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sweet swiss energy research for the energy transition

SWEET Call 1-2020

D1.3.3 - Data exchange standard and associated analysis/visualisation tools developed

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1 Background and need for a standard

In Work Package 1 (WP 1), our aim is to develop a comprehensive set of pathways for the Swiss energy system that are efficient, flexible, resilient, cost-competitive, and sustainable. We plan to achieve this by considering various flexibility and sector-coupling strategies. To achieve this goal, it is necessary to ensure that our modeling suite can accurately capture and model the following aspects:

- Interconnections between the Swiss and European energy systems, including energy commodity trades, infrastructure deployment, and policy implementation.
- A complete sector-wise representation of the Swiss energy system, enabling us to identify synergies between flexibility alternatives and sector-coupling dynamics.
- Providing Swiss energy system pathways with a higher level of spatial detail.

An effective way to ensure these aspects are captured and implemented is to develop a modeling suite composed of several modules soft-linked to one another. Soft-linking brings about several benefits, including:

- Increased flexibility. Soft-linking allows for greater flexibility in the modeling process, as it enables the use of different models for different parts of the energy system. This can help to capture more detailed and accurate representations of different sectors and processes.
- Improved accuracy. Soft-linking can improve the accuracy of energy system models by incorporating additional information from other models. This can help to increase the modeling details as well as uncertainties, aiming at improving the overall reliability of the modeling results.
- Better representation of system interactions. Soft-linking enables the modeling of interactions between different sectors and processes within the energy system, such as the interaction between the electricity system, heat, industry and transportation sectors. This can provide a more complete picture of the energy system and improve the understanding of how different sectors and processes are interdependent.

Soft-linking different modules can bring about several advantages, but it can also lead to challenges that can affect the success of the integrated energy system modeling approach. These challenges include:

- Model compatibility. Different energy system models may have different scopes, assumptions, and input data, which can make it difficult to integrate or exchange information between them. Soft-linking requires that the models be compatible, and this can be a challenge.
- Data consistency. Soft-linking requires that the data used in different models are consistent and have the same level of detail. This can be a challenge as different models may use different data sources or data formats.

- Model verification: Soft-linking requires that the results from each model be verified and the process may require more time and different procedures.
- Communication: Soft-linking requires effective communication between the modelers to ensure that the models are linked correctly and that the information exchange is properly understood.
- Scalability: Soft-linking multiple energy system models can increase the complexity of the modeling process and make it more difficult to manage and update. This can be a challenge, particularly for large-scale or complex energy system models.

Deliverable D1.3.3 aims at overcoming the majority of the above mentioned issues by formalising methods and formats to share data and link energy models across scales. Developing friction-less protocols might also contribute to:

- model debugging and sanity checks
- model inter comparison experiments
- provide a common ground for inter-operable visualization tools

2 Soft-linking the models and data exchange

In the current version of the document, we illustrate the model interconnections among Euro-Calliope (Pickering et al., 2022), Nexus-e (Gjorgiev et al., 2022a), and SecMOD (Reinert et al., 2022). Figure 2.1 depicts the conceptual interconnections between the three models. As of the development of this report, bilateral connections between Nexus-e and Euro-Calliope and between Nexus-e and SecMOD have been established and tested. The three models have been aligned regarding data and input parameters, ensuring compatibility to model the same flexibility dynamics.

To facilitate these connections, we are constructing a data flow interface capable of cascading Euro-Calliope results, which will then be utilised to supply both SecMOD and Nexus-e.

The remainder of the chapter is structured as follows: in Subsection 2.1.1, a more comprehensive explanation of the data that Euro-Calliope can provide to other models will be provided. Subsection 2.2.2 will detail the connection between Nexus-e and SecMOD.

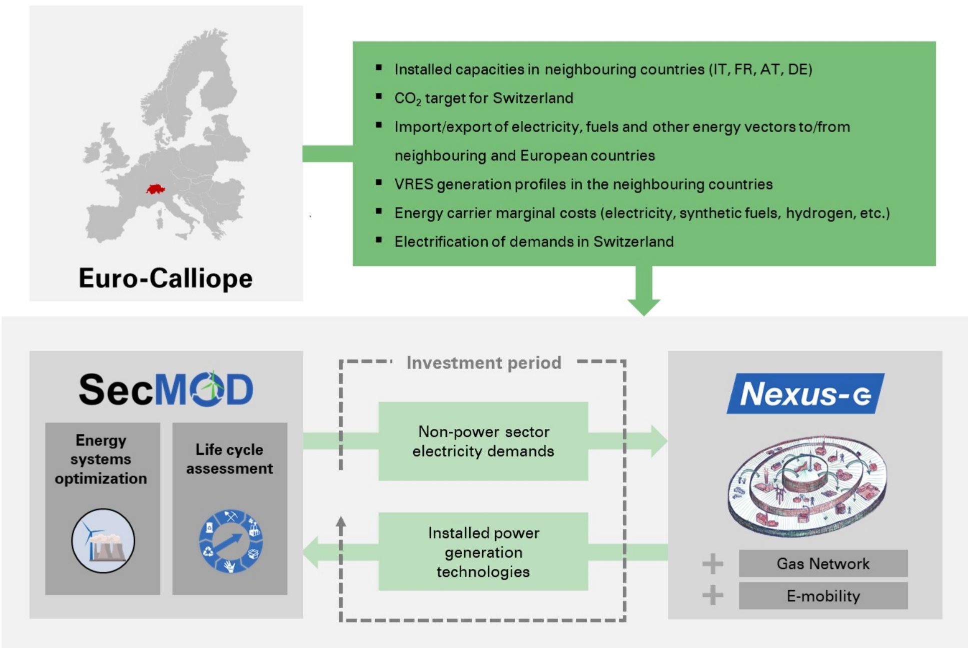

Figure 2.1: Conceptual dataflow between Euro-Calliope, Nexus-e and SecMOD frameworks.

2.1 Model gallery

2.1.1 Euro-Calliope

The energy system model builds upon the sector-coupled Euro-Calliope model (Pickering et al. 2022) based on Calliope. Calliope is a framework to build energy system models designed to analyse systems with arbitrarily high spatial and temporal resolution, with a scale-agnostic mathematical formulation permitting analyses ranging from single urban districts to countries and continents (Pfenninger and Pickering, 2018). Its key features include the ability to handle high spatial and temporal resolution and easily run on high-performance computing systems. Moreover, Calliope presents an inbuilt feature to model the generation of alternatives, which practically contributes to finding near-cost-optimal technology diverse and spatially explicit energy system configurations (Lombardi et al., 2020).

In this study, the sector-coupled Euro-Calliope model is based on version 0.6.8 of the Calliope framework, and it incorporates the electricity, heat, transport and industry sectors. The model encompasses 13 carriers: electricity, hydrogen, CO_2, liquid and gaseous hydrocarbons (kerosene, methanol, diesel, and methane), solids (residual biofuel and municipal waste), low-temperature heat (combined space heat and hot water, and cooking heat), and vehicle distance (heavy- and light-duty road vehicles). These carriers can be consumed, produced, and converted by a variety of technologies to meet demand. In addition, hydrogen, electricity, methane, low-temperature heat and CO_2 can be stored. Since future international energy commodity prices are highly uncertain, energy imports from outside our model region are not allowed. Although the sector-coupled Euro-Calliope model can be represented by 98 sub-national regions in Europe, in this study, the model is characterized by a national spatial scale considering 35 countries. The model is set up at hourly resolution for a full year and deploys technologies overnight to fulfill hourly demand in each modeled region. Carbon management is also implemented, making it possible to define carbon targets for single countries or groups of countries. Carbon dioxide is a tradeable commodity that can be exported or even compensated in other regions when allowed.

2.1.2 Nexus-e

Nexus-e is used to perform a national analysis of the Swiss electricity system at high spatial and temporal resolution. More specifically, it determines the cost-optimal expansion of the Swiss electricity system that complies with climate scenarios and is embedded within the wider European transition. Nexus-e represents the electricity system in great detail by combining bottom-up and top-down modeling approaches, and by accounting for the correlation between energy demand and supply, electricity price and other macroeconomic factors, energy policy drivers, and security of supply. A detailed description of the Nexus-e modeling platform and underlying equations are provided by Gjorgiev et al. (2022b). The main objective of Nexus-e is to provide a holistic assessment of the energy-economic system and thus to identify the cost-optimal investment in and operations of centralized and distributed energy resources, taking into account their socio-economic impact and changes in the security of supply.

2.1.3 SecMOD

SecMOD (Reinert et al., 2022) represents a sophisticated framework tailored for multi-sector energy system optimization, augmented by the integration of life-cycle assessment (LCA). This novel framework enables the simultaneous optimization of diverse sectors, encompassing industrial production and associated energy supply systems, as well as interconnected national energy networks. By incorporating LCA, SecMOD offers a comprehensive approach, systematically considering environmental impacts across the entire life cycle. Notably, it distinguishes itself as the first open-source framework to systematically incorporate LCA into multi-sector optimization, ensuring a holistic assessment. In addition to its sector-coupled functionalities, SecMOD encompasses power generation, heating systems, industrial heating across various temperature levels, and mobility. To address computational complexities, particularly in large-scale spatially resolved models, SecMOD integrates an automated spatial aggregation and disaggregation module. This feature facilitates the optimization of numerous smaller-scale problems, thereby mitigating computational demands while preserving analytical precision and granularity.

2.2 Data exchange protocols

2.2.1 Euro-Calliope and Nexus-e link

Euro-Calliope provides Nexus-e and SecMOD with the following data:

i) Electricity demands, hourly, for all countries (Switzerland, Italy, France, Austria, and Germany). These demands include conventional (base, electric heater, electric hob, DSM), rail, electrolysis (for hydrogen and fuels production), electrified mobility (light transport and heavy transport), electrified heating (heat pumps), and direct air capture (DAC). The DAC demand for Switzerland is not utilized since Nexus-e re-optimizes the investments in DAC to achieve the desired CO2 target. These Euro-Calliope demands are directly assigned to the single neighboring country nodes but must be disaggregated to over 160 transmission nodes within Switzerland defined by Nexus-e.

ii) Electricity imports and exports, hourly, between the Swiss neighbors (Italy, France, Austria, and Germany) and the rest of Europe. Since the Nexus-e modeling boundary does not include more of Europe, these flows are assumed and fixed such that an export to the rest of Europe appears as additional demand and in import from the rest of Europe appears as a negative demand. This properly accounts for the corresponding use of capacities for exports to Europe and the availability of imports from Europe.

iii) Installed electricity generating capacities and associated electricity storage capacities in the neighbouring countries (Italy, France, Austria and Germany). For Switzerland, Nexus-e includes existing infrastructure and re-optimizes additional capacity investment decisions on a nodal resolution.

iv) Cross border net transfer capacities (NTCs) between each modeled country (Switzerland, Italy, France, Austria, and Germany). These eight NTCs represent the maximum power exchange between each country Nexus-e models.

v) Electricity generation, hourly, in the neighbouring countries (Italy, France, Austria and Germany) for all non-dispatchable generators (wind onshore, wind offshore, rooftop PV, open field PV, alpine PV, and hydro RoR). These production profiles are fixed in Nexus-e to match. The corresponding Swiss profiles are not taken and instead Nexus-e utilizes it own nodal resolution data for wind and PV types along with unit specific data for hydro RoR.

vi) CO2 captured and emitted from all electricity sector resources (emitting generators, generators with CCS, and DAC). These data are used to quantify the net CO2 position of the Swiss electricity sector necessary to achieve the overall Swiss CO2 target. Since Nexus-e only models the electricity sector, the net CO2 position of Euro-Calliope's electricity sector is used as the corresponding CO2 target in Nexus-e.

vii) Wholesale prices of energy carriers for all countries (Switzerland, Italy, France, Austria, and Germany) including fossil methane, bio-methane, synthetic methane, hydrogen, coal. The annual average of these prices are used within Nexus-e for all appropriate electricity generators.

viii) Wholesale CO2 price for all countries (Switzerland, Italy, France, Austria, and Germany). The annual average of this price is used within Nexus-e for all CO2 emitting electricity generators.

2.2.2 Nexus-e and SecMOD link

Both Nexus-e and SecMOD are fed with Euro-Calliope results listed in the previous section. SecMOD utilizes the hourly import and export of electricity and fuels from and to other European countries. Moreover, carbon budget values are taken from Euro-Calliope if they are endogenous to the model (refer to the *compensation-abroad* scenarios).
SecMOD will reassess the optimal dispatch and technology deployment of technologies in the heating, transport and industry sectors of Switzerland. To do so, it uses a spatially resolved model with the same grid topology as Nexus-e. Thus, SecMOD offers a higher level of spatial detail for Switzerland compared to Euro-Calliope and the possibility to provide sector-coupled electricity demands from heating, transport, and industry applications to Nexus-e. Nexus-e, in turn, recalculates the optimal investments and dispatch for the electricity sector, incorporating a detailed representation of the power sector based on precise grid topology, power plant specifications, and both a centralized system and distributed consumer perspective. This iterative process occurs for each investment decision round, with Nexus-e feeding back the revised installed capacities to SecMOD. At the current stage of this document, the process remains tentative, requiring additional refinement and testing.

At the time of this publication, the link between Euro-Calliope and SecMOD has yet to be established, while the link between SecMOD and Nexus-e is in the development and testing process. The data interface between SecMOD and the other models will be clarified in the prosecution of the project.

2.2.3 Connection with other Work Packages

The fully integrated modelling framework composed of the three aforementioned models delivers optimal dispatch and capacity planning. Additionally, this framework generates outputs such as marginal cost time series, carbon budgets, and information regarding sectoral electrification, among others. These outputs can be accessed and utilised by other work packages as needed.

3 Visualization tools

The primary aim of this section is to offer overarching guidance on the nature of visual outputs the project aims to deliver. Given the project's emphasis on flexibility and sector-coupling dynamics, the visualization framework must adeptly capture these core elements. Consequently, meticulous attention will be paid to ensuring that the visualizations accurately portray and illuminate the intricate interconnections inherent in the project's scope.
Rather than imposing a standardized format, we prefer to outline the essential criteria for plotting that is necessary to convey the main insights effectively. Therefore, the specifics of the visualization products may evolve throughout the project in tandem with enhancements to the modeling framework. This approach allows flexibility and adaptation to ensure the visualizations remain relevant and informative as the project unfolds.

3.1 PATHFNDR visualization

In this section, we outline the minimal requirements regarding the type of plots, their characteristics, and the purposes that Work Package 1 will promote to enhance the effectiveness and communicability of results.

Yearly energy balance

The yearly energy balance plot should encompass the contributions of supply, demand, and import/export for each technology or group of technologies depicted in the models. Additionally, the plot should be specific to each energy vector represented in the model and correspond to a particular modeled year. The primary objective of this visualization output is to compare the significant differences among various scenarios concerning system production and consumption. This plot is crucial in capturing the primary sector-coupling dynamics and identifying the principal limiting factors characterizing each scenario.
As depicted in Figure 3.1, the results of four distinct scenarios are presented. This visualization allows us to readily identify the electrified loads and discern the primary differences between the scenarios.

Installed capacities

Installed capacities play a pivotal role in pathways as they delineate the pivotal actions and strategies for policymakers. Moreover, unlike production values, they convey the necessary investments and infrastructure, which may need to be more tangible to the broader public. Hence, the visualization of installed capacities becomes crucial, offering insights into the distribution of energy infrastructure across various technologies or technology groups for each scenario. Examining these plots allows us to discern the differences in investment priorities and strategic decisions underlying each scenario's energy system design.

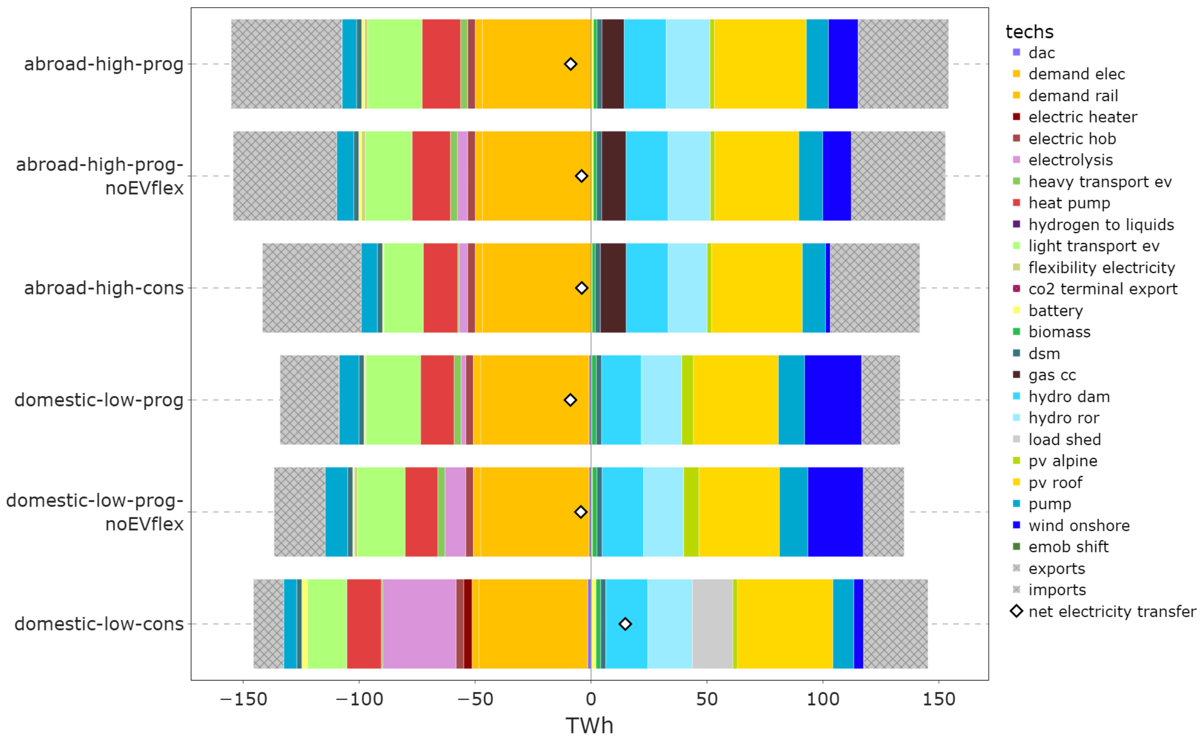

Figure 3.1: Explanatory figure representing the Swiss yearly electricity balance for the modeled scenarios in 2050.

In Figure 3.2, the installed capacities for each scenario are displayed. This visualization enables us to discern the distribution of installed capacities across different technologies or groups of technologies for each scenario. By comparing these plots, we can identify variations in the deployment of energy infrastructure among scenarios, providing insights into the strategic decisions and priorities underlying each scenario's energy system design.

Energy dispatch

Energy vector dispatches at hourly temporal resolution are instrumental in investigating seasonal dynamics, such as the winter problem affecting the electricity supply in Switzerland, and capturing the flexibility aspects of the transition. With an increasing number of sectors being electrified, examining the impacts on hourly dispatches becomes crucial. Moreover, the PATHFNDR project places particular emphasis on flexibility, making it equally important to assess what and when loads are shifted and which technologies can provide flexibility. These visualizations offer insights into the intricate interplay between energy supply and demand, highlighting the temporal variations in energy consumption patterns and the role of different technologies in facilitating flexibility throughout the day.

In Figure 3.3, the optimal electricity dispatch is illustrated for a specific week in summer. This visualization clearly shows that vehicle charging primarily takes place during daylight hours, coinciding with peak PV technology production. It's important to note that this is just one example; hourly dispatch data can effectively reveal and support various insights regarding flexibility across different scenarios.

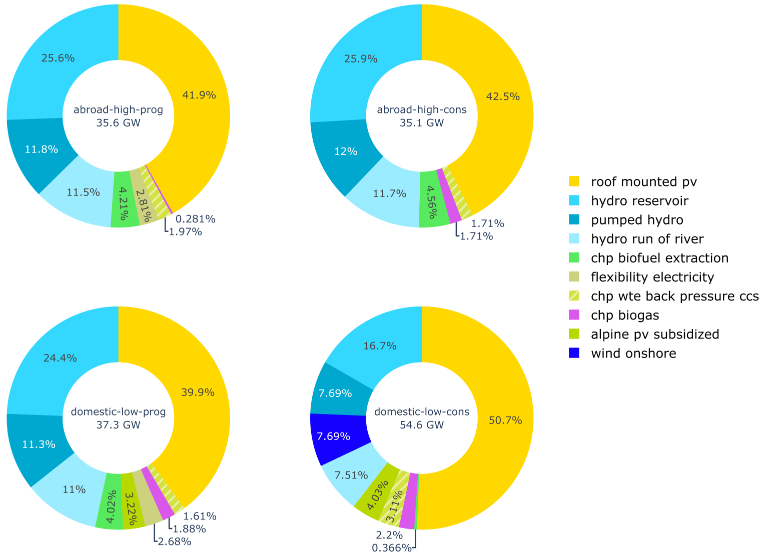

Figure 3.2: Explanatory figure representing the Swiss installed power capacities for the modeled scenarios in 2050.

Marginal cost of the energy carriers

All three considered models operate on optimisation principles, enabling the computation of dual variables for the problem. These dual variables, often termed shadow prices, provide a first-order approximation of wholesale market prices, particularly in the electricity sector. Each carrier within the system corresponds to a dual value, allowing modellers to endogenously determine the costs associated with energy carriers and carbon dioxide. These dual values are time-resolved, providing hourly resolution data. Nexus-e and SecMOD utilize these values to determine the costs of commodities whose supply chains are not explicitly modeled. The relative difference in these values is of particular significance when comparing different scenarios.

Figure 3.4 illustrates the relative disparity in shadow variable values across four scenarios alongside two variants depicting progressive cases where EV flexibility remains disabled.

3.2 SWEET model inter-comparison visualization standards

Given the critical need for ongoing exchange of insights and feedback among SWEET projects, we've implemented a standardized format for result comparison. This format utilizes a set of plots to visually depict outcomes consistently, fostering a comprehensive understanding across projects within the consortium. Adherence to these standards enables effective communication of findings, identification of trends, and meaningful comparisons, enhancing overall coherence and synergy within the SWEET initiative.

The model intercomparison results are accessible at sweet-cross.ch, serving as a centralized repository for stakeholders and researchers to explore and analyze comparative outcomes across various models involved in the SWEET initiative.

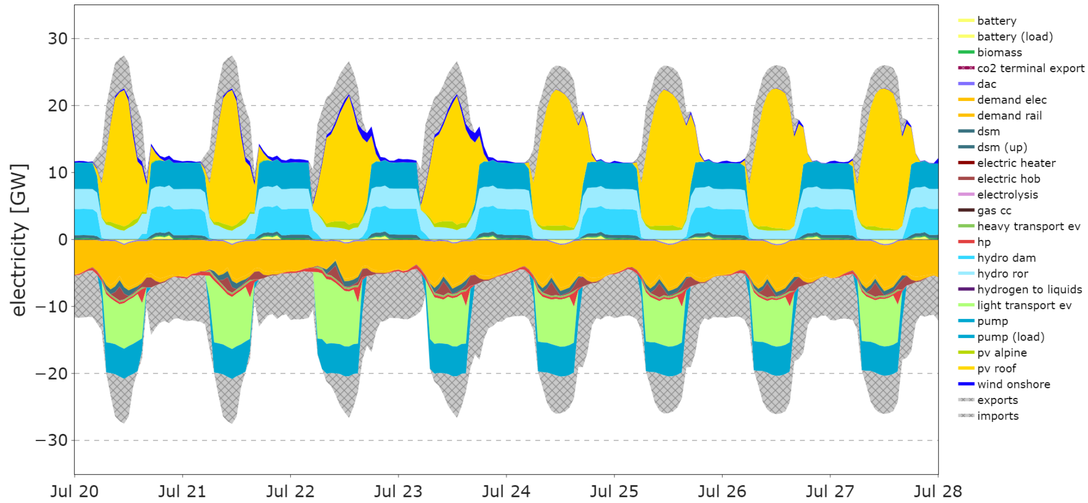

Figure 3.3: Explanatory figure representing the Swiss hourly electricity dispatch for a subset period of modeled time horizon. The results refer to the *abroad-together-conservative* scenario in 2050.

We underscore the importance of visualization outputs in capturing the intricacies of diverse model results. Central to this is the harmonization protocol, forming the foundation of our methodology. Shared standards are crucial for aligning technologies across different frameworks, defining meaningful technology groups, and facilitating a deeper understanding of primary dynamics observed in the outputs. These data standards, meticulously developed within the CROSS project, have enabled multiple rounds of model intercomparison. The efforts in PATHFNDR aim to build upon CROSS's foundation, ensuring continuity between projects and transparent evolution of the modeling process over time.
Figure 3.5 depicts scenario comparisons across distinct frameworks. It's essential to explore reasons for disparities in model outputs, highlighting the role of assumptions, modeling objectives, and specificities inherent to each framework. These features, including spatial, temporal, technological, and sectoral specifications, significantly influence outcomes and require meticulous analysis.

3.3 European energy system visualization standards

The visualization tool for Europe-level results was developed to show the diversity of European scenarios that can be generated through the SPORES algorithm coupled with the Euro-Calliope energy system model. The tool takes data, which is processed and summarised from the standard data package output from Euro-Calliope.
It is written in Python, using Plotly and the Plotly Dash framework to build interactive visualizations. The entire code is open-source on GitHub.

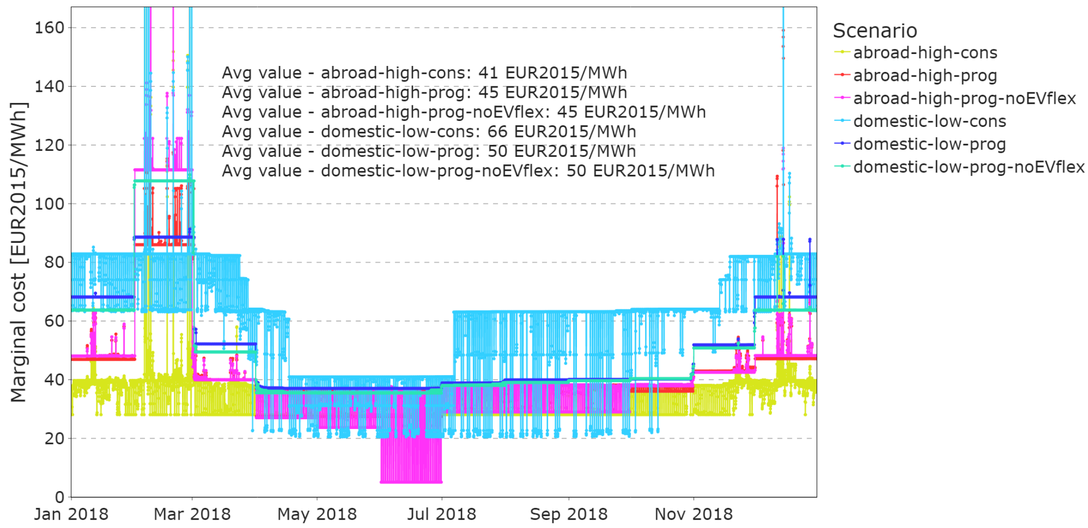

Figure 3.4: Explanatory figure showing the Swiss hourly electricity dual values in 2050 for different scenarios.

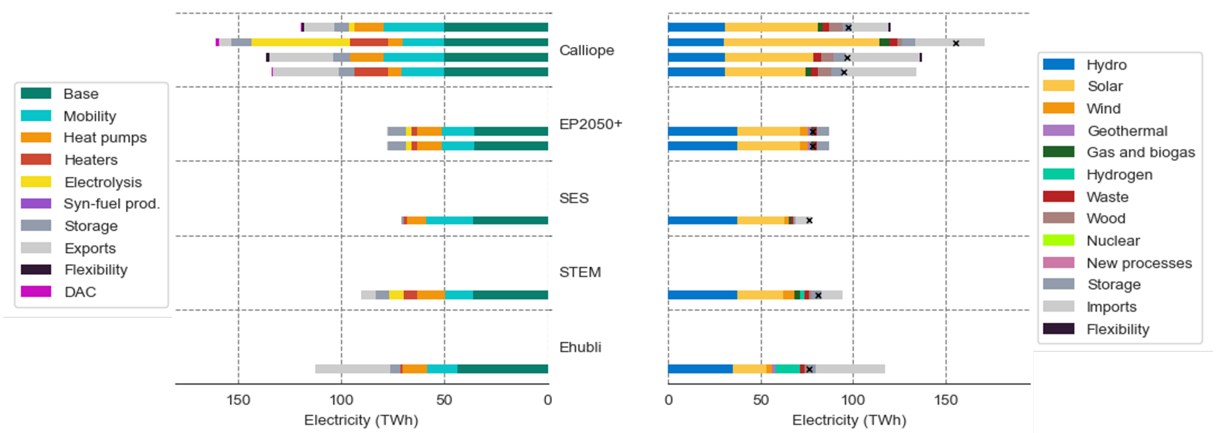

Figure 3.5: Visualization of the total electricity supply and demand in 2050 among different models and scenarios.

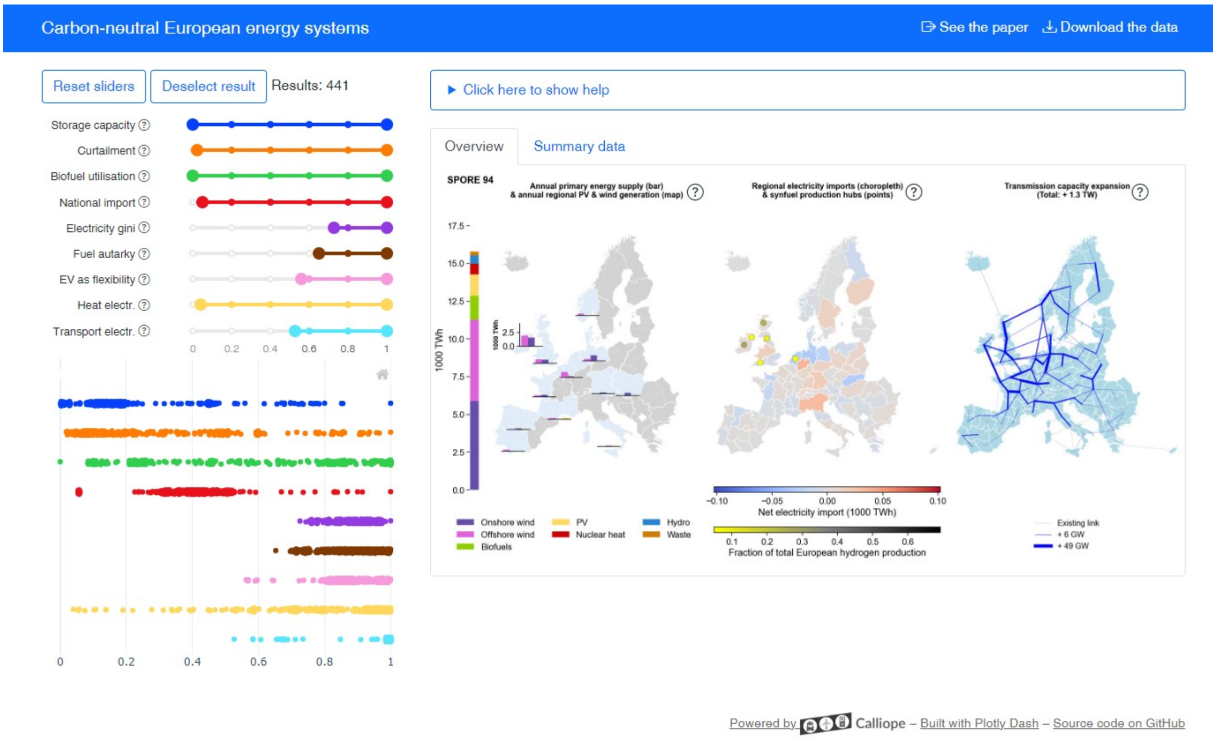

Figure 3.6: Euro-Calliope web-based result explorer. The tool allows the visualization of a number of equally feasible near-optimal solutions. The tool might be extended to host the automated generated storylines.

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