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Deliverable report

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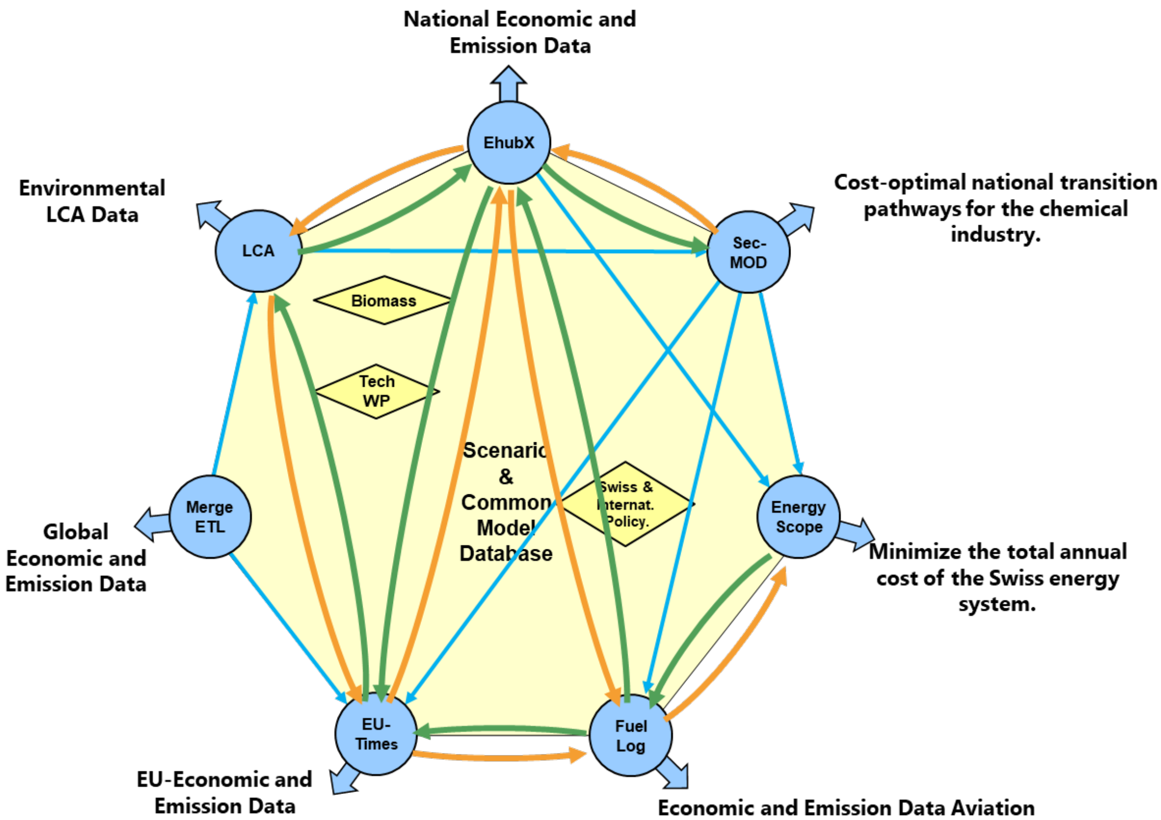
Summary

The reFuel.ch project aims to develop technologies and pathways towards the supply of Switzerland with sustainable fuels and platform chemicals to achieve a net-zero energy system 2050. The reFuel.ch project integrates research from different domains covering policy analysis, technology development, and energy system modelling and optimization from the regional to international scale. A key component in the project is the Swiss Energy System Modelling Framework (SESMF), developed in WP3, which assesses the impact of SF and SPC on the Swiss energy system. The SESMF harmonizes models from six research groups, using a Platform-Based Design (approach) for a tool agnostic interface definition and integration of different levels of abstraction. The interfaces between each platform are identified in this model harmonisation. Furthermore, a Common Model Database is developed to collect and harmonize data, adopting an ontology framework for consistency. This scenario and database development is closely aligned with related projects such as SWEET CoSi and MOTEL, ensuring comprehensive data integration and accessibility. The report discusses the interfaces between each platform, including input and output, as well as the methods, outcomes, challenges, and risks addressing M1 and D1 in WP3 towards model harmonization.



1 Introduction

1.1 Scope of the report

The reFuel.ch project aims to develop methods for synthesizing sustainable fuels (SF) and sustainable platform chemicals (SPC) and to evaluate pathways for transitioning from fossil fuels to SF and SPC. This interdisciplinary project integrates research from different domains, such as policy, technology development, and assessment. In WP3, the Swiss Energy System Modelling Framework (SESMF) is being developed to holistically assess the impact and transition pathways of SF and SPC on the Swiss energy system. This framework will provide insights into fuel logistics, demand within the Swiss chemical industry, and import dynamics with neighbouring countries. Due to the complexity of the challenge, the SESMF will be built upon the methods and knowledge of six different research groups and their established tools, models and knowledge. Since each tool and model was initially designed to operate independently, harmonizing the interfaces between the models within the framework is the first challenge and task to be addressed. Furthermore, the SESMF should not be tool dependent. Instead, a tool agnostic approach via Platform-based Design is chosen. In the reFuel.ch project, the model harmonisation has two specific subtasks:

a. Harmonize the models in WP3 with clearly defined interfaces and development requirements towards
the SESMF.

b. Establish data exchange with WP1 & WP2. Draft a data pipeline with WP4-7.

The method and outcome are summarised in the section 2 and section 3 & 4, respectively. The challenge and risk are also discussed in section 5.

1.2 What is the Swiss Energy System Modelling Framework (SESMF)?

This project significantly advances the field by combining individual models in a first-of-its-kind comprehensive modelling framework (i.e. SESMF), which is unique due to the following key features:

- Integration of the energy system with the carbon cycle and implementation of conversion paths towards SF and SPC

- Extension of the multi-criteria evaluation of the transition paths, which enables the evaluation of robust transition paths in the solution trilemma under uncertainty.

- Open access availability of the SESMF core model, datasets and results for further development in the research community

- Logistics optimization and requirement refinement for the synthesis, distribution, and use of Sustainable Aviation Fuels (SAF) to minimize CO2- and non-CO2-emissions from SAF production to consumption

- Conversion– and transition paths for energy- and carbon-emission-intensive industries. Identification of synergy potentials between energy – and carbon supply and demand.

- LCA evaluation of novel conversion paths towards SF and SPC building on the work conducted in SHELTERED and PATHFNDR projects.

- Impact analysis of low-and high TRL conversion paths investigated in the reFuel.ch project. Identification of critical technology parameter requirements to enhance potential impact.

• Dissemination strategies based on regional, national, and international case studies

• The models are connected via the Platform-Based Design approach while ensuring that each model operates at the appropriate level of abstraction.

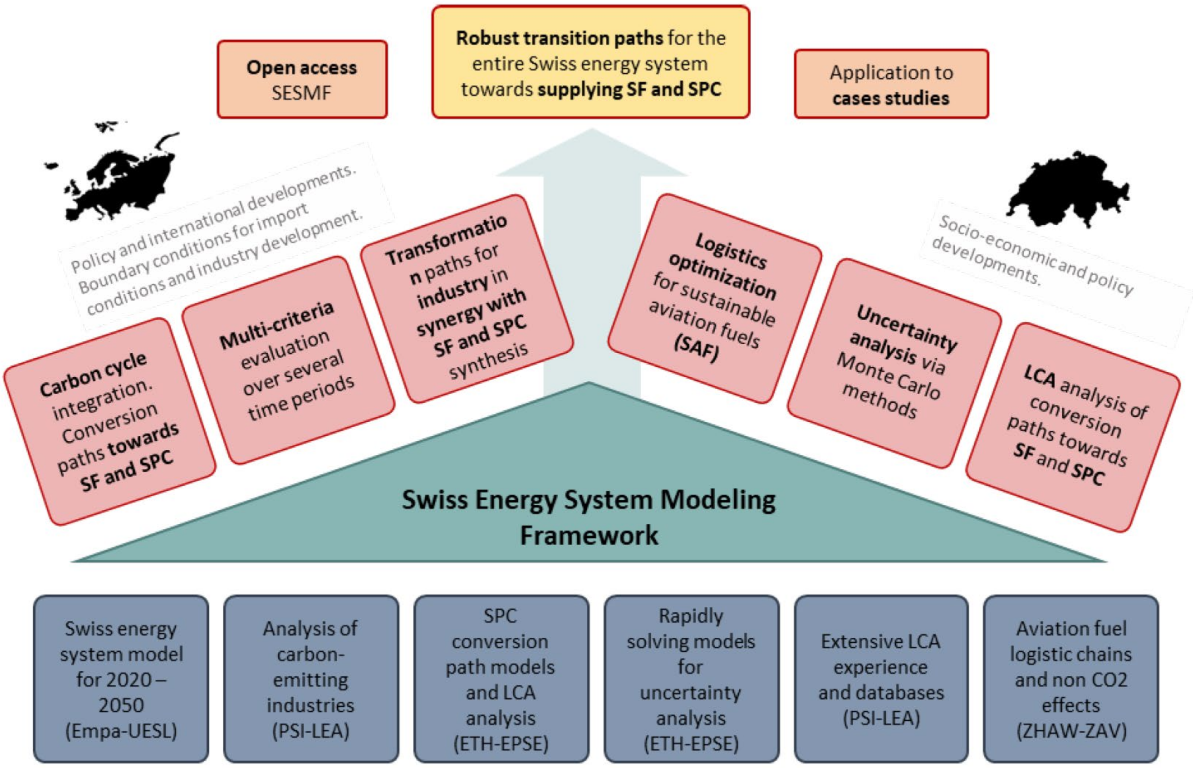


Figure 1: Fundamental building blocks of the SESMF based on proven and existing models and expertise (blue). The light red building blocks are to be developed in this project. The fundament and further developments build the SESMF. Information exchange with (a) WP2 on European and international developments (b) with WP1 on socio-economic and policy developments for Switzerland. The main results determined via the SESMF are robust transition paths for the entire Swiss energy system towards supplying SF and SPC in the required quantities.

2 Deliverable content

2.1 Model harmonisation

The SESMF integrates multiple models and methods from different research teams. Therefore, model harmonisation is the crucial first step in the framework development. In the past few months, a series of activities, including exchange workshops were arranged within WP3 to facilitate model harmonization. Two methods were introduced to the team to accelerate the harmonisation process: 1) the concept of Platform-Based Design [1] and 2) the common model database.

2.1.1 Activities for Model Harmonisation

The model harmonisation can be divided into two phases: harmonisation preparation and definition of interfaces and data exchange.

In the harmonisation preparation phases, the scope of the project and WP3 were aligned with the WP3 partners, the models from each partner were introduced to the team, and the model information and specifications were exchanged within the team. This provides information on how each model could interact and/or overlap with other models and the foundation of the model harmonisation.

During the interface and data exchange definition phase, each model's inputs, outputs, methodologies, and key assumptions were shared to ensure partner alignment. Several potential interfaces and the parameters and data that would be exchanged were identified. In the end, the first version of the model interfaces was defined, and a Common Model Database was developed for data exchange.

2.1.2 Platform-Based Design (PBD)

Platform-based Design is a concept initially developed for the silicon chip industry. It enabled a rapid scaling of the industry due to a novel approach on how to define interfaces between components. We have recently adapted and further developed this concept for energy systems [1]. By defining platforms at appropriate levels of abstraction and by connecting the platforms with well-defined interfaces, we can integrate detailed chemical synthesis paths into an integrated energy system of Switzerland while also informing the underlying synthesis paths on policy requirements from higher levels of abstraction. This approach is furthermore tool agnostic and ensures that the SESMF can also operate with a different set of tools used by the refuel.ch team.

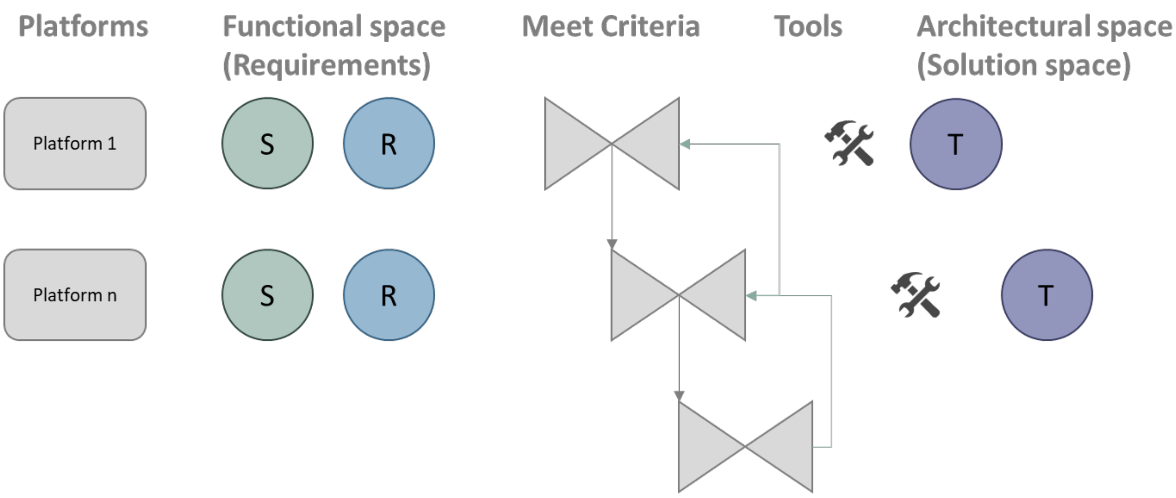


Figure 1: Concept of the PBD approach. The functional space defines the requirements of each platform. In the case of the Swiss energy system, those requirements are set by the society (S) and the availability of resources (R). The Architectural space (solution space) provides options on how the requirements

can be fulfilled; in this example via technology solutions (T). The level of abstraction of the platforms can be defined based on the problem at hand. Furthermore, each tool suitable at each level can be applied to map the functional – to the architectural space.

2.1.3 **Common Model Database**

A Common Model Database is developed to collect, manage, review and document the data used in the SESMF and provide a platform to harmonise the data to parameterize the models within the framework, ensuring consistency. The concept of ontology [2] is adopted in the development of the database: a structured framework that defines common terms, relationships, and rules, enabling different models and datasets to share and interpret information consistently within a unified database.

Currently, the common model database summarises the key inputs to the modelling frameworks, such as carriers (i.e. energy carriers and platform chemicals), processes (e.g. all the conversion processes that are considered in the frameworks), and technology specifications (e.g. costs, efficiency, embodied carbon). This data will be made available for open access within the reFuel.ch project.

The Common Model Database in the reFuel.ch project will also align with two other related projects: SWEET CoSi (led by ETZH-ESC) and MOTEL (led by USEL-Empa). A common data format for energy system models has been developed in SWEET CoSi, which is also considered in the database development. MOTEL is developing a platform to collect energy technology data in the graphical database and provide the conversion process to export technology data for different energy models. The works from both projects will be implemented and/or linked to the Common Model Database for reFuel.ch.

2.2 Model interfaces

This section explains the defined interfaces between each model. The model interfaces will be refined during the implementation stage of the project between M12 and M24.

2.2.1 Swiss-based model, ehubX (Empa-USEL)

Model/expertise description: The Swiss-base model developed in the refuel.ch project is implemented in Empa's ehubX framework. The ehubX framework is based on Pyomo and will soon be released as open source (in 2025). The Swiss-base model is a multi-stage and fully sector-coupled energy system model of Switzerland. In the refuel.ch project, the Swiss-base model will be extended to enable an analyse towards conversion paths for SF and SPC and further determine robust transition paths using uncertainty evaluation methods. ehubX is an energy system optimisation tool developed at the UESL (Empa) and has been applied in multiple national and international projects [3].

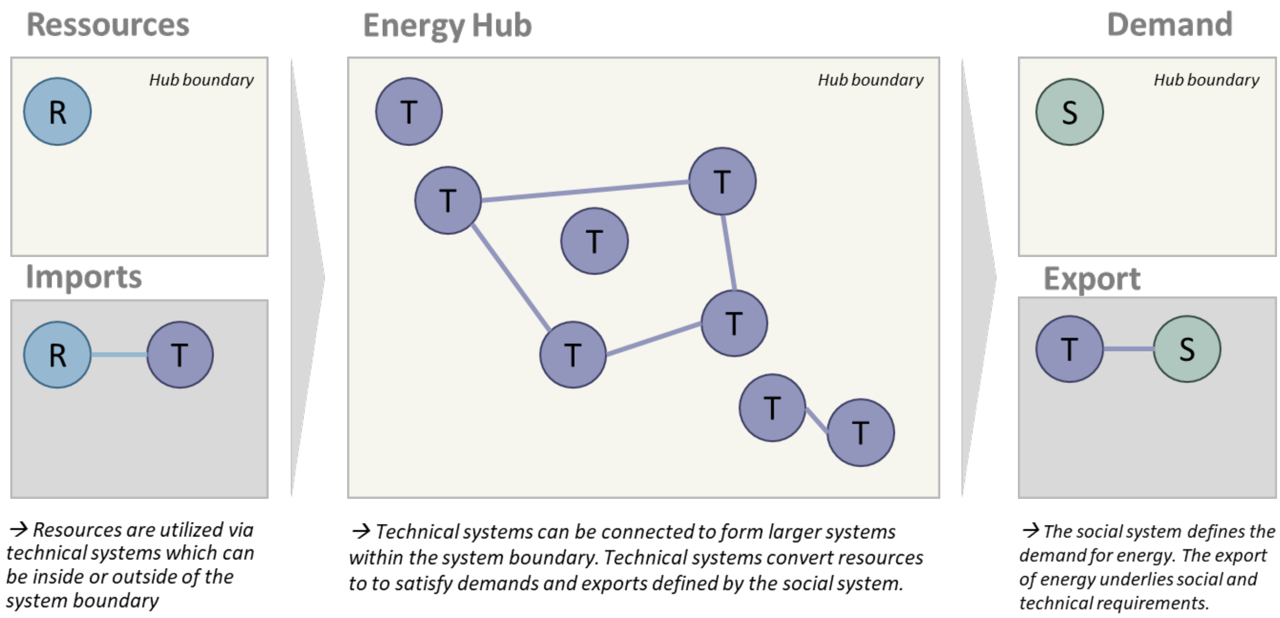


Figure 2: EhubX follows the Energy Hub concept. It maps the demand for energy from society (S) to the available resources (R) via technology candidates (T). The system is represented via Mixed-Integer Linear Programming (MILP) and the optimal system configuration and operation is determined via optimization algorithms.

Key inputs: Energy supply via resources and imports, energy demand time series, available conversion and storage technologies, energy balancing zones (hubs), network connections between hubs. Potential SF and SPC synthesis paths to consider. Demands for SF and SPC over time. Boundary conditions depending on policy requirements.

Methodology: Mixed-Integer Linear Programming (MILP) and optimization.

Key outputs:

- System cost, system CO2 emissions, system self-sustainability index
- Energy planning (e.g. installed capacity of energy generation or storage units)
- Operational profile (e.g. hourly energy production profiles, charging and discharging profiles of storage)
- Selection of robust conversion -and transition paths towards SF and SPC

Interface with other models:

Model/expertise	Input	Output
Swiss policy (WP1)	Scenario definitions; boundary conditions on emissions, trade (import/export) and commodity prices and technology and infrastructure developments; regulations and costs for compensating emissions aboard; involvement of Switzerland in the European Carbon Trading System (ETS); minimum quota for domestic production for selected commodities;	Impact on different policy scenarios on transition paths and system cost Identification of critical parameters and values for the uncertainty analysis
International policy (WP2)	Import/export constraint for energy carriers and platform chemicals; scenario derivation of international developments & SAF quotas	System cost and domestic production capacity and volume based on scenarios
International / European energy system (WP2)	Import/export costs of energy carriers and platform chemicals	System cost and energy carrier selection of the Swiss system
Industry sector (WP3)	List of available conversion technologies and their parameters	Feedback on the most relevant changes in each industry sector from a system perspective
Platform chemicals	Selection of most relevant and representative platform chemicals, costs of feedstock, abstracted details and costs of SPC pathways	List of favourable platform chemical conversion paths based on system boundary conditions and scenarios, energy demand of conversion paths of the Swiss energy system
Fuel logistics	Fuel production and logistic scenarios (e.g. location of CO2 point sources and sinks. Sources and sinks for H2 and SAF and SPC; transport methods and their costs and carbon emissions per fuel type.	SAF production volumes in Switzerland; import volumes and conversion paths of SAF and their components to Switzerland
LCA	Embodied carbon emissions of energy technologies / conversion paths and infrastructures	List of technologies to be considered per stage (reference years)
Biomass (WP6)	Availability of biomass for energetic use; type of biomass;	Role of biomass in the Swiss energy system.
Technologies (WP4-WP7)	Development -and cost estimates for conversion and storage technologies related to the SF and SPC synthesis	Relevance of technology / scenario depending on selection of the technology Investigation under which circumstances (e.g. efficiency or CAPEX / OPEX) the technology would be selected in the system

2.2.2 International/ European energy system, JRC-EU-TIMES (PSI-EEG)

Model/expertise description: JRC-EU-TIMES model [4] is a multi-region, multi-sectoral, multi-carrier, and multi-period energy system model of 30 European countries, including Switzerland. It is built on the TIMES energy system modeling framework developed by IEA-ETSAP [5]. The model has a detailed representation of the energy supply, conversion, transmission, distribution, storage, and end-use. It also models endogenous trading of energy commodities and corresponding infrastructures e.g., electricity transmission lines, hydrogen pipelines.

Key inputs: Energy service demands and industrial production volumes, technology characterization attributes (e.g., investment costs, efficiencies, inputs, outputs), resource profiles, costs and potentials, trade links and capacities, extra-EU trade prices of commodities, energy and climate policies (subsidies, targets, mandates, bans etc.)

- **Industrial Sector Representation:** The JRC-EU-TIMES model has a detailed representation of various key industrial sectors, and their subsectors as outlined in the following table. It models various technologies and commodities to produce the end-use industrial products/ energy demands. It represents the current industrial production routes as well as future possible technological options which it optimizes based on scenario assumptions. Being a multi-sectoral model, the evolution of industrial sector i.e., future technology and fuel choices are closely linked with development in other sectors, e.g., supply sector.

Sector	Sub-sector	End-uses
Industry	Iron and Steel	Steel
	Non-metallic minerals	Cement production Lime production Glass production (hollow, flat) Other non-metallic minerals production
	Chemical	Ammonia production Chlorine production Other chemical production
	Non-Ferrous metals	Aluminium production Copper production Other non-ferrous metals production
	Pulp and paper	High-quality paper production Low-quality paper production
	Other industries	Machine drive Process heat Steam
	Non-energy use	Non-energy demand

Methodology: Linear Programming. Partial Equilibrium. System cost minimization (capital cost, fixed and variable annual O&M costs, cost for imports and domestic resource extraction and production, revenues from exogenous export, delivery costs for commodities, taxes and subsidies, salvage value of processes and embedded commodities)

Key outputs: Annual stock and activity of supply, demand, and trade technologies, including associated material, energy, and emission flows for each region and period. The model also provides operation and maintenance costs, investment costs, and prices (approximated as marginal costs) of energy and materials commodities. It provides investment and decommission pathways for technologies and their operational time profiles. Trade flow origins, destinations for energy carriers, and emissions are also outputs of the model.

Interface with other models:

Model/expertise	Input	Output
International policies (WP2)	European regulations and directives related to EU green deal implementation and SAF blending mandates as well as international aviation policies (e.g., CORSIA)	ETS (Emissions Trading System) prices, availability of SAF imports for Switzerland.
Swiss policies (WP1)	Scenario definitions, boundary conditions on emissions, trade (import/export) and technologies. Regulations and costs for compensating emissions aboard; involvement of Switzerland in ECTS.	availability of SAF imports for Switzerland.
Scenario definitions (WP3)	Harmonized scenarios and driver definitions for Switzerland and Europe.	n/a
MERGE-ETL (WP2)	Supply routes, mode of transport, and quantities of fuels (e.g., H2, NH3, Biofuels, SAF) to Europe; corresponding marginal costs. Import-export bounds to/ from Europe from/ to international regions. Cost of CO2 compensation abroad approximated through marginal cost of CO2.	Cost of import of SAF and availability of imports for Switzerland from countries outside the EU. Cost of CO2 compensation abroad for Switzerland.
Swiss-base model (WP3)	Switzerland specific insights related to local sustainable fuel production such as list of relevant technology, their characterization (cost, efficiencies, inputs, outputs), envelope of their deployment levels and mixes.	Trade routes, means of transport to bring fuels to Swiss border, and quantities of sustainable fuels. Prices of imported fuels including electricity. Import/ export volumes to/ from European countries. ETS prices. List of relevant technologies for the industrial sector, their potential deployment, and their parameters.
Platform chemicals (WP3)	Chemical demand in Switzerland Technology choice, Sectoral insights/ constraints for technology deployment. selection of platform chemicals, costs of feedstocks, mass flows and costs of final chemicals and SPC.	Imported/ exported fuel quantities and prices, ETS price, carbon footprints
Fuel logistics (WP3)	Switzerland specific insights regarding supply logistics of sustainable fuels. Infrastructure cost and capacities for SAF distribution in Switzerland for various modes of distribution (pipeline, rail, road, ship). Infrastructure violation constraints/ insights.	Origin and mode of fuel transport to Switzerland and their prices. Demands of sustainable fuels for international aviation (and if requested also for other sectors).
LCA (WP3)	Embodied carbon of energy and industry technologies	Origin and type of imported fuels and chemicals.
WP4, WP5, WP6, WP7	Technology overview and data related to CO2-Electrolysis for Synthesis Gas Production Technology overview and data related to High-Conversion and Load-Flexible Methanol Synthesis Biomass potentials, technology overview and data for Manure to Sustainable Fuels and Platform Chemicals	Technology deployment pathways List of Competitive technologies barring the deployment Technology learning improvement required for competitiveness

	Technology overview and data related to MTO and OTF processes	

2.2.3 Fuel Logistics (ZHAW)

Model/expertise description: Within the scope of the project, ZHAW aims to build a model that optimizes the logistics of sustainable aviation fuels (SAF) within Switzerland, with a focus on identifying the optimal location(s) for domestic SAF and SPC production. The model evaluates optimality based on cost and CO2 footprint dimensions. It considers both domestic production of CO2 and H2 from point sources and the import of these materials from external sources. Key demand centers include major national airports such as Zurich and Geneva. The model outputs the optimal SAF and SPC production location(s), as well as the corresponding transportation volumes and routes across Switzerland.

Key inputs: Domestic SAF demand volumes per location, location of domestic raw material (i.e., CO2 and H2) point sources and supply potential, SAF import volumes into Switzerland, raw material import volumes into Switzerland, SAF production technologies, raw material capturing/production technologies, technology characterization attributes (e.g., fixed and variable costs, efficiencies, inputs, outputs), transportation routes and costs per material.

Methodology: Linear programming, facility location problem, calculation of scenarios

Key outputs: Optimal production location(s) of SAF, associated transportation volumes of raw material and SAF from respective sources to sinks, CO2 emissions and costs associated with transportation, potential limitations of raw material supply

Interface with other models:

Model/expertise	Input	Output
International/European energy system (PSI-EEG)	Import volumes per material (i.e., CO2, H2, SAF) and source country (incl. mode of transportation, CO2 emissions and costs)	Feasibility of domestic production volumes and cost to supply SAF to demand locations
Swiss-base model (Empa-UESL)	Domestic SAF demand; domestic production volumes of SAF and raw materials; used production technologies and technology characterization attributes	Feasibility of domestic production volumes and cost to supply SAF to demand locations
Swiss Energy Scope SES-ETH (ETHZ)	Domestic SAF demand; domestic production volumes of SAF and raw materials; used production technologies and technology characterization attributes	Feasibility of domestic production volumes and cost to supply SAF to demand locations

2.2.4 Life Cycle Assessment, LCA (PSI-TAG)

Model/expertise description: PSI's Technology Assessment Group (TAG) brings to WP3 and the ReFuel.ch project its expertise in prospective life cycle assessment (LCA). In particular, TAG's open-source software tool "premise" is crucial in assessing the future environmental performance of novel technologies like e-fuels and green hydrogen-based chemicals. In particular, premise allows to modify large LCA databases like "ecoinvent" according to the temporal dynamics. Premise applies a number of transformations on energy supply, markets and energy-intensive activities found in the inventory database ecoinvent according to projections provided by IAMs according to future scenarios and global climate policies.

Key inputs: Technologies/processes [technology/process, unit, geographic location, year], Production location, SSP [1,2 or 5], RCP [None, 1.9 °C or 2.6°C], Integrated Assessment Model [REMIND, IMAGE, others].

Methodology: Prospective environmental LCA.

Key outputs: One of the key tasks of the PSI TAG in WP3 is to provide prospective embodied and operational carbon emissions for energy technologies, energy carriers, and infrastructures. These emissions are generated using the LCA tool "premise" and will be soft-linked to the Swiss-base energy system model ehubX. Specifically, the embodied carbon of imported fuels and chemicals will be derived from an import mix that aligns as closely as possible with the assumptions and outputs of WP2. In addition, PSI TAG generates life cycle inventory data and results for novel conversion pathways for fuels and chemicals. Compared to the LCAs performed in WP6, which focus on biofuels, the emphasis in WP3 is on novel fuels and chemicals produced in favourable locations for CO_2 capture from the air and water electrolysis, with a particular focus on methanol for what regards chemicals. An LCA evaluation, incorporating new datasets for a broad range of e-fuels and chemicals made publicly available [6], has been conducted building on work from the SWEET PATHFNDR project [7]. This project identified several cost-effective production locations in Iceland, Spain, and the Netherlands for a wide range of e-fuels and chemicals relevant to the Swiss market. These datasets can also be easily adapted to represent other locations relying on the same power sources. These datasets are now being utilized to conduct a joint LCA with ETH-EPSE on alternative fuels for gas turbines, with and without carbon capture, as part of a preliminary study for P&D1. Furthermore, PSI TAG coordinates several cross-cutting activities where LCA expertise is particularly relevant across work packages. These include the sub-group on aviation's climate impacts from non-CO_2 emissions, which is part of the platform on demand and model assumptions, and the sub-group on the environmental dimension co-lead with WP6 LCA experts, which contributes to the sustainability assessment platform. An LCA-based cost-effectiveness analysis of sustainable aviation fuels for the global market, including non-CO2 emissions, has been published [8].

Interface with other models:

Model/expertise	**Input**	**Output**
MERGE-ETL (WP2)	Supply routes, mode of transport, and quantities of fuels (e.g., H2, NH3, Biofuels, SAF) to Europe; Import-export bounds to/ from Europe from/ to international regions.	n/a
ehubX, Swiss-base model (Empa-UESL)	List of technologies to be considered per stage (year)	embodied and operational carbon emissions of energy technologies and infrastructures
JRC-EU-TIMES (PSI-EEG)	Origin and type of imported fuels and chemicals.	Embodied and operational carbon of energy and industry technologies
Swiss-base model (WP3)	Switzerland specific insights related to local sustainable fuel (SF) and SPC production such as list of relevant technology, their characterization (cost, efficiencies, inputs, outputs), envelope of their deployment levels and mixes.	More detailed LCAs of applications of novel synthetic fuels and chemicals considering other environmental impacts e.g. toxicity-related etc. Life cycle climate impacts of chemicals
WP6	LCAs of manure-based pathways	LCAs of e-fuels pathways

2.2.5 Uncertainty analysis, Swiss Energyscope-ETH (SES-ETH)

Model/expertise description: SES-ETH is a linear optimization model of the energy system. It determines the investment and operation strategies that minimize the total annual cost of the energy system, given the end-use energy demand, the efficiency and costs of the conversion technologies, and the availability and costs of the energy resources. SES-ETH represents the main energy demands: electricity, heat and mobility. It is a snapshot model, i.e., it models the energy system in a target year, but it does not make any statements on the trajectory to reach this future state. Given the simplicity and compactness of the model (single node, typical day approach) it is well-suited for multiple runs, e.g. Monte Carlo analysis to understand the impact of uncertainty.

Key inputs: End-use demands, technology characteristics (e.g., investment costs, efficiencies, inputs, outputs), resource profiles, costs and potentials. Since the rest of Europe is not explicitly modelled, a key input is the price, maximum volume and maximum rate of energy imports and exports (including CO_2 exports). This has to be provided by other models inside the SESMF.

Methodology: Linear Programming. Partial Equilibrium. System cost minimization (capital cost, fixed and variable annual O&M costs, cost for imports and domestic resource extraction and production, revenues from exogenous export).

Key output: Optimal configuration of the energy system; optimal operation including energy, material and emission flows; operation and maintenance costs, investment costs, and prices (approximated as marginal cost) of energy and materials commodities.

Interface with other models:

Model/expertise	Input	Output
International policies (WP2)	European regulations and directives related to EU green deal implementation and SAF blending mandates as well as international aviation policies (e.g., CORSIA)	n/a
Swiss policies (WP1)	Scenario definitions, boundary conditions on emissions, trade (import/export) and technologies. Regulations and costs for compensating emissions aboard; involvement of Switzerland in ECTS.	n/a
Scenario definitions (WP3)	Harmonized scenarios and driver definitions for Switzerland and Europe.	n/a
ehubX (WP3)	Detailed description of fuel production technologies, possibly to be simplified within SES-ETH model; agreed ranges of uncertainty for key parameters.	Robustness of solutions and pathways.
Platform chemicals (WP3)	Chemical demand in Switzerland. Description of technologies (investment and O&M costs, efficiencies) to produce chemicals in Switzerland.	Quantities of platform chemicals imported to or produced in Switzerland.
Fuel logistics (WP3)	Switzerland specific insights regarding supply logistics of sustainable fuels. Infrastructure cost and capacities for SAF distribution in Switzerland for various modes of distribution (pipeline, rail, road, ship). Only in an aggregated way since no explicit representation of spatial aspects.	Quantities of fuels imported to or produced in Switzerland.
WP4, WP5, WP6, WP7	Technology overview and data related to CO2-Electrolysis for Synthesis Gas Production Technology overview and data related to High-Conversion and Load-Flexible Methanol Synthesis Biomass potentials, technology overview and data for Manure to Sustainable Fuels and Platform Chemicals Technology overview and data related to MTO and OTF processes	n/a

2.2.6 <u>Platform chemical, SecMOD-ChemMOD (ETH-EPSE)</u>

Model/expertise description: SecMOD [9] is an open-source framework for multi-sector system optimization incorporating LCA. It enables the optimization and assessment of linear multi-sector systems for different time and spatial details. Within the first year of the reFuel.ch project, the framework was interfaced with ChemMOD, a comprehensive database for the chemical industry, encompassing prices and life cycle emissions of more than 400 engineering-level datasets and more than 90% of the current plastics production [10], [11].

Key inputs: demands of chemicals in Switzerland, costs of feedstocks, technology matrix (mass flows of reactants and energy demands per chemical), costs of final chemicals and SPCs, embodied and operational CO2 emissions for the production, use and end-of-life of considered chemicals.

Methodology: Linear programming. Total annualized cost minimization (capital cost, fixed and variable annual O&M costs, cost for imports and domestic resource extraction and production, revenues from exogenous export, delivery costs for commodities, taxes and subsidies, salvage value of processes and embedded commodities).

Key outputs: technology choice, sectoral insights/ constraints for technology deployment, selection of cost-optimal platform chemicals for each year, annual chemical industry overall costs (with a breakdown for every technology) including associated energy demand/cost and life cycle emissions. The model will ultimately provide cost-optimal transition pathways for the chemical industry under environmental targets (e.g., net-zero constraint).

Interface with other models:

Model/expertise	**Input**	**Output**
Swiss policies (WP1)	Scenario definitions, boundary conditions on emissions, trade (import/export) and technologies. Regulations and costs for compensating emissions abroad; involvement of Switzerland in ECTS.	Selection of most relevant and representative platform chemicals for each year depending on scenarios Chemical industry cost dependent on scenarios
International policies (WP2)	European regulations and directives related to EU Green Deal implementation. Import/export constraint and costs of energy carriers and platform chemicals; minimum quota for domestic production.	Selection of most relevant and representative platform chemicals for each year depending on scenarios Chemical industry cost dependent on scenarios
Scenario definitions (WP3)	Harmonized scenarios and driver definitions for Switzerland and Europe.	n/a
Swiss-basemodel (WP3)	Switzerland-specific insights related to electricity, heat, mobility and fuels. List of relevant technologies and related parameters (costs, efficiencies, inputs, outputs).	Chemical demands in Switzerland and quantities of SPCs. Volumes and prices of imported/exported chemicals. List of relevant chemicals and chemical processes for Switzerland, their potential development and technology-related parameters.
Fuel logistics (WP3)	Switzerland-specific insights regarding supply logistics of fuels and SAFs. Infrastructure cost and capacities for SAF distribution in Switzerland for various modes of distribution (pipeline, rail, road, ship). Fuel production and logistic scenarios (e.g. location of CO2 point sources and sinks). Sources and sinks for H2, SAF and SPC; Transport methods and their costs and carbon emissions per fuel type.	Interactions and synergies between SAF and SPC logistics and infrastructures.
LCA (WP3)	Embodied and operational carbon emissions of chemicals, energy and industry technologies	Selection of the most relevant and representative platform chemicals for each year to meet climate targets (e.g., net-zero constraint). Life cycle emissions of the chemical industry per year
Industry sector (WP3)	List and key parameters of industrial sectors Costs and energy demand of key chemicals for the industrial sectors	Chemical industry interactions and synergies with other industrial sectors
Technologies (WP4, WP5, WP6, WP7)	Technology overview and data for SF and SPC synthesis, in particular related to CO2-Electrolysis for Synthesis Gas Production, High-	Technology deployment pathways List of competitive technologies barring the deployment

	Conversion and Load-Flexible Methanol Synthesis, Manure to Sustainable Fuels and Platform Chemicals and MTO and OTF processes Biomass potentials	Technology learning improvement required for competitiveness

2.3 Data exchange pipeline

The data exchange pipeline summarises how data flows between the models within the SESMF.

Due to the complexity of the data exchange within the SESMF, the platform-based design concept is applied within the SESMF. Each model/export field performs analysis and simulation with the information (e.g. data, assumptions) obtained from other platforms. Moreover, the outcomes of each platform are provided to other platforms to finetune or further develop the analysis/simulation done by each platform.

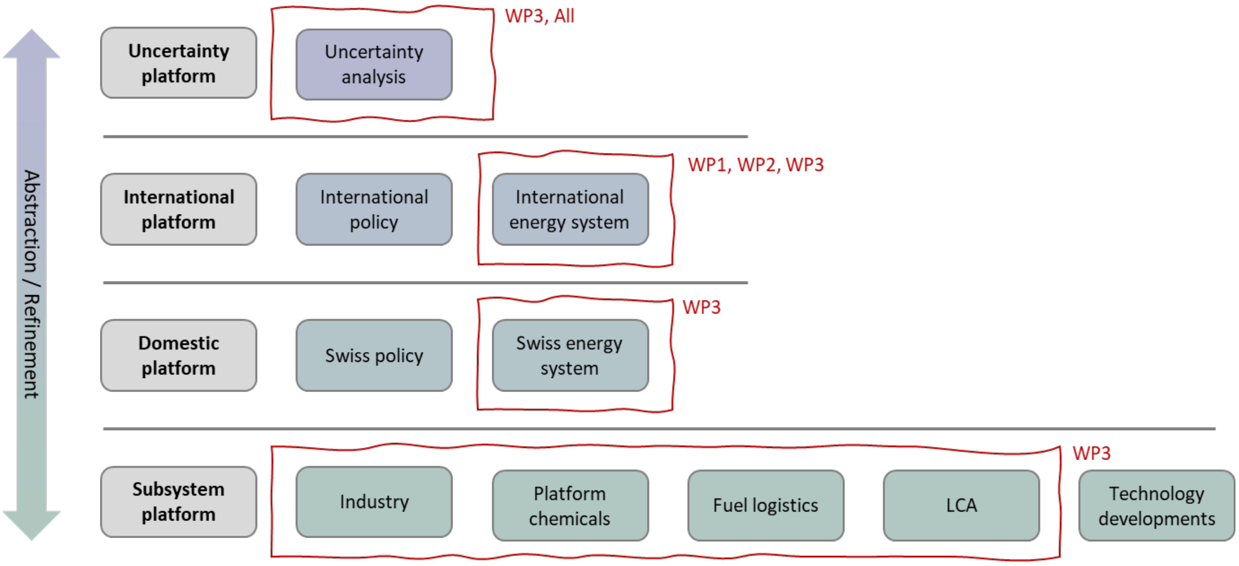


Figure 3: Platforms applied in WP3 and in the reFuel.ch project.

The data exchange between each platform can be divided into the following steps:

1. Data harmonisation: the common model data (e.g. carrier definition, technology specification, fuel properties and their supply and demand…) that multiple models could use are aligned within the project partners and summarised in a Common Model Database.
2. Starting phase: each platform provides the data to other platforms that can be obtained based on the existing information (e.g. results from previous studies or analysis/simulation without input from other platforms)
3. First analysis: each platform performs analysis/simulation based on the data obtained in previous steps, creating new results or updating the data provided in the starting phase.
4. Refine analysis: the new or updated data from each platform are provided to other platforms, and the analysis/simulation is refined; the updated outcome is then updated to other platforms

In the SESMF, the Swiss-based model plays the key role of integrating the data from other models and evaluating the pathways of fuels and platform chemicals development for the Swiss energy systems (see figure below). The key inputs across models are collected in the Common Model Database in a tabular format in a shared space. Each team contributes to the database and can extract the required data from the database.

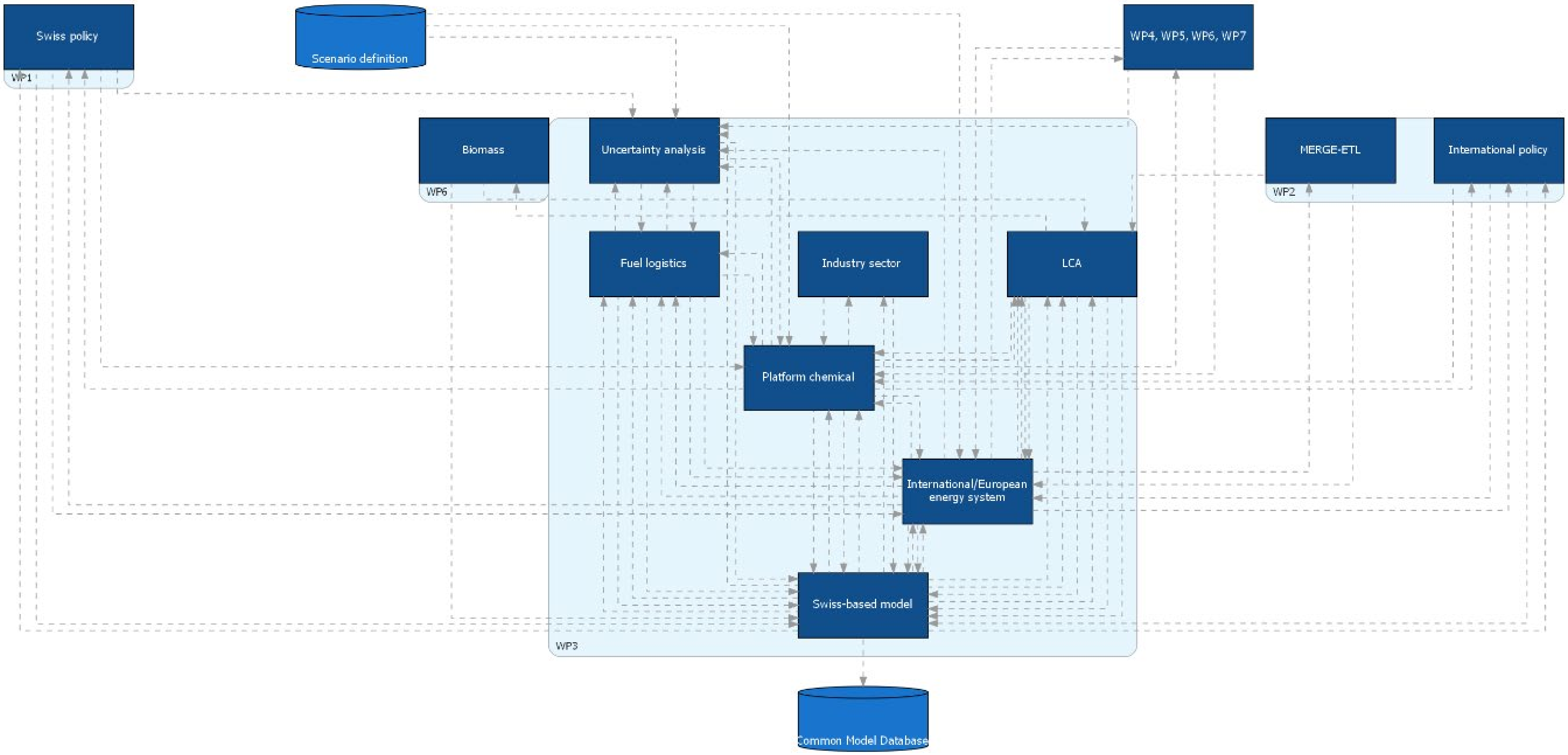
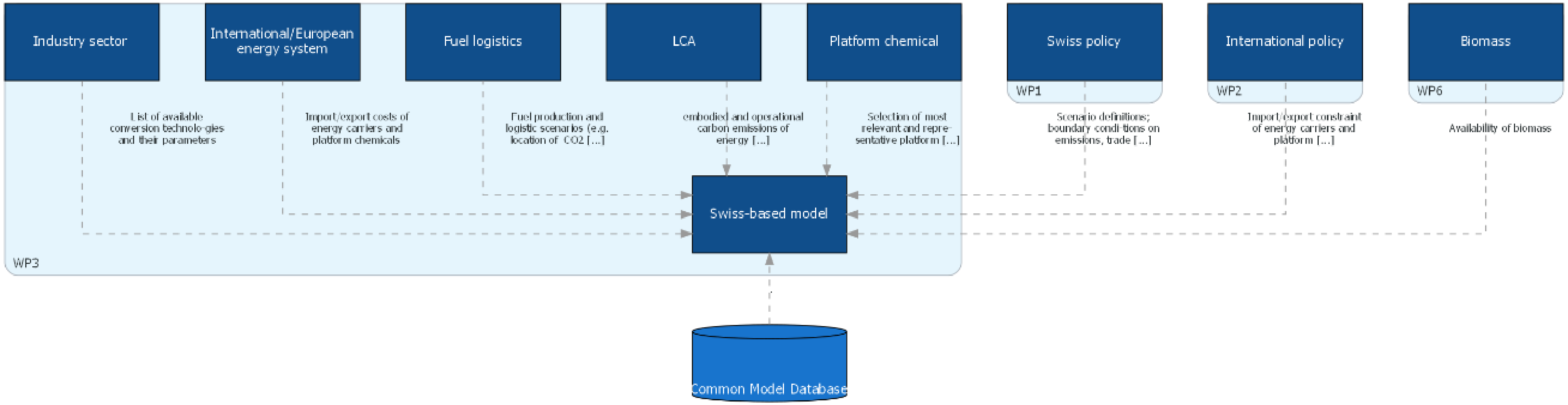
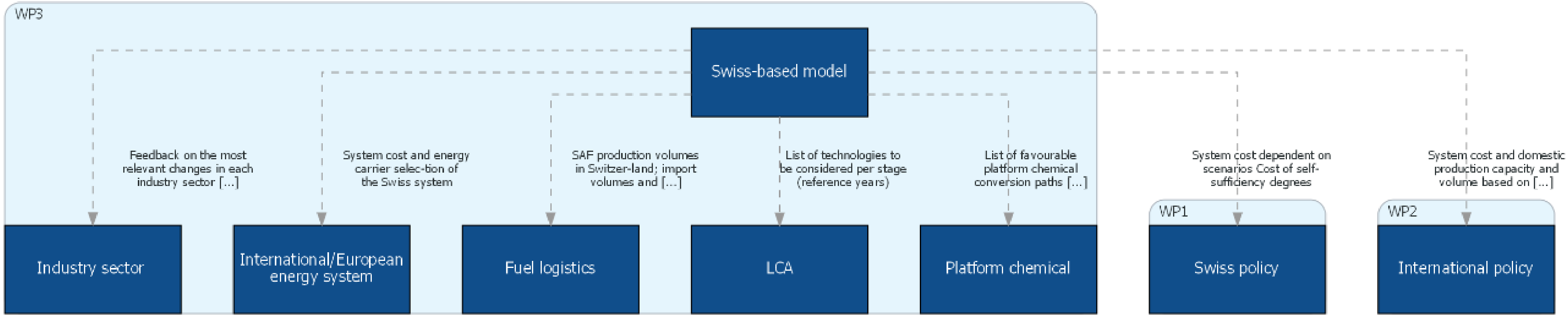


Figure 4: The overview of data flows within the Swiss Energy System Modelling Framework.



Input to Swiss-based model



Input to Swiss-based model

Figure 5: The data flows focused on the input and output of the Swiss-based model.Challenge and risk of model harmonisation

The harmonisation of models in a complex energy system simulation framework, such as reFuel.ch, involves aligning diverse methodologies, data structures, and interactions. This process is critical for ensuring consistent and reliable outputs, but it presents several challenges and risks.

2.3.1 Challenges

Data Harmonisation:

- Parameter Definitions: Aligning definitions across models is complex, as each model may use different units, assumptions, or calculation methods. For instance, energy efficiency metrics for conversion processes may vary in definition and calculation approach. To ensure consistency, we will establish a common glossary.
- Key Parameter Definitions: Different models might define technologies or key parameters inconsistently, creating conflicts in data interpretation. To ensure consistency, we established the common technology database (A draft has been developed as of July 2025). The effort to develop the technology database has been coordinated closely with SWEET Cross+ / CoSi. The technology database will be published and hence made accessible to everyone.
- Resolution and Detail Levels: Models often operate at varying levels of resolution. Harmonising these requires careful aggregation or alignment and definition of system boundaries to maintain accuracy while enabling compatibility. To be able to develop the models at different levels of abstraction, we introduced the Platform-Based Design approach.
- The data structure and assumptions of some models may be changed with the model development. Version control is needed to make the data exchange between platforms compatible with the development of some models.

Method Harmonisation:

- Scenario and Data Dependency: Certain scenarios or datasets may be tied to methodologies specific to individual models. Ensuring compatibility without compromising the methodology's integrity is a significant challenge. Update July 2025: We will tackle this challenge via Platform 1.

Model Interaction:

- Data Exchange Workflow: The sequence of data exchange in the simulation workflow can vary in complexity. Determining whether data flows one way or involves iterative feedback loops between models is essential for workflow design.
- Dependency Complexity: Excessive interdependence between models may lead to unsolvable problems or difficulties in debugging.
- Some models (for example the logistics model) may not be fully automated. Therefore, changes in the input data could lead to increased workload for recalculation.
- Computational Time: Iterative workflows that involve multiple feedback loops can significantly increase computational time, potentially making the modelling framework impractical for timely analysis.

2.3.2 Risks

Incomplete Models:

- Model Maturity: The readiness level of each model poses a risk. If some models are underdeveloped or do not meet the expected standards, the overall framework's effectiveness could be compromised.

- Data Gaps: If a model cannot provide the expected data outputs, this can disrupt the harmonisation process and lead to incomplete or inaccurate results.
- Uncertainty within the model: Some model inputs may include uncertainty ranges which some models may not be able to process by nature while also having binary outputs (e.g. logistics model). This could lead to a false assumption of certainty of model results.

Development Uncertainty:

- Interfaces between models may evolve as the overall framework develops, leading to unforeseen challenges in maintaining harmonisation.
- Additional challenges and risks may emerge as model interfaces are more clearly defined, requiring flexibility and adaptability in the harmonisation process.

2.3.3 Mitigation and next steps

To mitigate these challenges and risks, the following actions are taken:

- Define Interfaces Clearly: Refine the interfaces between models to facilitate data exchange and minimise ambiguity via the application of the developed workflows.
- Assess Model Maturity: Perform a comprehensive evaluation of each model's development stage and identify gaps requiring additional work (see following table).
- Balance Complexity: Design the modeling workflow to balance detail and computational feasibility, avoiding excessive interdependence and lengthy runtimes.
- Iterative Refinement: Accept that harmonisation is an iterative process, with adjustments needed as the framework evolves.
- Uncertainty within the models: perform thorough sensitivity analysis for the model parameters and clearly declare which output values have high uncertainty.

By addressing these challenges proactively, the reFuel.ch framework can achieve a robust and harmonised model integration to support its energy system simulation goals effectively.

Framework*	Model maturity	Development required
ehubX	High	• Data conversion and translation to the input data of ehubX
TIMES	High	• No further development necessary at this stage.
LCA	High	• No further development necessary at this stage.
Fuel logistics	Low	• Model SAF production, i.e. the green facility location problem, in existing software package. • This involves mapping of sources, sinks and potential facility locations, including capacities, costs, as well as production processes and their efficiencies • Assessing the sources of GHG emissions associated with the location of the facilities taking into account mobile sources (transportations) and stationary sources (construction of facility production, storage and handling) • This involves definition of potential transportation links, including mode choice and its respective capacity and cost data. • Python script for preprocessing inputs from other models • Sensitivity analysis for model parameters
Platform chemicals	High	n/a
Swiss-base model including SF and SPC	• Medium	• Built the link to the platform interfaces and incorporate/translate the inputs from other platforms to the Swiss-based model
SES-ETH	• High	• n/a
Uncertainty analysis	• Medium	• Develop and implement the analysis methods based on the framework developed in the whole modelling framework

3 Conclusion

This report summarises the outcome of the harmonized models from different research groups, creating a cohesive framework essential for the Swiss Energy System Modelling Framework (SESMF). This harmonization process involved:

- Preparation Phase: Aligning the project scope and introducing models from each partner, ensuring a clear understanding of how each model interacts and overlaps.
- Interface and Data Exchange Definition Phase: Sharing inputs, outputs, methodologies, and key assumptions to define model interfaces and develop a Common Model Database.

The introduction of Platform-Based Design (PBD) and the development of a Common Model Da-tabase were crucial in this process. These tools facilitated the integration of detailed chemical synthesis paths into the Swiss energy system, ensuring consistent information sharing and effective model operation at appropriate abstraction levels.

Moving forward, the project will focus on defining and fine-tuning the parameters and data for-mats to be exchanged via platform interfaces. The development and execution of the SESMF will be based on the established data pipeline. Additionally, the model interfaces and data flows will be refined, ensuring the framework's practical applicability and effectiveness

Overall, the harmonization of models with defined interfaces has laid a strong foundation for the SESMF, enabling the comprehensive assessment of transition pathways for the Swiss energy system.

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