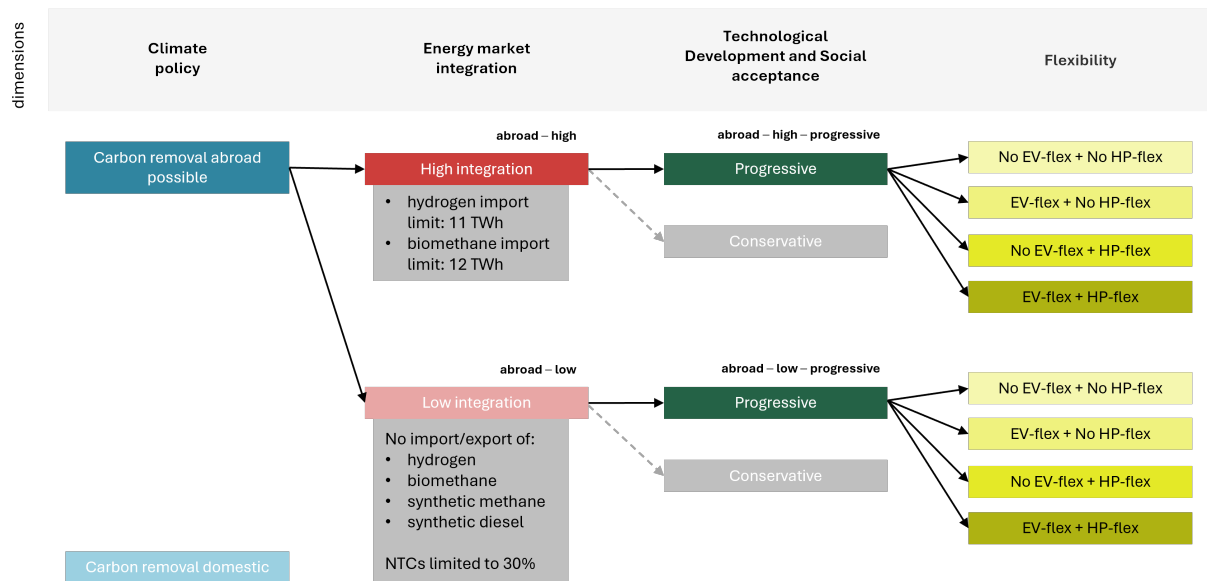


Figure 4.1: Eight main PATHFNDR scenarios to be evaluated using our soft-link approach as a next step. These scenarios vary the market integration dimension and the flexibility option dimension to holistically study the role of flexibility from heat pumps (HP) and battery electric vehicles (EV) in the net-zero Swiss energy system.

Nomenclature

Symbol	Description	Unit
CHP	combined heat and power	
LT	low temperature	
MT	medium temperature	
HT	high temperature	
CCS	carbon capture and storage	
DSM	demand-side management	
DAC	direct air capture	
EV	electric vehicle	
HP	heat pump	
LP	linear program	
MILP	mixed integer linear program	
SOC	state of charge	
TES	thermal energy storage	
WW	wastewater treatment	
$c \in C$	Set of clusters representing each typical day	
$cat \in CAT$	Set for categorizing provision technologies	
$n \in N$	Set of nodes	
$p \in P_{cat}$	Set of heat provision technologies	
$t \in T$	Set of time steps within each typical day	
$q \in Q$	Set of cantons	
$m \in M_q$	Set of communes within each canton	
$i \in I$	Set of industrial sectors	
$j \in J_i$	Set of industrial sites within an industrial sector	
$tl \in TL$	Set of temperature levels	
Q^{ph}	Swiss annual heat demand of private households	MWh _{th}
Q^{co}	Swiss annual heat demand of commercial buildings	MWh _{th}
Q_q^{ph}	Cantonal annual heat demand of private households	MWh _{th}
Q_m^{ph}	Commune annual heat demand of private households	MWh _{th}

(Continued from previous page)

Symbol	Description	Unit
$Q_{m,t}^{ph}$	Commune hourly heat demand of private households	MWh_{th}
f_q^{hd}	Cantonal heat demand share of total Swiss heat demand	-
Q_m^{co}	Commune annual heat demand of commercial buildings	MWh_{th}
$Q_{m,t}^{co}$	Commune hourly heat demand of commercial buildings	MWh_{th}
$Q_{m,t}^{res}$	Commune hourly residential heat demand	MWh_{th}
p_{CH}	Swiss population	
p_q	Canton population	
p_m	Commune population	
Q_p^{nom}	Nominal heat capacity	MW_{th}
$Q_{dem,max}$	Maximum heat demand	MW_{th}
$Q_{p,c,t,n}$	Heat supply	MW_{th}
$Q_{cat,c,t,n}^{in, VES}$	Charging virtual energy storage	MW_{th}
$Q_{cat,c,t,n}^{out, VES}$	Discharging virtual energy storage	MW_{th}
$SOC_{cat,c,t,n}^{VES}$	Storage level virtual energy storage	MWh_{th}
Q^{CH}	Swiss annual industrial heat demand	MWh_{th}
Q_j	Annual heat demand of an industrial site	MWh_{th}
$Q_{j,tl}$	Annual heat demand of an industrial site for a specific temperature level	MWh_{th}
Q_i	Annual heat demand of an industrial sector	MWh_{th}
f_j	Heat demand factor of an industrial site	-
$f_{i,tl}$	Heat demand factor of an industrial sector for a specific temperature level	-
δ_{flex}	Binary parameter allowing for using heat flexibility	
Δt_{flex}	Flexibility duration	h
ϕ	capacity share	

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