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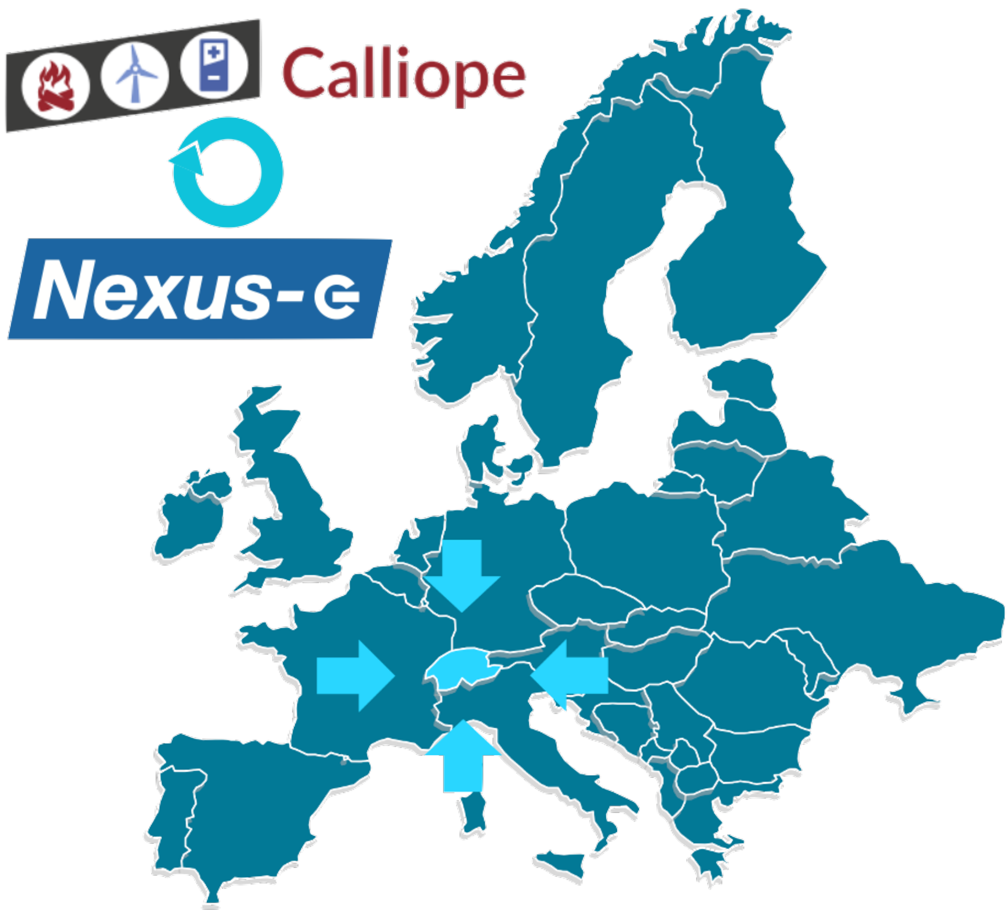
Final report

Nexus-e: Interconnected Energy Systems Modeling Platform

CH2040 Project Technical Report



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Summary

Driven by climate and environmental targets, energy systems are transitioning toward renewable and sustainable energy technologies. The scale of these transitions is not only significant to the energy systems themselves but also to the wider economies. To help address the energy transition, the research community has made strides to model and assess the impacts of energy transitions and to provide guidance for policy makers. Typically, these models either provide regionally detailed analysis by focusing on a limited subset of the different components of the energy system or provide broad characterizations by focusing on a wider scope with aggregated representations of the energy system. Since many research questions require broad regional scopes but also detailed representations of technologies and networks, the research community has emphasized the need to connect models across domains to leverage their unique capabilities and enhance the robustness of their results. The Nexus-e: interconnected energy systems modeling platform aims to address this challenge by providing an interdisciplinary set of models that are integrated in a model framework and linked through structured interfaces. This platform combines multiple bottom-up models that capture different aspects of the electricity system in detail and one top-down macro-economic model that represents a much broader scope of the energy-economic system as compared to traditional stand-alone modeling approaches. And while Nexus-e itself is a powerful combination of models across domains, it still lacks a wide geographical scope and a representation of the energy system beyond electricity. For this reason, the Nexus-e platform was created with the goal of partnering with and connecting to other energy system models with broad but aggregated scopes of study.

This project is one example of how the detailed electricity system representation of Nexus-e can be combined with a continent-scale aggregated energy system model, in this case Euro-Calliope. In this work, the Euro-Calliope model provides insights about the overall transition of the European energy system to achieve the desired climate and environmental targets under a range of scenario assumptions. This overall assessment is followed up by a more detailed investigation, performed by Nexus-e, of how such a European transition would impact the development and operation of the electricity system in Switzerland. The combination of these two models serves as a comprehensive, transparent, and credible analysis of the affordability and feasibility of Switzerland becoming decarbonized by 2040 while also considering other important policy concerns such as maintaining Swiss energy security and the impact of a lack of an agreement with the European Union on the operation of the Swiss electricity market.

The overall transition from 2020 to the Baseline 2040 scenario is characterized by a phase out of Swiss nuclear power and a high level of electrified mobility which therefore increases the total electricity demands by around 26%. These changes are met through consumer investments in rooftop PV and increased imports. Is it evident that, given the ability to import and export up to today's trade limits, the most economically efficient solution for Switzerland is to import more electricity, especially when the neighboring countries' electricity prices have been driven down by expansion of wind and solar. However, if Switzerland were to be faced with a restricted ability to trade power, a significant reduction in electricity imports and exports will be accompanied by a focus on expansion of domestic capacities, namely PV and gas-fired generators. The impacts of such a case would be felt beyond Switzerland since the ability to transit power through Switzerland would also be much more limited. Alternatively, increasing the ability to trade electricity beyond today's limits does enable increases to both Swiss imports and exports but leads to only minor changes to the investments and operations of Swiss generators. In contrast, a less strict requirement for balancing the annual electricity trade would yield similar trends but with less severe magnitudes. The decreased imports still yield increased domestic capacities, this time in the form of PV and wind; and the impacts on the neighboring countries would be more mildly felt. In the face of restricted trade limits, the decision to completely restrict gas-fired generators in Switzerland drives the need for other domestic production capacities, such as wind and batteries, along with even more seasonally concentrated imports and exports as well as a significant need to shed load in Winter. Finally, requiring fuel autarky for the Swiss energy system is clearly the most extreme scenario considered and leads to

a doubling of the electricity demand, an increase in all invested generating capacities, a substantial shift to import electricity, and still a major need to shed electricity load in all months.

The combination of Euro-Calliope and Nexus-e provides a unique and powerful set of tools to investigate a wide range of impacts for possible future paths of the European and Swiss energy system. Within this work, Nexus-e provides a detailed assessment of the developments necessary for the existing Swiss electricity system when confronted by a specific European context. The combination of bottom-up models in Nexus-e accounts for the complexity and interplay of energy demand-supply and energy policy drivers with granular time and geospatial resolutions. In terms of the modeled electricity network levels, Nexus-e represents both the centralized and distributed levels of the energy system, which enables a holistic assessment of the system development and operation to supply electricity as well as the need for and supply of flexibility across Switzerland at both regional and national scales. Also, the capability of modeling hourly dynamics allows Nexus-e to capture important short-term behaviors, such as how hydro pumps, batteries, and demand shifting could be critical for short-term flexibility to ensure a balance between supply and demand of electricity.

Contents

Abbreviations

BESS	battery energy storage system
BFE	Bundesamt für Energie
Cascades	Network Security and Expansion Module
CC	combined cycle
CCS	carbon capture and storage
CentIv	Centralized Investments Module
CHP	combined heat and power
CO_2	carbon dioxide
DER	distributed energy resources
DistIv	Distributed Investments Module
DSM	demand-side management
DSO	distribution system operator
ElCom	Swiss Federal Electricity Commission
eMark	Electricity Market Module
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
GemEl	General Equilibrium Module for Electricity
GEP	generation expansion planning
MILP	mixed-integer linear programming
MW	megawatt
MWh	megawatt hour
NTC	net transfer capacity
PV	photovoltaic
PVB	photovoltaic battery
RES	renewable energy source
RoR	run of river
TSO	transmission system operator
VOM	variable operation and maintenance

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1 Introduction

This section provides a brief overview of the entire Nexus-e energy systems modeling platform (Section 1.1) and the Euro-Calliope modeling tool (Section 1.2) along with a description of the modules utilized with the CH2040 project (Section 1.1.1). Additionally, a description is provided of the relevant differences between the Euro-Calliope and Nexus-e models that compel the collaboration between the two modeling groups for this analysis (Section 1.3).

1.1 Nexus-e overview

Nexus-e combines bottom-up and top-down energy modelling approaches. The platform accounts for energy demand and supply, macro energy-economic factors, and energy policy drivers across multiple time-scales and levels of aggregation. It assesses the mutual influences of large-scale, centralized and small-scale, decentralized generation as well as the security of supply in light of a transition of the electricity sector. Nexus-e is based on modularity such that it can integrate cross-disciplinary, new and existing modules through a flexible structure to capture and develop know-how [1]. Overall, Nexus-e (i) soft-links one economic module and four high-resolution electricity system modules, (ii) extensively calibrates and validates the modules, (iii) represents the electricity system in high detail, and (iv) provides a more granular geospatial resolution than typical energy transition analysis tools.

Figure 1 provides an overview of the Nexus-e platform and the five modules that are part of the platform: General Equilibrium Module for Electricity (GemEl), Centralized Investments Module (CentIv), Distributed Investments Module (DistIv), Electricity Market Module (eMark), Network Security and Expansion Module (Cascades). The modules can communicate with each other through well-defined and automated interfaces within three loops (e.g., Investments, Energy-Economic, Security loops).

1.1.1 Nexus-e application for CH2040

Within the CH2040 project, we apply the two modules within the Investments loop of Nexus-e (i.e., CentIv and DistIv). Together, these two modules represent the centralized and distributed levels of the electricity system and optimize the investments and operation of the new and existing generation capacities. Based on the scope of the CH2040 project, the eMark, Cascades, and GemEl modules are not utilized. The Investments loop is implemented as a bi-directional soft-link between CentIv and DistIv. In this loop, CentIv and DistIv exchange data to enable a coordinated generation expansion planning process at the transmission and distribution system levels.

After its first iteration, CentIv provides information on the investments in and operation of centralized technologies and electricity market prices. DistIv uses this information to assess whether it is more economically viable to invest in new capacities at the distribution level (considering policies such as subsidies, injection tariffs, tax rebates, etc.) than purchasing the available electricity from the transmission system. To capture the investment decisions for rooftop photovoltaic (PV) from the consumer's perspective, DistIv calculates a retail price as a combination of (i) the wholesale electricity price, (ii) the total network fee including both the grid charge and additional fees, and (iii) an additional markup charge [2].

After the DistIv simulation is complete, DistIv provides information on the operation and investments at the distribution level back to CentIv. This set-up, while not resulting in an optimal mix of investments, aims to emulate coordination between the transmission system operator (TSO) and distribution system operators (DSOs), whereby investments are made at TSO and DSO levels based on the information exchange. The residual hourly demand, provided as an input from DistIv to CentIv, represents the re-

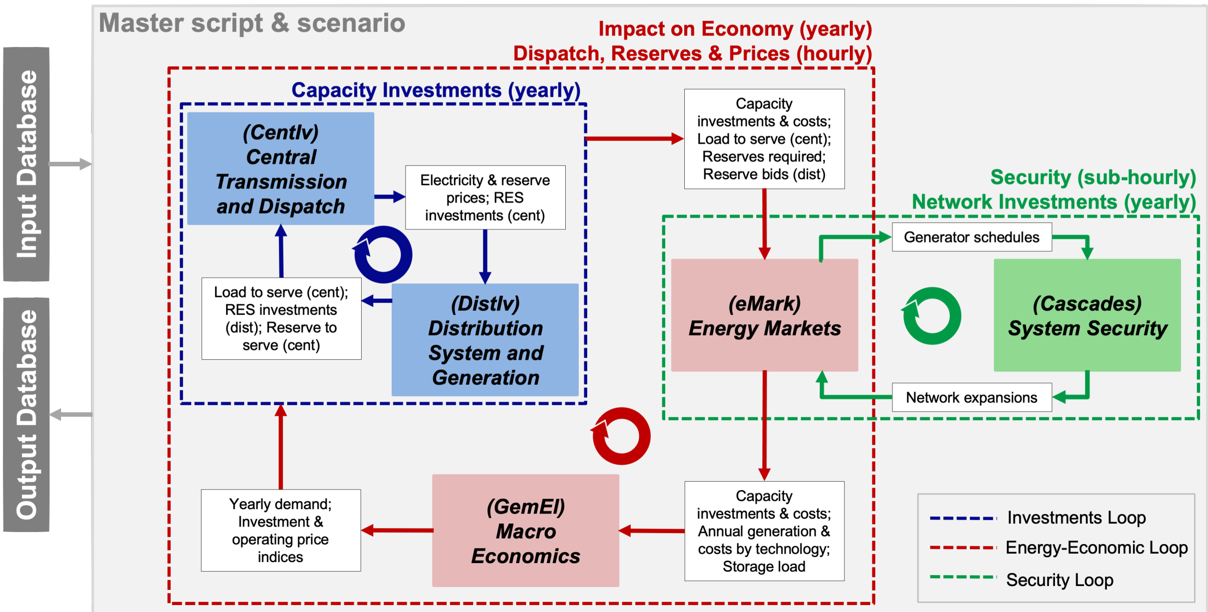


Figure 1: Overview of the Nexus-e platform including the five modules (colored boxes), the three 'loops' (colored arrows), and the interfaces (white boxes). For visualization purposes some of the interfaces are aggregated in the figure.

maining load that must be supplied by CentIv, considering all distributed generation as well as demand-side management (DSM)/battery energy storage system (BESS) load shifting performed in DistIv. As a last step, CentIv re-evaluates its optimal investments and operations, resulting in an updated centralized capacity expansion plan. More details of the data exchange between the CentIv and DistIv modules can be found in [1, 3].

1.2 Euro-Calliope overview

Calliope is a framework to develop energy system models, with a focus on flexibility, high spatial and temporal resolution, the ability to execute many runs based on the same base model, and a clear separation of framework (code) and model (data). Its primary focus is on planning energy systems at scales ranging from urban districts to entire continents.

A model based on Calliope consists of a collection of text files (in YAML and CSV formats) that define the technologies, locations and resource potentials. Calliope takes these files, constructs an optimisation problem, solves it, and reports results in the form of xarray Datasets which in turn can easily be converted into Pandas data structures, for easy analysis with Calliope's built-in tools or the standard Python data analysis stack. Calliope is developed in the open on GitHub and contributions are very welcome (see the Development guide).

Key features of Calliope include:

- Model specification in an easy-to-read and machine-processable YAML format
- Generic technology definition allows modelling any mix of production, storage and consumption
- Resolved in space: define locations with individual resource potentials

- Resolved in time: read time series with arbitrary resolution
- Able to run on high-performance computing (HPC) clusters
- Uses a state-of-the-art Python toolchain based on Pyomo, xarray, and Pandas

Calliope has been used to model several energy systems across scales worldwide. Some of those are available as “pre-built” models that can be simply run and customised in terms of assumptions, parameters and scenarios. One of these pre-built models is the Europe-scale energy system model Sector-Coupled Euro-Calliope, which is one of the leading high-resolution sector-coupled European energy system models. The model covers 13 energy carriers and service demands: electricity, hydrogen, carbon dioxide, 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 travelled (heavy- and light-duty road vehicles). These carriers can be consumed, produced, and converted by a variety of technologies to meet demand. In addition, low temperature heat, hydrogen, electricity, and methane can be stored. The current model depicts Europe as 98 zones (breaking larger countries into sub-regions) and can run at resolutions of 1-hour to accurately depict the challenges and opportunities of transitioning towards 100% renewable energy. The model has been recently published in the high-impact journal Joule [4] and the results have been made available via an interactive interface at (explore.callio.pe).

1.3 Comparing Nexus-e and Euro-Calliope

Nexus-e and Euro-Calliope, while both representing aspects of the Swiss and European energy system have notably different scopes and levels of detail. Below is a brief description of these two important differences followed by a listing of the aspects relevant to the CH2040 project that set Nexus-e apart from Euro-Calliope.

Scope: While the scope of Nexus-e encompasses the electricity sector of Switzerland (in detail) and its neighboring countries (aggregated), the scope of Euro-Calliope extends to other energy sectors (heat, transport, etc) and to all European countries.

Level of detail: Naturally, the wide scope of coverage achievable from the Euro-Calliope model necessitates a reduction in certain levels of detail to maintain computational tractability. Generally, in Euro-Calliope, the geospatial resolution of all energy supplies and demands is reduced to one node per country with an increased resolution only in Switzerland of 20 nodes. Technologies are represented in aggregate at each node by technology type. Similarly, the time resolution utilized within Euro-Calliope is slightly reduced to half the hours of the year (i.e., every other hour). In contrast, the geospatial resolution used in Nexus-e is more granular in terms of the electricity network (nodal in Switzerland), the electricity generators (by unit in Switzerland), and the rooftop photovoltaic potentials (individual rooftops clustered into 12,480 customer groups). The time resolution in Nexus-e is similar (i.e., half the hours of the year) but structured differently by utilizing continuous days (i.e., every second day is simulated).

In addition to these differences in scope and level of detail, some other important aspects are unique between the two modeling frameworks that are relevant to the Ch2040 project:

- Euro-Calliope takes a green-field approach to optimize the future production capacities that compose the energy system (i.e., existing infrastructure is ignored), while Nexus-e utilizes the green-field results for the Swiss neighbours, the existing electricity generating capacities in Switzerland are included along with planned new hydro plants. The presence of the existing infrastructure influences the investment decisions for additional generating capacities in Switzerland.

- Euro-Calliope applies NTC-type limits on trade flows between neighboring countries for electricity and other energy carriers. While such limits are accurate for some energy carriers, when used for electricity trading, these NTC limits do not account for the physical flow of electricity according to Kirchhoff's laws and therefore do not quantify the actual import/export flows of electricity for a given set of nodal power injections and demands. The NTC limits also do not ensure that intra-country transmission line limits are not violated which could in reality require redispatch to allieviate. In Nexus-e, the full Swiss high-voltage transmission network is represented using data provided by the Swiss TSO Swissgrid and a sophisticated network reduction process is utilized to create an aggregated representation of the neighboring country networks that maintains the physical flow characteristics. In this way, Nexus-e includes the impact of the transmission network while Euro-Calliope is allowed to reach optimal solutions that transmit power in ways that omit the physical network.

- In Euro-Calliope, the investments in new PV capacities is based on the maximum potentials across the 20 Swiss regions, an assumed aggregated production profile for each region, and an assumed investment cost per kW of installed capacity that is constant across all PV units of a given type in Switzerland (rooftop PV and open-field PV are two types). In Nexus-e, the rooftop PV potentials are clustered groupings of similar individual rooftops based on the Sonnendach dataset for Switzerland [5]. The production profiles are based on solar irradiation profiles from nearly 200 measuring stations spread across Switzerland. Lastly, the investment cost per kW are separated in to 5 options based on the size of the PV built.

- Euro-Calliope uses a system perspective to optimize the technologies selected to be utilized in the target year that minimize the costs of supplying the various energy sector demands, including whether to build rooftop PV or open-field PV. In Nexus-e, the investments decisions at the distribution level are made based on the perspective of the actors who would actually be making the investment decisions. For rooftop PV, a retail customer's perspective is used, as described in Section 2.1.2, to evaluate the real economic trade-offs faced by homeowners or building owners who would be considering investing in a new rooftop PV unit. Similarly unique perspectives are taken for distributed-level investments by large consumers and by DSOs. Additionally, as part of this perspective-specific investment decision, Nexus-e accounts for regional differences in the economic trade-off calculation (i.e., different locations across Switzerland have different available subsidies, retail electricity prices, and injection tariffs) to increase the geospatial accuracy of capacity investments such as the consumer-driven rooftop PV development.

- In Nexus-e, the distributed level investments and operation are impacted by the power flow limit of the transformer that links each represented distribution region and the transmission network. The inclusion of this limit also enables Nexus-e to evaluate the possible expansion of this transformer that would enable higher injections from the DSO to the TSO. No such physical transformer limit nor the possibility to expand it is represented in Euro-Calliope.

- Euro-Calliope is a multi-sector energy system model and as such, includes that possibility for sector-coupling that can enable the shared use of resources for improving operations (i.e., flexibility use across sectors) and for reducing system costs. While Nexus-e does not account for other energy sectors, it does utilize the results of Euro-Calliope that would have been impacted by the improvements achieved from sector coupling, such as the shifting of shifting of e-mobility charging demand to better align with the flexibility needs of the electricity sector.

- Some potential electricity system capacities that are allowed within Euro-Calliope are not allowed within Nexus-e (i.e., open-field PV in Switzerland) and other potentials are represented by Nexus-e but with much lower allowed potentials (wind turbines in Switzerland). The potential capacities that are included as options to build in Nexus-e are based on a commonly assumed limits that are impacted by social acceptance and thought to be realistically achievable.

2 Method

This section provides a brief description of the CentIv and DistIv methodologies (Section 2.1) along with details of the modifications implemented as part of the CH2040 project (Sections 2.2 and 2.3). Additionally, the details of the data exchange from the Euro-Calliope model to the Nexus-e platform are covered (Section 2.4).

2.1 Methodologies of CentIv and DistIv

In this section we provide a brief overview of the purpose and methodology of both the CentIv and DistIv modules. More detailed descriptions of these modules can be found in several of the Nexus-e publications [1, 6, 7, 8, 9, 10, 11].

2.1.1 CentIv purpose and methods

The goal of CentIv, which is based on previous work [6, 10], is to co-optimize the capacity investment and operational decisions of units at the transmission system level. This includes large-scale thermal generators (nuclear, gas, biomass, etc.), hydro power plants (run-of-river, dam and pump storages), large-scale renewable energy sources (RESs) (wind, PV) and utility-scale batteries. Mathematically, CentIv minimizes the sum of the annualized investment costs and the operating costs of all existing and candidate generation and storage technologies over the planning horizon T (typically one year):

$$\min \underbrace{\sum_{d\in D}\alpha_d^{\text{inv}}C_d^{\text{inv}}u_d^{\text{inv}}}_{\text{(i)}} + \underbrace{\gamma\sum_{j\in J}\sum_{t\in T}(C_j^{\text{voc}}+C_j^{\text{fuel}}+C_j^{\text{emi}})p_{j,t}}_{\text{(ii)}} + \underbrace{\gamma\sum_{k\in K}\sum_{t\in T}C_k^{\text{voc}}p_{k,t}^{\text{dis}}}_{\text{(iii)}} + \underbrace{\gamma\sum_{r\in R}\sum_{t\in T}C_r^{\text{voc}}p_{r,t}}_{\text{(iv)}} + \underbrace{\gamma\sum_{n\in N}\sum_{t\in T}C^{\text{ls}}ls_{n,t}}_{\text{(v)}} \quad (1)$$

where (i) is the investment cost of building a candidate generator or storage d, (ii-iv) are the total operating costs of each thermal unit j, energy storage unit k, and renewable generator r for each time step t and (v) indicates the load shedding cost at transmission node n. The factor γ is used to account for modeling every second day of the year and is therefore applied to all hourly quantities. Also, to account for not simulating every day, the operation of hydro storages is adjusted accordingly using the heuristic outlined in Section 3.1 of [6]. To derive the operational costs, we multiply a constant generation cost, C^{voc}, by the power produced by each thermal unit $p_{j,t}$, each hydro or battery storage device $p_{k,t}^{\text{dis}}$, and each renewable generator $p_{r,t}$. For thermal generators, the fuel cost C_j^{fuel} and CO_2 emissions cost C_j^{emi} are also accounted for. The load shedding cost, C^{ls}, is fixed at 10,000 €/megawatt hour (MWh). The investment cost (including fixed O&M cost) for unit d among all candidate units D is C_d^{inv}. The investment decision variable is u_d^{inv} and the annuity factor is denoted by α_d^{inv}.

Objective (1) is subject to four sets of constraints related to: a) investments, b) operation, c) reserve provision, and d) the transmission system (i.e. DC power flow). Section 2.2 details the changes in the formulation relevant to this work as compared to that in [6].

2.1.2 DistIv purpose and methods

The goal of DistIv, which is based on previous works [7, 9, 11], is to co-optimize the capacity investment and operational decisions of units at the distribution system level (i.e., distributed energy resourcess (DERs) including DSM) with an hourly resolution. To represent the economic trade-offs faced by different investment groups, the DistIv module is divided into three submodules. As shown in Fig. 2, the three submodules correspond to three investment models built for households (HH), large consumers (LC) and DSOs, respectively. For each considered region, the HH submodule and the LC submodule run in parallel to optimize their investments considering the individual demand profiles and electricity tariffs, but the DSO submodule executes subsequently to optimize investments in grid-batteries and transformer expansions, taking the injections from the HH and LC submodules into account.

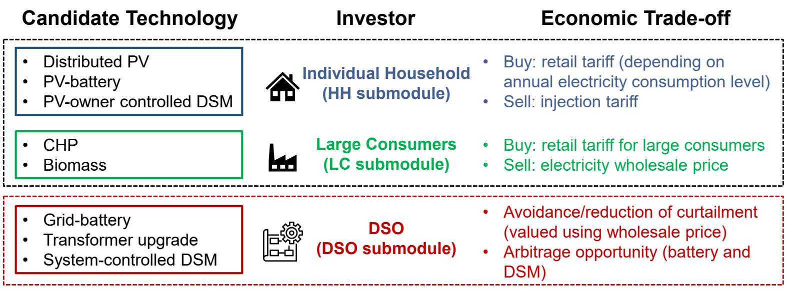


Figure 2: Overview of the DistIv submodules that represent three different investment groups at the distribution level: households (HH), large consumers (LC) and DSOs.

In each submodule, Switzerland is divided into regions $k \in K$ (e.g., municipalities or cantons), and each region is represented as a separated single-node distribution system (i.e., the distribution network is not modeled). Investment decisions for each region are made independently, using the perspective of the households, the large consumers or the DSOs. Note that while large consumers and DSOs are aggregated as one per each municipality (i.e., the regions are defined as the more than 2000 municipality), the HH submodule optimizations are carried out for multiple household groups within each Canton (i.e., the regions are defined as the 26 Cantons). These household groups are formed using a clustering method based on the geographical region (26 Cantons) as well as the annual irradiation (4 categories), roof size (20 categories) and annual electricity consumption (6 categories). For each one of the 26*4*20*6 = 12'480 household groups, an optimization problem considering individual input data (e.g., electricity tariff, solar irradiation) is solved. In this way, the economic trade-offs for a wide range of residential customers across Switzerland are captured in the HH submodule.For simplification purposes, the index to indicate the regions is omitted in the following formulations.

HH submodule: The HH submodule aims to optimize the trade-off between making local investments and purchasing electricity at the retail electricity price so as to minimize the cost for residential consumers. It is assumed that the households can invest in rooftop solar and PVB units. Four types of PV units corresponding to four size categories (i.e. 0-10 kW, 10-30 kW, 30-100 kW and $>$ 100 kW) are considered. Mathematically, for each one of the household groups, an optimization model is constructed with the objective to minimize the total costs to cover the electricity demand considering possible investments in rooftop solar and PVB units over the lifetime of the PV unit (typically 30 years):

$$\min \underbrace{\sum_{pv \in PV} C^{inv}_{pv} u^{inv}_{pv} + \sum_{b \in B} (C^{inv}_{b,e} u^{inv}_{b,e} + C^{inv}_{b,p} u^{inv}_{b,p})}_{\text{(i)}} + \underbrace{\sum_{y=y0}^{L^{sys}} \frac{C^{out}_y - R^{in}_y}{(1+wacc)^y}}_{\text{(ii)}} + \underbrace{\sum_{n'=1}^{\lfloor (L^{sys}-1)/L^{bat} \rfloor} C^{rpl}_{y'=L^{bat} n'+1, b} - R^{res}_b}_{\text{(iii)}} \tag{2}$$

where (i) is net the investment cost for the PV unit $pv \in PV$ and the PVB unit $b \in B$ (accounting for available subsidies) using unit capacity cost C^{inv} and investment capacity u^{inv} (note that the PVB investment cost is split into an energy $C_{b,e}$ and a power $C_{b,p}$ component); (ii) represents the total discounted net cash flows over the considered simulation horizon L^{sys} starting from the examined year y_0, calculated using yearly cash outflows C^{out} and inflows R^{in} (outflows include the variable operating costs while the inflows include incomes from injecting power to the grid and savings from self-consumption); and (iii) includes the potential replacement cost C^{rpl} of the PVB unit as a result of its shorter lifetime L^{bat} than the PV unit, along with its residual value R^{res} by the end of the simulation horizon. Objective (2) is subject to three sets of constraints related to: a) investments, b) operation of the PVB system, and c) the power balance. Details of the HH submodule can be found in [7].

LC submodule: Similarly, the LC submodule aims to optimize the trade-offs between making local investments and purchasing electricity at the large consumer's retail electricity price. Unit types considered for the large consumers include combined heat and power (CHP) and biomass units. The objective is to minimize the annualized total cost while satisfying the demand for all large consumers within the region over the planning horizon T (typically one year):

$$\begin{aligned}\min \underbrace{\sum_{g\in G}\alpha_g^{\mathrm{inv}}C_g^{\mathrm{inv}}u_g^{\mathrm{inv}}}_{\text{(i)}}+\underbrace{\sum_{g\in G}\sum_{t\in T}[C_g^{\mathrm{foc}}u_g^{\mathrm{tot}}+\gamma\frac{(C_g^{\mathrm{voc}}+C_g^{\mathrm{fuel}}+C_g^{\mathrm{em}})p_{g,t}}{(1-\beta_g^{\mathrm{oc}})}]}_{\text{(ii)}}+\underbrace{\gamma\sum_{t\in T}PR_t^{\mathrm{el,lc}}p_t^{\mathrm{buy,lc}}}_{\text{(iii)}}\\ \underbrace{-\gamma\sum_{g\in G}\sum_{t\in T}(PR_t^{\mathrm{inj,lc}}p_t^{\mathrm{inj,lc}}+R_g^{\mathrm{heat}}p_{g,t})}_{\text{(iv)}}\end{aligned} \tag{3}$$

where (i) is the annualized investment cost for unit type $g\in G$ calculated using annuity factor α^{inv}, unit capacity cost C^{inv} and investment capacity u^{inv}; (ii) is the combination of fixed operating costs C^{foc} considering the total capacity u^{tot} for all newly built and previously built units along with the variable costs, including variable operating costs C^{voc}, fuel costs C^{fuel} and emission costs C^{em} for the total generation output $p_{g,t}$ of each unit type at time t considering the electricity used to operate the power plant using the electricity own-consumption rate β^{oc}; (iii) represents costs of purchasing electricity $p^{\mathrm{buy,lc}}$ at the large consumer retail electricity tariff $PR^{\mathrm{el,lc}}$ (note that savings from any self-consumption are therefore implicitly incorporated); (iv) includes the revenues earned by injecting excess electricity $p^{\mathrm{inj,lc}}$ back to the grid at the injection tariff $PR^{\mathrm{inj,lc}}$ and revenues from heat production with a heat credit indicated by R^{heat}. Similar to CentIv, the factor γ is used to model every second day of the year and is therefore applied to all hourly quantities. Objective (3) is subject to three sets of constraints related to: a) investments, b) operation of the considered LC units, and c) the power balance.

DSO submodule: Given investment capacities and power injections from the HH and LC submodules, the DSO submodule aims to minimize the costs incurred by the DSO to supply their customer's demands that were not self-supplied, which must be purchased from the centralized system at the wholesale price. These costs could be reduced by either expanding the transformer capacities to reduce any unnecessary curtailments of excess injections going from the DSO to the TSO or to shift the timing of DSO's electricity purchases by investing in grid-battery units or dispatching DSM. The objective is to minimize the annualized total costs of the DSO over the planning horizon T (typically one year):

$$\min \underbrace{\sum_{s\in S}\alpha_s^{\mathrm{inv}}C_s^{\mathrm{inv}}u_s^{\mathrm{inv}}+\sum_{tr\in TR}\alpha_{tr}^{\mathrm{inv}}C_{tr}^{\mathrm{inv}}u_{tr}^{\mathrm{inv}}}_{\text{(i)}}+\underbrace{\sum_{s\in S}\sum_{t\in T}C_s^{\mathrm{foc}}u_s^{\mathrm{tot}}}_{\text{(ii)}}+\underbrace{\gamma\sum_{t\in T}C^{\mathrm{dr}}ls_t^{+}}_{\text{(iii)}}\underbrace{-\gamma\sum_{t\in T}PR_t^{\mathrm{DA}}p_t^{\mathrm{DA}}}_{\text{(iv)}} \tag{4}$$

where (i) is the annualized investment costs for investment capacities u_s^{inv} and u_{tr}^{inv} of grid-battery unit $s\in S$ and upgrading transformer $tr\in TR$, calculated using unit capacity costs C^{inv} along with the annuity factors α^{inv}; (ii) is the fixed operating cost of the grid-battery units (variable operating cost is assumed to be zero); (iii) represents the payments for discomfort costs of DSM, calculated based on the unit cost C^{dr} and hourly upward load shifting ls^{+} (note that the total upward and downward load shifting are required to be equal); (iv) includes the revenues from selling and costs of purchasing electricity p^{DA} at the wholesale electricity price PR^{DA} to and from the transmission grid ($p^{\mathrm{DA}}>0$ if selling and $p^{\mathrm{DA}}<0$ if purchasing). Objective (4) is subject to four sets of constraints related to: a) investments, b) operation of the grid-battery, c) operation of DSM, and d) the power balance. Details of the DSO submodule can be found in [].

While more details of the DistIv module and submodules can be found in the referenced works, below Section 2.3 details the changes in the formulation relevant to this work as compared to that in [7, 9].

2.2 CentIv extensions

To facilitate the investigation desired for the CH2040 project, some model extensions were needed within CentIv compared to [6]. Most importantly were the modifications to make the whole optimization problem linear, to interface with and utilize results of DistIv, to split the demand into some separate categories, and to enable shifting of some demands within defined limits.

2.2.1 Changes to investment constraints

To improve the run-time of CentIv, all investment decisions are linearized, i.e. u_d^{inv} is always a continuous variable. The new formulation for candidate thermal generators (i.e: $j \in J^D$) is simplified by removing the Unit Commitment (UC) and investment constraints (2)-(9) and (19) in [6]. Instead, the generated power in each time step is limited by (5a), ramping constraints allowing for reserve provision are implemented in (5b)-(5c) with continuous decisions for investment in thermal units as given in (5d):

$$0 \leq p_{j,t} \leq P_j^{\text{max}} u_j^{\text{inv}}, \qquad \forall j \in J^D, \forall t \tag{5a}$$

$$p_{j,t-1} - p_{j,t} + (r_{j,t}^{\text{SCR}\downarrow} + r_{j,t}^{\text{TCR}\downarrow}) \leq R_j^{\text{D}} u_j^{\text{inv}}, \qquad \forall j \in J^D, \forall t \tag{5b}$$

$$p_{j,t} + (r_{j,t}^{\text{SCR}\uparrow} + r_{j,t}^{\text{TCR}\uparrow}) - p_{j,t-1} \leq R_j^{\text{U}} u_j^{\text{inv}}, \qquad \forall j \in J^D, \forall t \tag{5c}$$

$$0 \leq u_j^{\text{inv}} \leq 1, \qquad \forall j \in J^D \tag{5d}$$

where P_j^{max} is the maximum power output, $R_j^{\text{U/D}}$ are the ramp-up/ramp-down limits and $r_{j,t}^{\text{SCR}\uparrow\downarrow}$, $r_{j,t}^{\text{TCR}\uparrow\downarrow}$ are the variables for the unit's contribution towards upward/downward secondary (SCR) and tertiary (TCR) reserves. We include ramp limits as studies have shown that their omission could be the most distorting simplification of the UC in generation expansion planning (GEP) studies [12]. The existing thermal units are also constrained by (5) with u_d^{inv} set to 1. The constraints for candidate battery storages are identical to (10)-(16) and (20) in [6]. Similarly to the case of thermal generators, the binary investment variable for candidate storages (i.e: $k \in K^D$) is relaxed:

$$0 \leq u_k^{\text{inv}} \leq 1, \qquad \forall k \in K^D \tag{6}$$

The constraints for candidate RES technologies are identical to (21) in [6].

2.2.2 Changes to transmission system constraints

The modifications in the formulation of the transmission system constraints in CentIv required for interfacing with DistIv are detailed in [8] and are also included in (7) of this section. The active power balance at each bus node $n \in N$ is formulated in (7a) where $P_{n,t}^D$ is the nodal demand, $ls_{n,t}$ refers to the load shedding variable, $dcurt_{n,t}$ is the variable for the curtailment of power injections from the distribution grid, and the remaining terms correspond to the power output of each generator and storage system. It is important to note that $P_{n,t}^D$ is an input parameter defined over real numbers ($P_{n,t}^D \in \mathbb{R}$). Positive values indicate loads while negative values are power injections. Load shedding is allowed at each bus with associated demand and constrained by (7b) while the curtailment of power injections is constrained by (7c). The nodal active power $p_{n,t}$ is the sum of the active power flows of all lines $l \in L$ connected to n as shown by (7d). The active power flow p_l of a single line is constrained by (7e) and (7f) where B_l is the admittance, δ_n, δ_i are the voltage angles at the start and end nodes and P_l^{max} is the line thermal limit:

$$p_{n,t} = P^D_{n,t} - ls_{n,t} - dcurt_{n,t} + \sum_{k \in K_{n,t}} p^{ch}_{k,t} - \sum_{j \in J_{n,t}} p_{j,t} - \sum_{k \in K_{n,t}} p^{dis}_{k,t} - \sum_{r \in R_{n,t}} p_{r,t}, \qquad \forall n, \forall t \tag{7a}$$

$$ls_{n,t} \leq max(0, P^D_{n,t}), \qquad \forall n, \forall t, \qquad ls_{n,t} \geq 0 \tag{7b}$$

$$dcurt_{n,t} \geq min(P^D_{n,t}, 0), \qquad \forall n, \forall t, \qquad dcurt_{n,t} \leq 0 \tag{7c}$$

$$p_{n,t} = \sum_{i \in l(n,i)} p_{l(n,i),t}, \qquad \forall n, \forall t \tag{7d}$$

$$p_{l(n,i),t} = B_l(\delta_{n,t} - \delta_{i,t}), \qquad \forall l(n,i), \forall t \tag{7e}$$

$$-P^{max}_l \leq p_{l(n,i),t} \leq P^{max}_l, \qquad \forall l(n,i), \forall t \tag{7f}$$

In this work, we split the hourly nodal electricity demand profile $P^D_{n,t}$ into several different profiles, namely heat pump demand $P^{HP}_{n,t}$, electric mobility demand $P^{EM}_{n,t}$, hydrogen demand $P^{H_2}_{n,t}$ and conventional demand $P^{conv}_{n,t}$, i.e.:

$$P^D_{n,t} = P^{HP}_{n,t} + P^{EM}_{n,t} + P^{H_2}_{n,t} + P^{conv}_{n,t}, \qquad \forall n, \forall t \tag{8}$$

In order to facilitate load shifting in CentIv we introduce four new variables, namely $e^{up/down}_{n,t}$ for upward/downward shifting of the e-mobility load and $l^{up/down}_{n,t}$ for the upward/downward shifting of other DSM (which is part of the conventional load). In each hour, the upward and downward shifting is constrained as shown in (9a) and (9d) where $E^{hr,max}$ is the maximum hourly power shift allowed for shifting the e-mobility load and $L^{hr,max}$ is the maximum hourly power shift allowed for shifting the remaining load. The equations guarantee that we can never shift down more load than the load in a given hour. Similarly, the maximum energy shifted within a day is constrained by (9b) and (9e) where t_0 indicates the starting time of each simulated day and $E^{day,max}/L^{day,max}$ are the daily energy shifting limits. Equations (9c) and (9f) ensure that over each day, the up and down shifts are equal:

$$0 \leq \; e^{up}_{n,t} \; \leq E^{hr,max} \quad \text{and} \quad 0 \leq \; e^{down}_{n,t} \; \leq min(E^{hr,max}, P^{EM}_{n,t}), \qquad \forall n, \forall t \tag{9a}$$

$$\sum_{t=t_0}^{t_0+24} (e^{up}_{n,t} + e^{down}_{n,t}) \leq E^{day,max} \tag{9b}$$

$$\sum_{t=t_0}^{t_0+24} (e^{up}_{n,t} - e^{down}_{n,t}) = 0 \tag{9c}$$

$$0 \leq \; l^{up}_{n,t} \; \leq L^{hr,max} \quad \text{and} \quad 0 \leq \; l^{down}_{n,t} \; \leq min(L^{hr,max}, P^{remain}_{n,t}), \qquad \forall n, \forall t \tag{9d}$$

$$\sum_{t=t_0}^{t_0+24} (l^{up}_{n,t} + l^{down}_{n,t}) \leq L^{day,max} \tag{9e}$$

$$\sum_{t=t_0}^{t_0+24} (l^{up}_{n,t} - l^{down}_{n,t}) = 0 \tag{9f}$$

It is important to note that the linear formulation in (13) allows for simultaneous up and down shifting in each hour[1]. In the present work, load shifting is done without incurring any costs. The four newly introduced and constrained variables are included in the nodal balance (10) and the new equation is:

[1] To impose mutual exclusivity, it is necessary to introduce additional binary variables [13], resulting in a mixed-integer linear programming (MILP) formulation characterized by significant increase in solver run-time.

$$p_{n,t} = P^D_{n,t} + e^{up}_{n,t} + l^{up}_{n,t} - e^{down}_{n,t} - l^{down}_{n,t} - ls_{n,t} - dcurt_{n,t} + \sum_{k \in K_{n,t}} p^{ch}_{k,t} - \sum_{j \in J_{n,t}} p_{j,t} - \sum_{k \in K_{n,t}} p^{dis}_{k,t} - \sum_{r \in R_{n,t}} p_{r,t}, \quad \forall n, \forall t \tag{10}$$

For the scenarios in which the total annual electricity exports equal the total annual electricity imports in a given region (i.e. Switzerland), the following constraint is introduced where *CB* denotes the set of the cross-border lines:

$$\sum_{t \in T} p_{l,t} = 0, \qquad \forall l \in CB \tag{11}$$

In order to account for the cost of any power injections to the transmission grid which are not curtailed (excess PV from consumers), an additional term (vi) is added to the objective function in (1) where C_n^{dinj} is the nodal cost of the power injection and $P^{\mathrm{D}}_{n,t}$ is the nodal demand:

$$\underbrace{\gamma \sum_{n \in N} \sum_{t \in T} C_n^{\mathrm{dinj}} (-P^{\mathrm{D}}_{n,t} + dcurt_{n,t})}_{\text{(vi)}}, \qquad \forall n, \forall t \quad \text{if} \quad P^{\mathrm{D}}_{n,t} < 0 \tag{12}$$

2.3 DistIv extensions

To facilitate the investigation desired for the CH2040 project, some model extensions were needed within DistIv compared to [7, 9]. Most importantly were the modifications to interface with and utilize results of CentIv and to enable shifting of e-mobility within defined limits.

2.3.1 Changes to interface with CentIv

First, while household retail electricity tariffs in [7] are assumed to project into the future years based on the historical 2020 tariff and a fixed annual development rate, the retail tariffs for future years in this work instead develop based on the wholesale electricity price signals from CentIv. More specifically, the representation of the consumer's retail price is comprised of three parts: (i) the wholesale electricity price which is provided as a signal from the CentIv module, (ii) the total network fee including both the grid charge and additional fees, and (iii) the wholesale-to-retail price markup. Out of these three components of the consumer's retail electricity price, the wholesale-to-retail price markup and network fee are kept constant over all simulated years, while the wholesale price provided by CentIv is expected to vary over future years. Therefore, the combined retail electricity price seen by the consumers will also vary from year to year and will change depending on the scenario assumptions. The network fee and wholesale-to-retail markup are quantified using known historical data from 2018 [14] and are kept constant over the years; however, they differ by the geographical location and the consumption category. The wholesale-to-retail markup is only applied to the self-consumed portion of the PV and photovoltaic battery (PVB) generation to properly reflect the consumer costs that are offset by providing the consumer's demand from PV instead of from purchasing at the consumer's normal cost. For all other distributed technologies in the LC submodule, the price of electricity for purchasing from or selling to the transmission grid only comprises the first two parts (i.e., the wholesale price and network fee). More details along with the associated values can be found in the Nexus-e Input Data Report [2].

Second, for each examined investment year, simulations in [7] are carried out without considering investments in previous years, whereas in this work, deployment potentials for PV are updated considering the used rooftop area by previously built PV installations.

Third, modifications are made to the clustering of households into groups based on data entries from [5]. While the four parameters for clustering remain the same (i.e., depending on their annual irradiation, roof sizes, annual electricity consumption, and geographical regions), the categories within each parameter used to create the clusters is unique:

- **Roof sizes**: roofs are grouped based on their m^2 size into 20 categories [10-24, 24-36, 36-48, 48-60, 60-72, 72-96, 96-120, 120-144, 144-168, 168-210, 210-282, 282-354, 354-426, 426-498, 498-570, 570-900, 900-1'800, 1'800-3'000, 3'000-6'000, >6'000].
- **Irradiation levels**: roofs are grouped based on their annual irradiation level in kWh/m^2/year into 4 categories [1'000-1'150, 1'150-1'300, 1'300-1'450, and >1'450].
- **Electricity consumption**: roofs are grouped based on their annual electricity consumption in kWh/year[2] into 6 categories [0-2'500, 2'500-4'500, 4'500-7'500, 7'500-13'000, 13'000-30'000, and >30'000].
- **Region**: roofs are grouped based on their location/region corresponding to either of the 26 cantons or the 143 districts in Switzerland.

After clustering, all data entries are categorized into the 20*4*6*26 = 12'480 residential customer groups.

2.3.2 Changes to model the flexibility potential of e-mobility

To account for the use of flexibility of e-mobility demand (i.e., shifting of e-mobility demand), in DistIv we introduce two new variables for the upward/downward shifting of the electricity demand from e-mobility $e_{r,t}^{up/down}$. In DistIv the e-mobility demand is represented in the DSO submodule and therefore each region r includes one aggregate demand profile for the e-mobility within that region. Similar to the added constraints in CentIv, the e-mobility shifting is structured to have an hourly maximum power shift (13a) and a daily maximum energy shift (13b) along with ensuring the up and down shifts balance within each day (13c).

$$0 \leq \; e_{r,t}^{up} \; \leq E^{hr,max} \quad \text{and} \quad 0 \leq \; e_{r,t}^{down} \; \leq min(E^{hr,max}, P_{r,t}^{EM}), \qquad \forall n, \forall t \tag{13a}$$

$$\sum_{t=t_0}^{t_0+24} (e_{r,t}^{up} + e_{r,t}^{down}) \leq E^{day,max} \tag{13b}$$

$$\sum_{t=t_0}^{t_0+24} (e_{r,t}^{up} - e_{r,t}^{down}) = 0 \tag{13c}$$

$$\tag{13d}$$

2.4 Interfacing Euro-Calliope and Nexus-e

Since the primary focus of this project was to combine the beneficial aspects of the two modeling frameworks, Euro-Calliope to provide the full European perspective for the energy system transition toward net-zero and Nexus-e to provide a more detailed assessment of the impacts and development on the Swiss electricity system, the connection of these two models is at the core of the project. This connection is implemented as a uni-directional soft link (i.e., data are only transferred from Euro-Calliope to Nexus-e and this transfer is done without integrating the models themselves). The Euro-Calliope results are provided as a set of CSV files in the 'frictionless data format' [18] and read by the Nexus-e team using the dataprotocols.org standard tabular data package for Matlab [19]. After reading the data files,

[2] Since the annual electricity consumption data are not available, the annual electricity load is approximated as 125% of the warm water consumption [15, 16, 17]

the Matlab script processes all the desired information that is to be incorporated into the Nexus-e input data. This intermediate set of processed data is stored as a MAT file for each scenario. Finally, during the creation process of the Nexus-e scenario database, the data transferred from Euro-Calliope overwrite the corresponding reference data used by Nexus-e in previous studies. Both the Euro-Calliope data processing and Nexus-e database creation steps are automated using Matlab scripts.

2.4.1 Euro-Calliope data used by Nexus-e

The following list describes the input data that Nexus-e utilizes from the Euro-Calliope simulation data files (these data are either results produced by Euro-Calliope to be used by Nexus-e or input data used by Euro-Calliope to be harmonized):

- **Electricity demand**: the hourly electricity demand profiles by country for each of the demand types below are fixed to represent the demand side of the electricity system;
  - *Base*: the conventional electricity demand from current demand sources
  - *Rail*: the electricity demand of the railway system (Swiss only) is subtracted from the Base demand (i.e., since the Swiss railway electricity has a separate transmission network)
  - *Electrified Mobility (e-mobility)*: new electrification of non-rail transport
  - *Electrified heating (heat pumps)*: new electrification of space heating
  - *Hydrogen production*: electricity consumption from hydrogen production
- **Installed generating capacity**: the installed electricity generating capacities by generator type for the neighboring European countries are fixed;
- **Installed storage volumes**: the installed electricity storage volumes by generator type for the neighboring European countries are fixed;
- **Net transfer capacities**: the allowed net transfer capacitys (NTCs) that limit the electricity flows between each neighboring country are fixed;
- **Non-dispatchable electricity production**: the hourly electricity production profiles for the neighboring European countries and for each of the appropriate generator types (i.e., hydro run of river (RoR), wind onshore, wind offshore, PV, and CHP) are fixed to represent these non-dispatchable supply sources;
- **Flows to rest of the EU**: the hourly electricity flow profiles from each of the Swiss neighboring countries to the rest of Europe are fixed and represented as an added net demand within each neighbor.

2.4.2 Euro-Calliope data not used by Nexus-e

Other results or input data available from Euro-Calliope were chosen not to implement or harmonized within Nexus-e and instead the reference Nexus-e data, used in previous studies, were kept. Generally, this decision was taken for data that were already represented in greater detail within Nexus-e. The data that were not utilized from Euro-Calliope include:

- **Swiss installed generating capacities**: Since Euro-Calliope takes a green-field approach (i.e., ignores all existing infrastructure), the Euro-Calliope results for Swiss generator capacities are ignored and instead Nexus-e utilized the known existing generator capacities along with planned hydro power expansions, a complete Swiss nuclear phase out prior to 2040, and removal of all existing Swiss gas-fired and oil-fired generators;

- **Swiss installed storage volumes**: Similarly, the existing Swiss electricity storage volumes are kept along with the planned hydro storage expansions;

- **Swiss candidate generator capacities**: As described in Section 1.3, Euro-Calliope and Nexus-e include different options for candidate generator capacities within Switzerland. As discussed in Section 3.3, Nexus-e has elected to include as candidates for investment at the centralized level: 240 MW of waste-fired, 1960 MW of wind, 5500 MW of gas-fired combined cycle (CC) with carbon capture and storage (CCS), 5500 MW of gas-fired CC that use synthetic methane, and 4100 MW of BESS. Additionally, Nexus-e includes as candidates for investment at the distributed level: 37000 MW of rooftop PV along with PVB at the household level, biomass and CHP at the large consumer level, and grid-connected batteries at the DSO level.

- **Swiss non-dispatchable electricity production**: Since the reference Nexus-e capacities of Swiss non-dispatchable units (i.e., hydro RoR, wind, PV) are used, so too the reference Nexus-e data for the hourly production profiles of these units are used.

- **Generator variable operation and maintenance (VOM) costs**: Since the reference Nexus-e data for generator VOM costs include greater detail and diversity, the VOM cost data from Euro-Calliope are not utilized.

- **Generator fuel and carbon dioxide (CO_2) prices**: Similarly, the reference Nexus-e data for generator fuel and CO_2 prices are kept; however, since most CO_2-emitting producers are removed, few fuel consuming units are included in the simulation.

- **Swiss generator investment and fixed costs**: Lastly, because the potential generator investments are unique in Nexus-e, the associated investment costs and fixed operating costs for these candidate units are kept as in the reference Nexus-e data.

2.4.3 Representing e-mobility flexibility

One of the main modeling extensions implemented within Nexus-e as part of the CH2040 project was to represent the electricity demand from e-mobility along with its ability to be flexible. While the hourly profile of the e-mobility demand in each country was taken from the Euro-Calliope results, the limits on the flexibility of this demand within the Nexus-e simulations was fixed separately from the Euro-Calliope representation of e-mobility flexibility. Nexus-e therefore represents the ability to shift e-mobility demand within Switzerland and its neighboring countries.

The e-mobility demand profiles provided by Euro-Calliope are already optimized by shifting the hourly demands within the limits Euro-Calliope allows to reduce the overall energy system supply costs. While Nexus-e sets these already shifted profiles as the e-mobility demands for each appropriate country, we also include the possibility for additional shifting that would be beneficial to reduce the supply costs of the detailed electricity system represented within Nexus-e. To place limits on the allowed shifting potential of e-mobility, two assumptions were taken. First, the maximum annual energy that can be shifted is around 10% of the annual e-mobility demand (note for Switzerland, this limit is instead allowed to be 25%). Second, over the day a maximum of 20 hours are allowed to have an up or down shift of the e-mobility power demand.

Using these two assumptions, Nexus-e places limits on the flexibility of e-mobility demand as described in Sections 2.2.2 and 2.3.2 by limiting the amount of energy that can be shifting in any individual hour, the amount of energy that can be shifting within one day, and that the energy shifted up must equal the amount shifted down within each day. Table 1 provides details on the e-mobility demand and shifting potentials.

Table 1: Limits on the flexibility of e-mobility are based on the annual electricity demand (all values shown in GWh). Constraints are defined to limit the daily and hourly maximum energy that can be shifted for each country.

Country	Annual E-mobility Demand	Max Annual Shifting Percentage	Max Annual E-mobility Shifting	Max Daily E-mobility Shifting	Max Hourly E-mobility Shifting
CH	30,382	25	7,595	20	2.0
AT	41,567	10	4,157	11	1.1
DE	339,678	10	33,967	93	9.3
FR	288,301	10	28,830	79	7.9
IT	199,684	10	19,968	54	5.4

3 Scenarios

To achieve the objectives of the CH2040 project, the Nexus-e team connects with Euro-Calliope to simulate eighteen scenarios of the year 2040. In addition to these 2040 scenarios, a 2020 historical simulation is also completed to serve as a reference for comparison. This section provides a description of the distinct categories used to define the scenarios (Section 3.1), details about the structure of the electricity system simulated and the necessary input data (Section 3.2), and additional information about the candidates included for potential new infrastructure investments (Section 3.3).

3.1 Scenarios breakdown

These scenarios, shown in Table 2, are broken down by three categories: the use of synthetic natural gas, the allowed Swiss NTCs, and the Swiss annual import/export relationship. Among these scenarios, scenario s1, which uses the current Swiss NTCs, no Swiss import/export restriction and the ability to import synthetic fuels, is considered the Baseline scenario which many other scenarios will be compared against since it is the most similar to the electricity system today.

Table 2: Categorization of the eighteen simulated 2040 scenarios along with the 2020 historical reference scenario.

Scenario	Year	Swiss Synthetic Gas Use	Swiss NTCs	Swiss Import/Export
s0	2020	Pipeline gas as historical	Current NTC	Free import/export
s1	2040	Can import synthetic gas	Current NTC	Free import/export
s2	2040	Can import synthetic gas	Current NTC	Balanced import/export
s3	2040	Can import synthetic gas	Reduced NTC	Free import/export
s4	2040	Can import synthetic gas	Reduced NTC	Balanced import/export
s5	2040	Can import synthetic gas	Expanded NTC	Free import/export
s6	2040	Can import synthetic gas	Expanded NTC	Balanced import/export
s7	2040	Only self-produced synthetic gas	Current NTC	Free import/export
s8	2040	Only self-produced synthetic gas	Current NTC	Balanced import/export
s9	2040	Only self-produced synthetic gas	Reduced NTC	Free import/export
s10	2040	Only self-produced synthetic gas	Reduced NTC	Balanced import/export
s11	2040	Only self-produced synthetic gas	Expanded NTC	Free import/export
s12	2040	Only self-produced synthetic gas	Expanded NTC	Balanced import/export
s13	2040	No allowed gas units	Current NTC	Free import/export
s14	2040	No allowed gas units	Current NTC	Balanced import/export
s15	2040	No allowed gas units	Reduced NTC	Free import/export
s16	2040	No allowed gas units	Reduced NTC	Balanced import/export
s17	2040	No allowed gas units	Expanded NTC	Free import/export
s18	2040	No allowed gas units	Expanded NTC	Balanced import/export

Swiss synthetic gas use In scenarios s1-s6 gas candidate units in Switzerland are allowed to use imported synthetic natural gas (that is zero-carbon) or pipeline gas (but these units must include CCS to be nearly zero-carbon); alternatively in scenarios s7-s12 gas candidates in Switzerland can only use synthetic gas that is produced in Switzerland or the pipeline gas with CCS; and in scenarios s13-s18 no gas-fired generators are allowed in Switzerland.

From the Euro-Calliope perspective, both the 'can import' and 'no gas units' categories refer to a single scenario where Switzerland is allowed to import synthetic fuels from other European countries for any fuel needs across the full energy system. The 'only self-produced' category refers to a different Euro-Calliope scenario where all Swiss fuel needs can only be satisfied from synthesized fuels produced within Switzerland (i.e., fuel autarky). Since other difficult to decarbonize energy sectors still use fuels, a significant amount of fuel synthesis is therefore required in Switzerland and the associated increased electricity need is huge. In effect, the Nexus-e scenarios s7-s12 include nearly double the Swiss electricity demand as their alternatives in scenarios s1-s6 and scenarios s13-s18.

Swiss NTCs To reflect the relevant uncertainty in the ongoing negotiations between Switzerland and the European Union (EU) and the upcoming new European Network of Transmission System Operators for Electricity (ENTSO-E) rules on minimum available cross-border transmission capacities, an option with reduced Swiss NTCs is defined. This 'Reduced NTC' case sets the Swiss cross-border electricity trade limits equal to 30% of the 'Current NTC' case. Additionally, to reflect possible enhancements to the integration of the Swiss electricity market with the EU market, an option with increased Swiss NTCs is defined. In this 'Expanded NTC' case, the value of each NTC is a variable in the Euro-Calliope optimization which is then taken and fixed in the Nexus-e scenario simulations. Tables 3 and 4 list the recent historical Swiss NTC values that are applied for the 'Current NTC' case and the values after reducing to only 30% of the current.

Table 3: NTC trade limitations between Switzerland and neighboring market zones in megawatt (MW) as modeled for the 'Current' case.

		FROM				
		CH	**AT**	**DE**	**FR**	**IT**
TO	**CH**	—	1200	4000	3000	4240
	AT	1200	—	—	—	—
	DE	4000	—	—	—	—
	FR	3000	—	—	—	—
	IT	4240	—	—	—	—

Table 4: NTC trade limitations between Switzerland and neighboring market zones in MW as modeled for the 'Reduced' case.

		FROM				
		CH	**AT**	**DE**	**FR**	**IT**
TO	**CH**	—	400	1333	1000	1413
	AT	400	—	—	—	—
	DE	1333	—	—	—	—
	FR	1000	—	—	—	—
	IT	1413	—	—	—	—

In all three NTC cases, the non-Swiss cross-border limits are always allowed to increase as part of the Euro-Calliope optimization (i.e., similar to the Swiss NTCs in the 'Expanded NTC' case). Since the expansion of NTCs are variables within Euro-Calliope, the values can depend on the individual Euro-Calliope scenario. These NTCs are always fixed within the Nexus-e simulations based on the results of

Euro-Calliope. Table 5 provides an example of the Swiss and neighboring country NTCs for the scenario s5 that allows all NTCs to increase as optimization variables.

Table 5: NTC trade limitations between Switzerland and neighboring market zones in MW as modeled for one of the 'Expanded' cases (s5).

		FROM				
		CH	**AT**	**DE**	**FR**	**IT**
TO	**CH**	—-	4852	12703	13921	8477
	AT	4852	—-	15700	—-	2300
	DE	12703	15700	—-	6254	—-
	FR	13921	—-	6254	—-	4800
	IT	8477	2300	—-	4800	—-

Swiss annual import/export relationship Lastly, to reflect the desire for Switzerland to be more self-reliant for its electricity supply, the option is created to require that the annual imports and exports of electricity are balanced. The alternative to such a balanced requirement is simply to have no constraint ('free') on the import/export relationship and instead allow each to optimize independently within the limits of the NTCs.

3.2 Input data and system setup

To perform the investigation in the CH2040 project, Nexus-e simulates the Central European electric energy system with the focus on Switzerland. As such, the simulated system includes a detailed representation of the power system of Switzerland (CH) and an aggregated representation of the four neighboring countries (Germany (DE), France (FR), Italy (IT), and Austria (AT)) as shown in Figure 3. Nexus-e represents the distribution system on an aggregated cantonal level. Hence, we connect the cantonal values (e.g., electricity load profiles) to the nodes of the transmission system and do not model the distribution grid.

In this project, at the centralized level the installed capacities in the Swiss neighboring countries are fixed based on the results of the Euro-Calliope simulations while the existing and new investment candidates are represented within Switzerland by Nexus-e. Along with the existing and candidate centralized generators, PV and PVB technologies are represented at the distribution level.

Details of the simulated system, the input data, and the sources of the data can be found in the most recent report on input data [2]. This report includes detailed descriptions of:

- the transmission network data and NTCs (Section 1);
- the capacities, operating parameters, hydro storage parameters, renewables data, operating costs, fuel prices, and candidate generator data for centralized Swiss (Section 2.1) and neighboring European (Section 2.2) generators;
- the capacity potentials, operating parameters, costs developments, as well as the clustering of rooftop PV potentials for Swiss distributed generators (Section 2.3);
- the reserve requirements and how they increase with added wind or PV capacities (Section 4);
- the policies included that impact the incentives for rooftop PV (Section 5.1)
- the method of quantifying the consumer's retail electricity price for the economic basis of the PV and PVB investment decisions (Section 5.2)

The data described in this report serve as the basis for the Nexus-e platform and in this work some of these input data are instead replaced with results from the Euro-Calliope simulations (see Section 2.4 for details of the data utilized from Euro-Calliope). In addition to the data directly implemented from the Euro-Calliope results, a few other modifications are made to the base Nexus-e inputs for the CH2040 project:

- all existing Swiss natural gas and oil-fired generators are removed to achieve the net-zero carbon emissions required for Switzerland;
- all non-Swiss natural gas generators are assumed to consume synthetic gas with a common European fuel price;

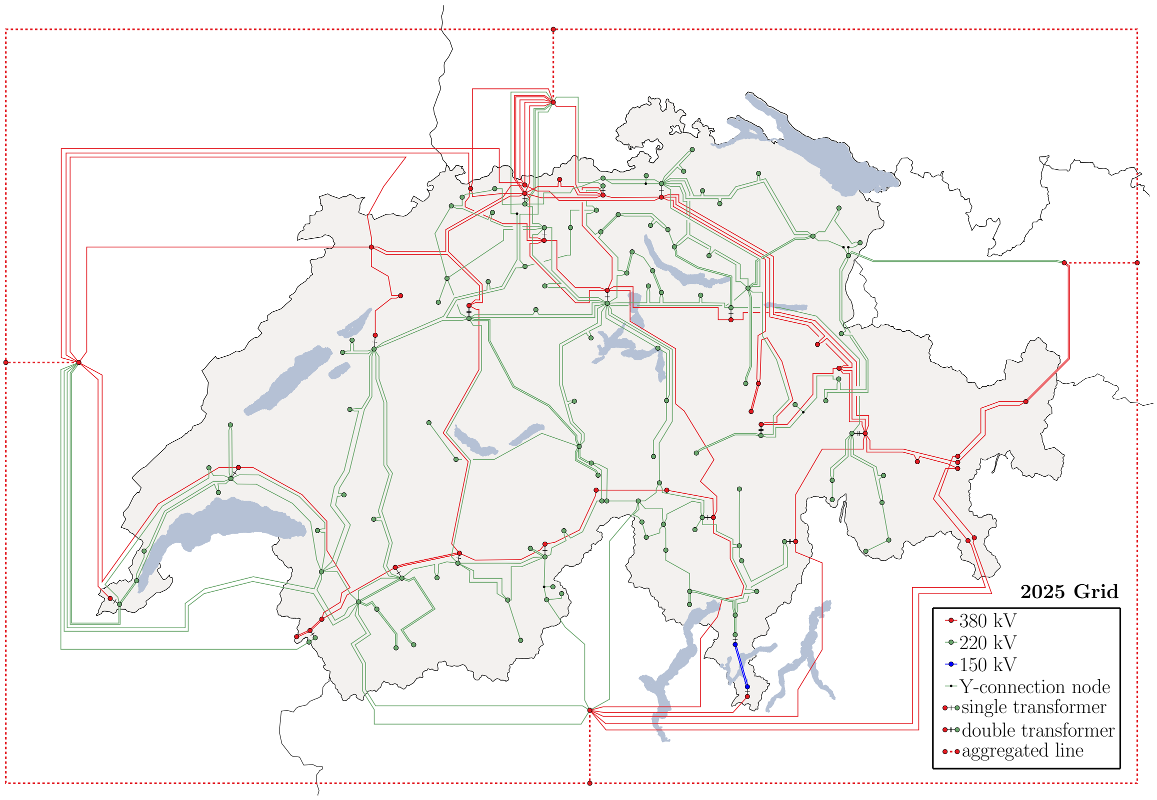


Figure 3: Overview of the modeled 2025 transmission system.

3.3 Swiss candidates for investment in Nexus-e

As part of the Nexus-e analysis, the investment decisions are optimized from both the centralized and distributed perspectives to determine when new generating capacities should be built in 2040 for each scenario. As noted in Section 2.4.2, the potential new Swiss capacities represented in Euro-Calliope are different than those represented in the Nexus-e modules. While Euro-Calliope takes a broadly encompassing approach to these potentials (i.e, including open-field PV in Switzerland) with limited differences in investment costs across Europe, Nexus-e instead limits the investment potentials to be inline with limits believed to be achievable within current environment regarding public acceptance (i.e., no open-field PV and only around 4 TWh of wind in Switzerland). The following generator candidates are included in the Nexus-e scenarios as options for new investments:

- Centralized level
  - Waste: 12 units of 20 MW each, 240 MW total;
  - Wind: 7 locations with a total of 1960 MW;
  - BESS: 41 locations of 100 MW each, 4100 MW total;
  - Gas Combined Cycle (synthetic methane): 11 units of 500 MW each, 5500 MW total;
  - Gas Combined Cycle (with CCS): 11 units of 500 MW each, 5500 MW total;
- Distributed level
  - Rooftop PV: 37 GW total based on rooftop locations;
  - PV-batteries (PVB): allowed at each rooftop PV location;
  - Biomass and Gas-CHP: at large consumer level of each distribution region;
  - Grid-connected BESS: at DSO level of each distribution region.

More details regarding the investment costs and operating parameters along with the data sources for these candidate units can be found in [2]. Locations for the gas units are selected based on the recommendations of a recent study from Swiss Federal Electricity Commission (ElCom) [20]. The fuel price of gas generators with CCS is meant to represent the additional cost of CO_2 transport and disposal and has been increased appropriately based on a recent Swiss study [21]. Lastly, the Swiss fuel prices of synthetically produced natural gas that would be imported to Switzerland or that could be produced within Switzerland are set based on an additional Swiss study [22]; while the fuel price of similar synthetic natural gas for the other European countries is set based on a recent study of the costs of producing methane from renewable hydrogen [23].

4 Results

This section presents our results for the development of the Swiss electricity system under the scenarios for 2040. While the sections below do not go into depth for every scenario, they instead present a comparison between two representative scenarios to illustrate the general trends that were observed between all similarly contrasting scenarios. This section first provides an example of the already shifted demand profile for e-mobility coming from Euro-Calliope and comments about the impact on the Nexus-e results (Section 4.1). The subsections continue into the Nexus-e results by providing illustrations and comments about the general energy transition between 2020 and 2040 (Section 4.2), the impacts of restricting Swiss NTCs (Section 4.3), the impacts of requiring an annual balance of the Swiss imports and exports (Section 4.4), the impacts of not allowing any type of gas-fired generators in Switzerland (Section 4.5), the impacts of expanding Swiss NTCs (Section 4.6), and the impacts of requiring Switzerland to synthesize all fuels consumed (Section 4.7). The results and plots that follow are all accessible at the dedicated results webviewer from the Nexus-e website [24].

4.1 Euro-Calliope's e-mobility demand shifting: Baseline 2040 (s1)

As part of the Euro-Calliope simulations, the extent of electrification of mobility and the hourly profile of this electrification is optimized within the whole energy system. Within this optimization, Euro-Calliope allows the e-mobility demand to be shifted from hour to hour depending on the number of electric vehicles plugged in during each hour while also satisfying the fixed monthly e-mobility demand. The resulting hourly demand profile for e-mobility is therefore already heavily shifted to align with the profile of electricity supply from the non-dispatchable generation sources (i.e., primarily PV). Figure 4 illustrates this alignment by showing the profile of the total Swiss demand (black line) and the production of electricity from the various Swiss resources for two summer days in the 2040 Baseline (s1) scenario. While only a part of the total demand, the e-mobility demand heavily influences the overall trend of demand peaking during the daylight hours when production from PV is also significant. The same trend is evident in the Euro-Calliope results for all countries.

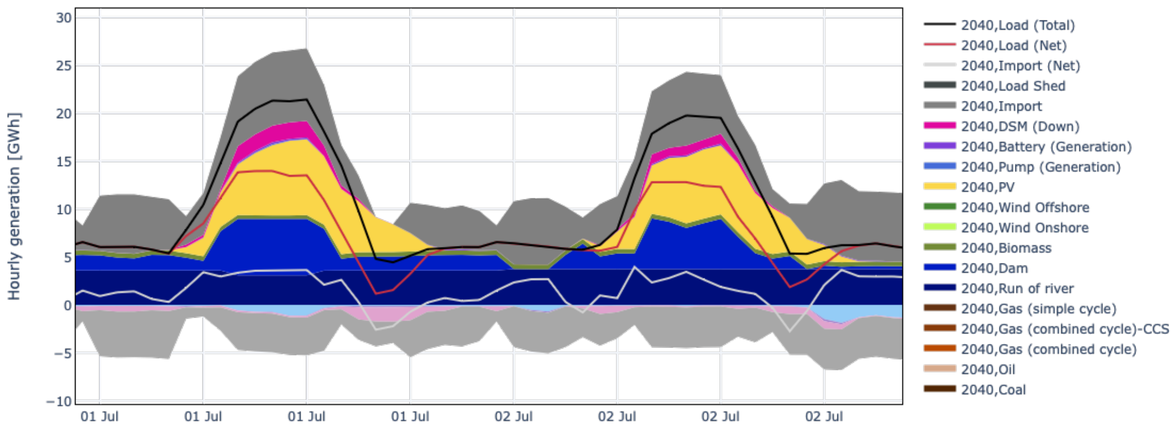


Figure 4: High utilization of e-mobility demand flexibility by Euro-Calliope yields an hourly demand profile that is shifted to align with production from PV.

The high level of flexibility utilized within Euro-Calliope from the e-mobility demand is highly relevant because its use reduces the need for other forms of flexibility within the electricity sector to match supply and demand. Since the Nexus-e simulations use these shifted e-mobility demand profiles from Euro-Calliope, the Nexus-e results will also be impacted and show less need for other forms of flexibility than would otherwise be needed. As mentioned in Section 2.4.3, Nexus-e does allow a limited amount of reshifting of these e-mobility profiles to benefit the electricity system represented within Nexus-e. Future work is already ongoing to improve and create customizable limits on the amount of e-mobility flexibility that Euro-Calliope can utilize.

4.2 Transition to 2040: Historical 2020 (s0) versus Baseline 2040 (s1)

The Swiss transition from 2020 to 2040 is characterized by a general decrease in traditional electricity demands but a large increase is electricity demand from the transport sector (e-mobility)[3]. Table 6 compares the total annual demand from the historical 2020 year as reported by Bundesamt für Energie (BFE) [25] with 2040 demands from two scenarios of the Swiss Energy Perspectives 2050+ study [26] and the simulated 2040 demand from Euro-Calliope for the Baseline scenario (s1). In the lower half of the table, the simulated 2040 Baseline (s1) demands are also broken down into their various components. The overall level of electricity demand in the Baseline 2040 simulation represents an increase of 26% compared to the 2020 demand. This 2040 amount is inline with the value reported by Prognos in the EP2050+ ZERO-A scenario. Electrification of mobility makes up over 37% of the 2040 electricity demand.

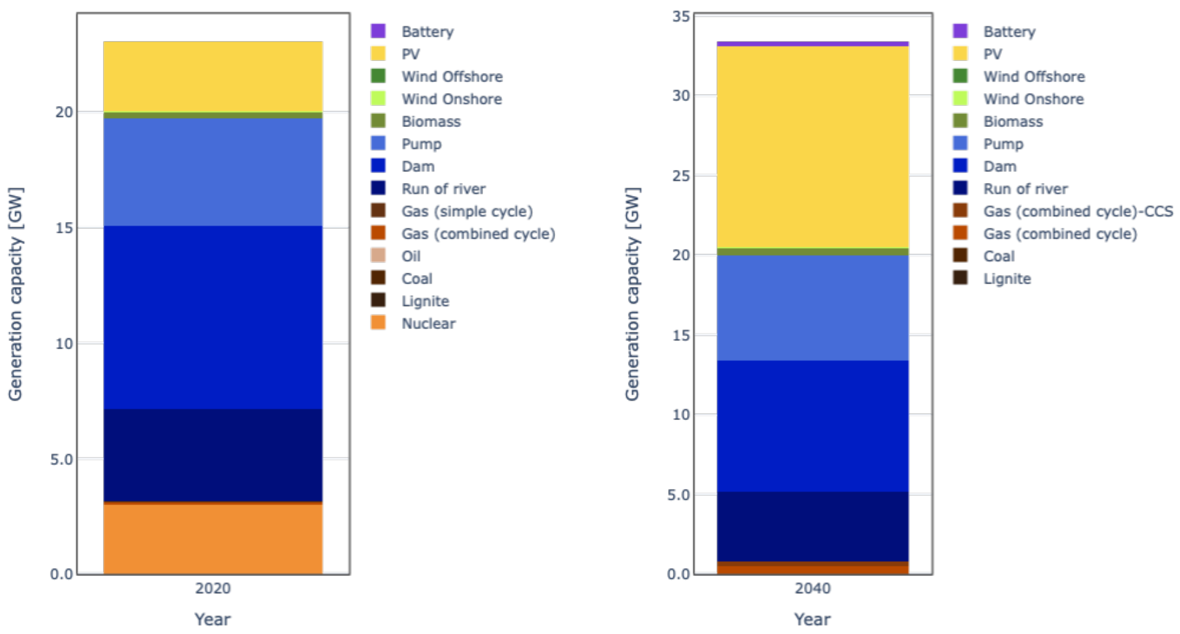
Table 6: Add caption.

Source	**Annual Demand [TWh]**
2020 Historical	59.9
2040 EP2050+ ZERO-Basis	71.5
2040 EP2050+ ZERO-A	80.1
2040 Scenario s1	81.3
2040 s1: Conventional	49.2
2040 s1: E-mobility	30.4
2040 s1: Heat Pumps	1.4
2040 s1: Hydrogen	0.3

Applying these demand totals along with their associated hourly profiles in the Nexus-e model, the CentIv and DistIv modules together determine the investments in new generating capacities as well as the hourly operation of new and existing generators and the needed imports and exports of electricity. In all 2040 scenarios simulated, the Swiss nuclear generators are assumed to be phased-out (-3.0 GW) and several new hydro dam, pump, and RoR units are added (+2.6 GW). To meet the increase in electricity demand while also making up for the removed nuclear generators, new rooftop PV capacity is selected (+9.5 GW) along with more minor additions of waste-fired (+0.24 GW), gas-fired (+0.75 GW), and BESS generators (+0.28 GW). Figure 5 compares the installed Swiss capacities in 2020 and in the 2040 Baseline scenario (s1).

Figure 6 shows the Swiss monthly production by generator type along with the imports and exports (bars) as well as the total demand, net demand, and net imports per month (lines) for both the 2020 historical and 2040 Baseline scenario (s1). Production from the new PV (+9.7 TWh) and a large shift in the net imports (+34.3 TWh) are the most notable changes to make up for the loss of nuclear (-24

[3]The electrification in 2040 is a result of the Euro-Calliope optimization of the European energy system.

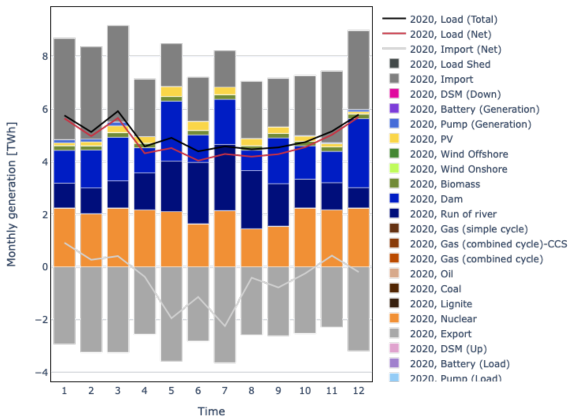


(a) Scenario s0: 2020 Historical

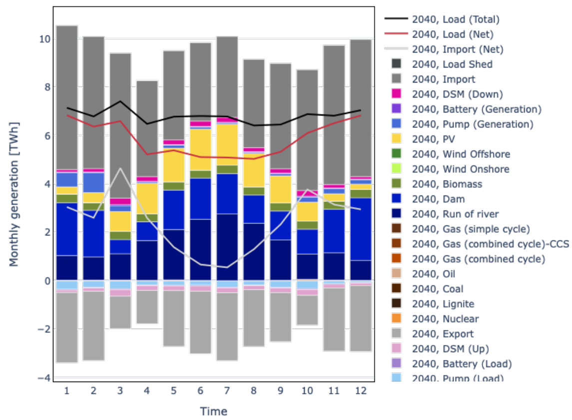
(b) Scenario s1: 2040 Baseline

Figure 5: The adoption of rooftop PV by Swiss consumers and the phase out of nuclear power are the main changes observed in the transition of the electricity system in 2020 (s0) to that of the Baseline (s1) scenario for 2040.

TWh) and increase in demand (+21.4 TWh). It is evident that, given the ability to import and export up to the NTC limits of today, the most economically efficient solution for Switzerland is to import more electricity and export less. This result aligns with the significant increases in renewable production in the neighboring Swiss countries, which drive down the wholesale prices in these countries and enable cheaper imports to Switzerland.



(a) Scenario s0: 2020 Historical



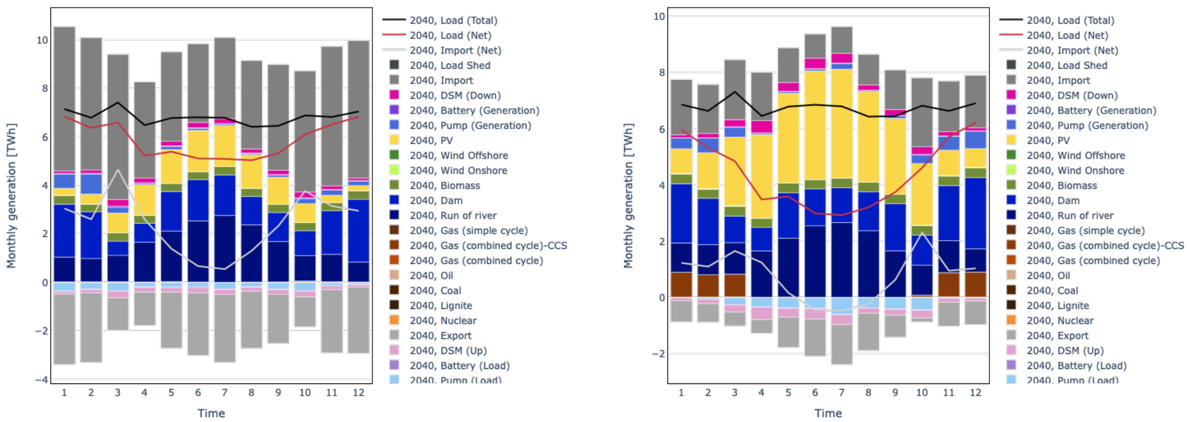
(b) Scenario s1: 2040 Baseline

Figure 6: The increased demand and loss of nuclear production compared to 2020 is made up for by increased PV generation and increased imports as well as decreased exports in 2040.

4.3 Restricting transfer capacities: Baseline (s1) versus Reduced NTCs (s3)

Focusing now on the 2040 scenarios, the first comparison to investigate is the impacts of restricting the ability for Switzerland to trade electricity with its neighbors. Figure 7 illustrates the changes to the monthly production and imports/exports of the scenario with restricted NTCs (s3) compared to the Baseline scenario (s1)[4]. The reduced NTCs have a clear and direct impact on the amount of power imported and exported across all months with the former dropping by over 65% to 19.2 TWh (-36.8 TWh) and the latter dropping by over 62% to 10.1 TWh (-17.0 TWh). The overall level of net imports goes from being an annual net importer of 29 TWh (s1) to a net importer of 9.1 TWh (-19.9 TWh). In response to the limited cross-border trading, Switzerland must focus on and expand domestic production sources, including rooftop PV (+23.7 GW, +16.8 TWh) and gas (+1.5 GW, +4.1 TWh). Additionally, both the imports and exports have concentrated into the months and seasons that they are most needed (i.e., imports in Winter and exports in Summer).

While no plots are shown here for the neighboring countries, the impacts of the reduced Swiss NTCs on the neighbors was clear. Since much power transits through Switzerland, the limited trading yields increased curtailments of renewables (especially from France), increased use of gas-fired generators in Italy, and much higher overall wholesale electricity prices in all months (especially Winter months).



(a) Scenario s1: 2040 Baseline

(b) Scenario s3: 2040 Reduced NTCs

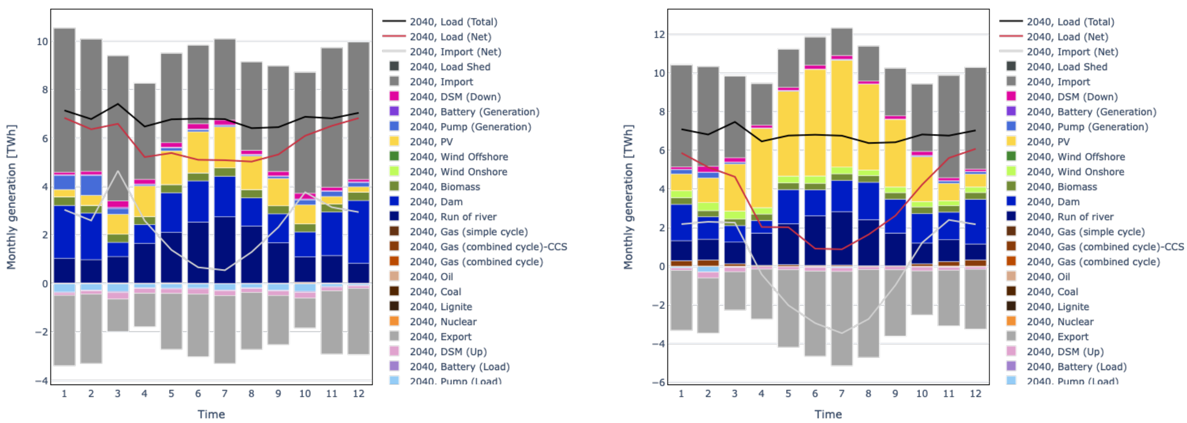
Figure 7: Restricting the Swiss NTCs to 30% of their current values heavily limits the imports and exports and causes Switzerland to instead focus on expanding domestic PV and gas capacities.

[4] In all Reduced NTCs cases, the four Swiss cross-border NTCs are set to be onlyu 30% of the current NTCs.

4.4 Requiring a balanced electricity trade: Baseline (s1) versus Balanced (s2)

The second comparison to assess is the impacts of requiring that Switzerland balance the annual imports and exports. Figure 8 illustrates the changes to the monthly production and imports/exports of the scenario with balanced trading (s2) compared to the Baseline scenario (s1). The balanced trade requirement has similar but less pronounced impacts to the restricted NTCs scenario. To achieve the balance, the imports have reduced by 28.5% to 40.0 TWh (-16 TWh) while the exports actually increase by 47.7% to 40.0 TWh (+12.9 TWh). In particular, the imports are concentrated into the Winter months resulting in a clear seasonal pattern of the net import/export behavior. Again, similar to the restricted NTCs case, the limitations placed on the imports and exports result in Switzerland expanding its domestic generation fleet by expanding to a similar level of rooftop PV (+23.7 GW, +24.6 TWh) but also with added wind power (+2.0 GW, +4.0 TWh) instead of gas.

Regarding the impact on the Swiss neighbors, in this case the Swiss wholesale prices are much higher than the Baseline case in all months, but the neighboring country prices are only a bit higher than the Baseline scenario. So, again the impacts are similar but less pronounced than the restricted NTCs scenario.



(a) Scenario s1: 2040 Baseline

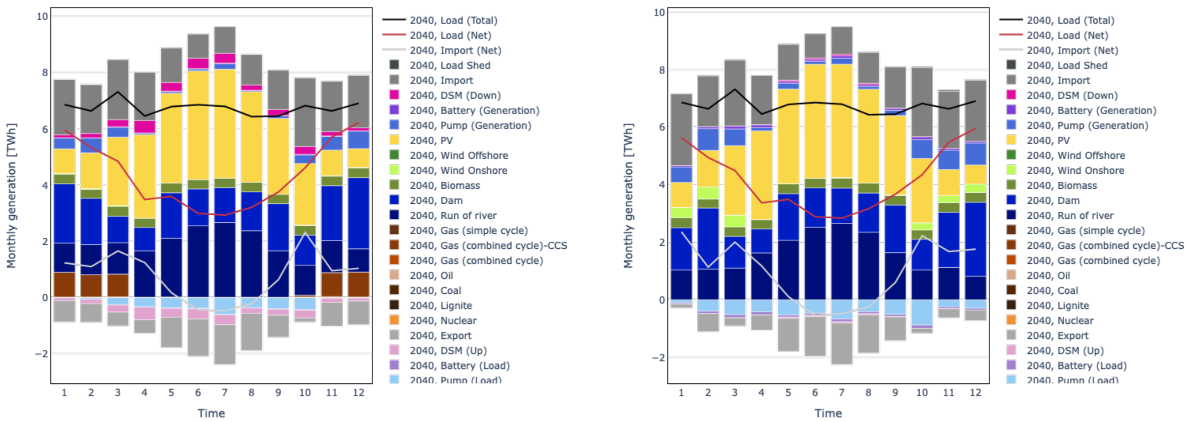
(b) Scenario s2: 2040 Balanced Trade

Figure 8: Requiring a balanced annual trade also yields greater expansion of PV but in combination with wind power and greater utilization of imports in Winter instead of gas-fired generators.

4.5 Restricting all gas generators: Reduced NTCs (s3) versus No Gas (s15)

The third comparison to investigate is the impacts of restricting the use of any type of gas-fired generators in Switzerland. For addressing this question, we are most interested in the scenarios with restricted NTCs since the gas-fired generators were noticeably used during the Winter for the (s3) scenario shown in Figure 7. Sticking with the restricted NTCs scenarios, Figure 9 illustrates the changes to the monthly production and imports/exports of the scenario with no gas and restricted NTCs (s15) compared to the restricted NTCs scenario (s3). The inability to build and produce with gas-fired generators leads Switzerland to instead built most other available domestic capacities, including wind (+1.9 GW, +1.9 TWh) and BESS (+0.7 GW, +0.7 TWh), while also generating more from the existing pumped hydro units (+1.7 TWh). The lack of gas units also shifts the trading behavior by requiring increased imports (+1.1 TWh), mostly in Winter, and therefore less exports (-1.6 TWh). This shift further exacerbates the concentration of the imports and exports into the months during which they are most critical. Additionally, for the first time, the need to shed load in Switzerland becomes significant with around 162 GWh shed across the Winter months.

The impact on the neighboring countries is even more significant with the Winter wholesale electricity prices in all countries increasing even more than they had in the restricted NTCs scenario.



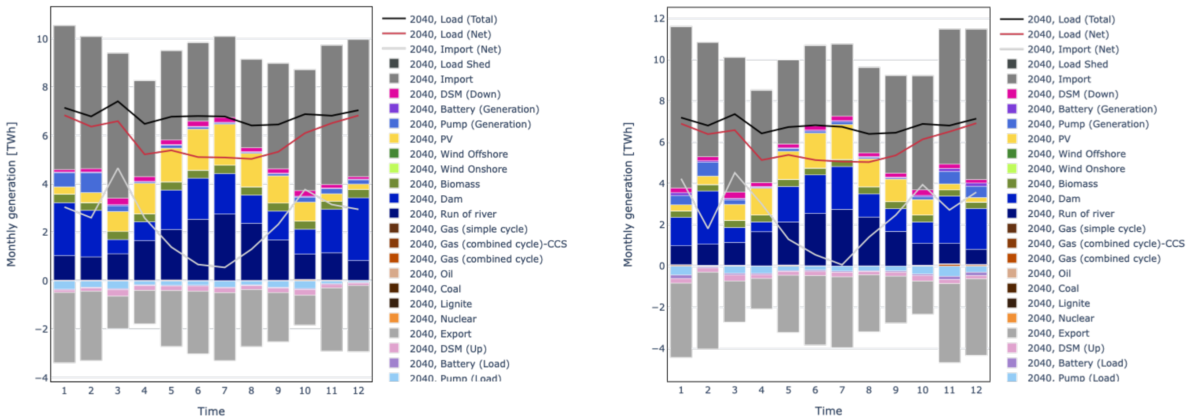
(a) Scenario s3: 2040 Reduced NTCs

(b) Scenario s15: 2040 No Gas

Figure 9: Restricting the use of any type of gas-fired generator in Switzerland while also restricting the NTCs leads to the most difficult solution for Switzerland so far. Almost all available potential capacities are built while imports and exports are heavily concentrated into the months of greatest need and still around 162 GWh of load shedding occurs.

4.6 Expanding transfer capacities: Baseline (s1) versus Expanded NTCs (s5)

Alternatively to the scenarios compared so far, expanding the ability for Switzerland to trade can be seen as a less restrictive scenario. Figure 10 illustrates the changes to the monthly production and imports/exports of the scenario with expanded NTCs (s5) compared to the Baseline scenario (s1)[5]. While the resulting values of the NTCs are between 2-5 times larger than the current NTCs (see Table 5 compared to Table 3), the actual imports and exports increase less substantially (imports increase by 8% to 64.1 TWh, +8.1 TWh; exports increase by 31% to 35.5 TWh, +8.4 TWh). The ability to rely more on trade from its neighbors results in Switzerland building a little less rooftop PV (-0.49 GW) but not making any other significant shifts to its generator investments nor utilization. These results indicate that the current Swiss NTCs are high enough to enable efficient use of the renewable resources in Switzerland and its neighboring countries.



(a) Scenario s1: 2040 Baseline

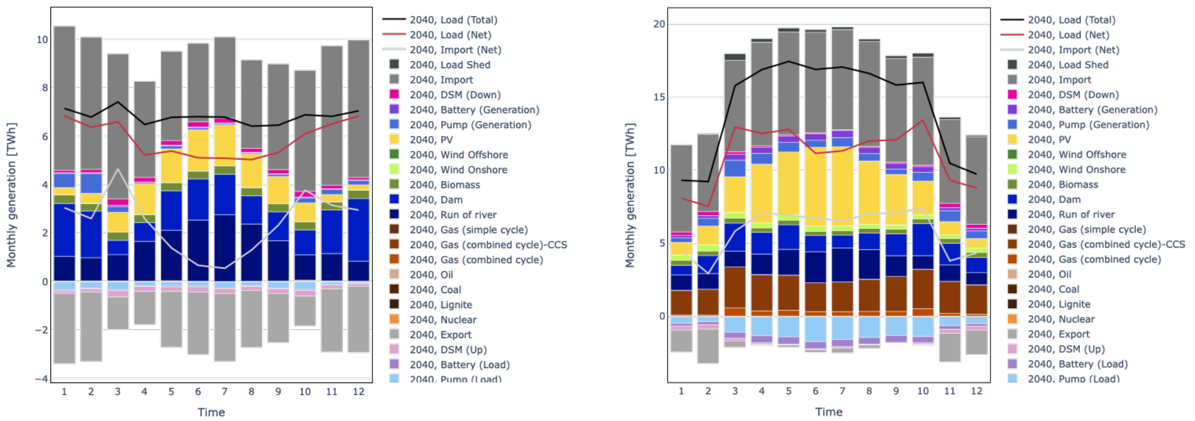
(b) Scenario s5: 2040 Expanded NTCs

Figure 10: Expanding the Swiss NTCs as part of the Euro-Calliope energy system optimization enables increases to both the Swiss imports and exports but only minor changes to the investments and operations of Swiss generators compared to the current NTCs.

[5]In all Expanded NTCs cases, the four Swiss cross-border NTCs are variables determined by the Euro-Calliope net-zero energy system optimization.

4.7 Requiring fuel autarky: Baseline (s1) versus Self-produced Gas (s7)

The final scenario comparison to make involves the requirement that Switzerland's energy system operate without any fuel imports (i.e., all fuels must be produced within Switzerland). This fuel autarky requirement applies to the full energy system including things such as aviation, industry, etc. Figure 11 illustrates the changes to the monthly production and imports/exports of the scenario with fuel autarky (s7) compared to the Baseline scenario (s1). It is immediately noticeable that the fuel autarky scenario is dramatically different than all other scenarios presented to this point. The requirement to self-produce all fuels (including any sythetic gas used in gas-fired power plants) results in more than doubling of the Swiss electricity demand, from 81.3 TWh to 170.7 TWh. With such a high demand to satisfy, nearly all potential electricity capacities are built in Switzerland, including all rooftop PV (36.2 GW), wind (2 GW), and biomass (0.5 GW), along with a large amount of the gas (7 GW) and BESS (2.7 GW). In addition to the added production from all these new capacities, the amount of imports needed increases substantially by around 41% to around 78.8 TWh while the amount of exports reduced substantially by around 67% to around 8.9 TWh. This results in the annual net imports increasing from 29 TWh in the Baseline scenario (s1) to 70 TWh in the self-produced gas scenario (s7). Even with the added production and huge shift to imports, the need to shed load also still increases from only 2.6 GWh in scenario (s1) to 2.2 TWh in scenario (s7) (i.e., an increase by over 850%).



(a) Scenario s1: 2040 Baseline

(b) Scenario s7: 2040 Fuel autarky

Figure 11: Requiring fuel autarky in Switzerland lead to a doubling of the electricity demand, an increase in all invested generating capacities, a substantial shift to import electricity, and still a major increase in the need to shed electricity load.

5 Conclusions

The Swiss Energy Strategy 2050 envisions a future Swiss power system that is characterized by the integration of high shares of renewables and distributed energy resources, the nuclear phase-out, the increase of energy efficiency, the interplay with the energy transitions in other European countries, and a consistent level of system security and resilience. Toward this goal, the aim of this work is to serve as a comprehensive, transparent, and credible analysis of the affordability and feasibility of Switzerland becoming decarbonized by 2040 within the wider European transition to decarbonize by 2050 while also considering other important policy concerns such as maintaining Swiss energy security and the impact of a lack of an agreement with the European Union on the operation of the Swiss electricity market. Within this project, the Euro-Calliope model provides insights about the overall transition of the European energy system to achieve the desired climate and environmental targets under a range of scenario assumptions. This overall assessment is followed up by a more detailed investigation, performed by Nexus-e, of how such a European transition would impact the development and operation of the electricity system in Switzerland.

The overall Swiss transition from 2020 to the Baseline 2040 scenario is characterized by a phase out of Swiss nuclear power and a high level of electrified mobility which therefore increases the total electricity demands by around 26%. These changes are met through consumer investments in rooftop PV and increased imports. Is it evident that, given the ability to import and export up to today's trade limits, the most economically efficient solution for Switzerland is to import more electricity, especially when the neighboring countries' electricity prices have been driven down by expansion of wind and solar. However, if Switzerland were to be faced with a restricted ability to trade power, a significant reduction in electricity imports and exports will be accompanied by a focus on expansion of domestic capacities, namely PV and gas-fired generators. The impacts of such a case would be felt beyond Switzerland since the ability to transit power through Switzerland would also be much more limited. Alternatively, increasing the ability to trade electricity beyond today's limits does enable increases to both Swiss imports and exports but leads to only minor changes to the investments and operations of Swiss generators. In contrast, a less strict requirement for balancing the annual electricity trade would yield similar trends but with less severe magnitudes. The decreased imports still yield increased domestic capacities, this time in the form of PV and wind; and the impacts on the neighboring countries would be more mildly felt. In the face of restricted NTCs, the decision to completely restrict gas-fired generators in Switzerland drives the need for other domestic production capacities, such as wind and BESS, along with even more seasonally concentrated imports and exports as well as a significant need to shed load in Winter. Finally, requiring fuel autarky for the Swiss energy system is clearly the most extreme scenario considered and leads to a doubling of the electricity demand, an increase in all invested generating capacities, a substantial shift to import electricity, and still a major need to shed electricity load in all months.

The combination of Euro-Calliope and Nexus-e provides a unique and powerful set of tools to investigate a wide range of impacts for possible future paths of the European and Swiss energy system. Within this work, Nexus-e provides a detailed assessment of the developments necessary for the existing Swiss electricity system when confronted by a specific European context.

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