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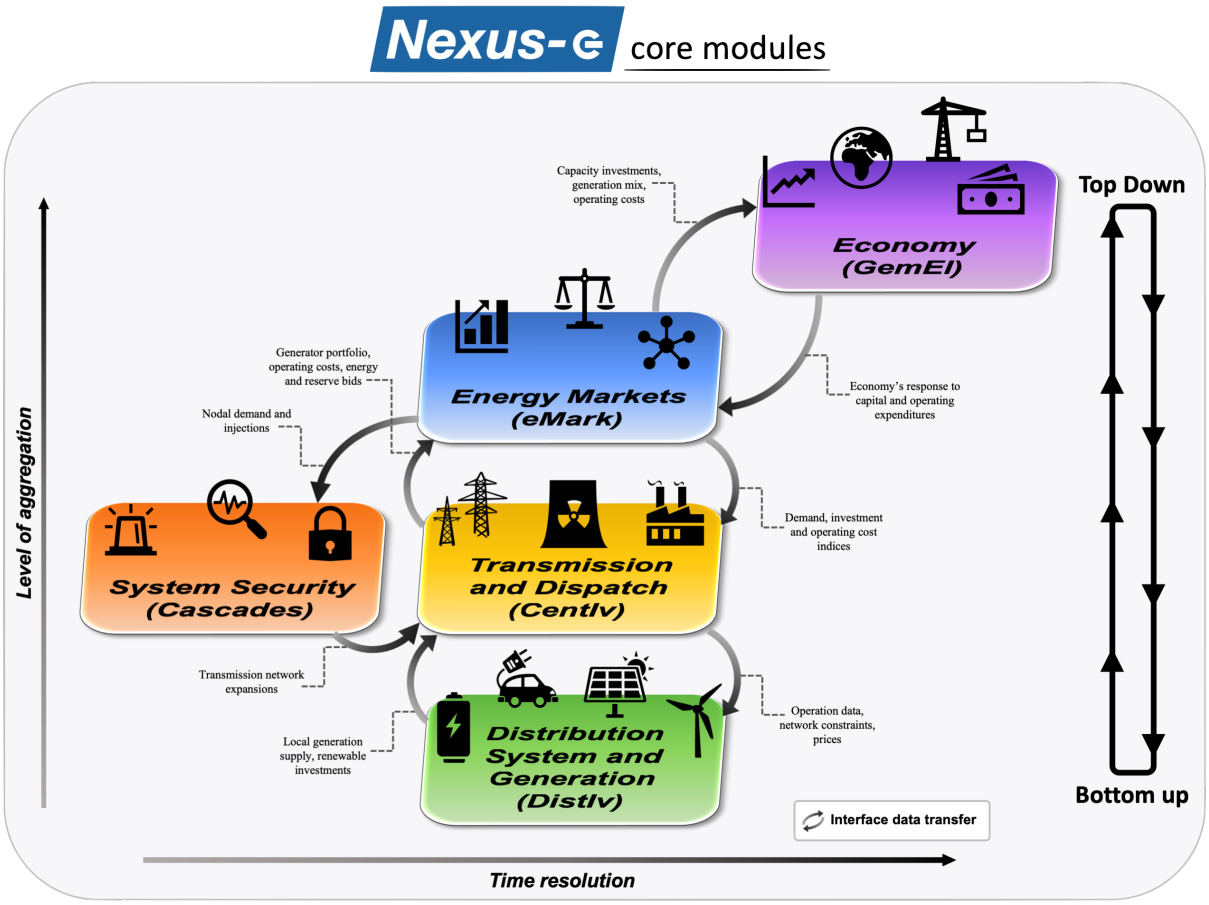
Final report

Nexus-e: Integrated Energy Systems Modeling Platform

Validation and Calibration of Modules



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Summary

Policy changes in the energy sector result in wide-ranging implications throughout the entire energy system and influence all sectors of the economy. Due partly to the high complexity of combining separate models, few attempts have been undertaken to model the interactions between the components of the energy-economic system. The Nexus-e Integrated Energy Systems Modeling Platform aims to fill this gap by providing an interdisciplinary framework of modules that are linked through well-defined interfaces to holistically analyze and understand the impacts of future developments in the energy system. This platform combines bottom-up and top-down energy modeling approaches to represent a much broader scope of the energy-economic system than traditional stand-alone modeling approaches.

In Phase 1 of this project, the objective is to develop a novel tool for the analysis of the Swiss electricity system. This study illustrates the capabilities of Nexus-e in answering the crucial questions of how centralized and distributed flexibility technologies could be deployed in the Swiss electricity system and how they would impact the traditional operation of the system. The aim of the analysis is not policy advice, as some critical developments like the European net-zero emissions goal are not yet included in the scenarios, but rather to illustrate the unique capabilities of the Nexus-e modeling framework. To answer these questions, consistent technical representations of a wide spectrum of current and novel energy supply, demand, and storage technologies are needed as well as a thorough economic evaluation of different investment incentives and the impact investments have on the wider economy. Moreover, these aspects need to be combined with modeling of the long- and short-term electricity market structures and electricity networks. This report illustrates the capabilities of the Nexus-e platform.

The Nexus-e Platform consists of five interlinked modules:

1. General Equilibrium Module for Electricity (GemEl): a computable general equilibrium (CGE) module of the Swiss economy,
2. Centralized Investments Module (CentIv): a grid-constrained generation expansion planning (GEP) module considering system flexibility requirements,
3. Distributed Investments Module (DistIv): a GEP module of distributed energy resources,
4. Electricity Market Module (eMark): a market-based dispatch module for determining generator production schedules and electricity market prices,
5. Network Security and Expansion Module (Cascades): a power system security assessment and transmission system expansion planning module.

This report describes the validation and calibration of the different modules within the Nexus-e framework. The objectives of the validation and the calibration of the Nexus-e modules is to develop trustworthy and high-fidelity modules as well as to adjust the modules to better represent the complexity of the involved real systems and processes.

Zusammenfassung

Politische Veränderungen im Energiesektor haben weitreichende Auswirkungen auf das gesamte Energiesystem und beeinflussen alle Sektoren der Wirtschaft. Aufgrund der hohen Komplexität der Energiewirtschaft, wurden bisher nur wenige Versuche unternommen, die Wechselwirkungen zwischen den einzelnen Komponenten dieses Systems zu modellieren. Nexus-e, eine Plattform für die Modellierung von integrierten Energiesystemen, schliesst diese Lücke und schafft einen interdisziplinäre Plattform, in welcher verschiedene Module über klar definierten Schnittstellen miteinander verbunden sind. Dadurch können die Auswirkungen zukünftiger Entwicklungen in der Energiewirtschaft ganzheitlicher analysiert und verstanden werden. Die Nexus-e Plattform ermöglicht die Kombination von „Bottom-Up“ und „Top-Down“ Energiemodellen und ermöglicht es dadurch, einen breiteren Bereich der Energiewirtschaft abzubilden als dies bei traditionellen Modellierungsansätzen der Fall ist.

Phase 1 dieses Projekts zielt darauf ab, ein neuartiges Instrument für die Analyse des schweizerischen Elektrizitätssystems zu entwickeln. Um die Möglichkeiten von Nexus-e zu veranschaulichen, untersuchen wir die Frage, wie zentrale und dezentrale Flexibilitätstechnologien im schweizerischen Elektrizitätssystem eingesetzt werden können und wie sie sich auf den traditionellen Betrieb des Energiesystems auswirken würden. Ziel der Analyse ist es nicht Empfehlungen für die Politik zu geben, da einige wichtige Entwicklungen wie das Europäische Netto-Null-Emissionsziel noch nicht in den Szenarien enthalten sind. Vielmehr möchten wir die einzigartigen Fähigkeiten der Modellierungsplattform Nexus-e vorstellen. Um diese Fragen zu beantworten, ist eine konsistente technische Darstellungen aktueller und neuartiger Energieversorgungs-, Nachfrage- und Speichertechnologien, sowie eine gründliche wirtschaftliche Bewertung der verschiedenen Investitionsanreize und der Auswirkungen der Investitionen auf die Gesamtwirtschaft erforderlich. Darüber hinaus müssen diese Aspekte mit der Modellierung der lang- und kurzfristigen Strommarktstrukturen und Stromnetze kombiniert werden. Dieser Report veranschaulicht die Fähigkeiten der Nexus-e Plattform.

Die Nexus-e Plattform besteht aus fünf miteinander verknüpften Modulen:

1. Allgemeines Gleichgewichtsmodul für Elektrizität (GemEl): ein Modul zur Darstellung des allgemeinen Gleichgewichts (CGE) der Schweizer Wirtschaft,
2. Investitionsmodul für zentrale Energiesysteme (CentIv): ein Modul zur Planung des netzgebundenen Erzeugungsausbaus (GEP) unter Berücksichtigung der Anforderungen an die Systemflexibilität,
3. Investitionsmodul für dezentrale Energiesysteme (DistIv): ein GEP-Modul für dezentrale Energieerzeugung,
4. Strommarktmodul (eMark): ein marktorientiertes Dispatch-Modul zur Bestimmung von Generator-Produktionsplänen und Strommarktpreisen,
5. Netzsicherheits- und Erweiterungsmodul (Cascades): ein Modul zur Bewertung der Sicherheit des Energiesystems und zur Planung der Erweiterung des Übertragungsnetzes.

Dieser Bericht beschreibt die Validierung und Kalibrierung der verschiedenen Module im Rahmen von Nexus-e. Das Ziel der Validierung und Kalibrierung ist es, vertrauenswürdige und originalgetreue Module zu entwickeln und diese so anzupassen, dass sie die Komplexität der beteiligten realen Systeme und Prozesse besser repräsentieren.

Résumé

Les changements de politique dans le secteur de l'énergie ont de vastes répercussions sur l'ensemble du système énergétique et influencent tous les secteurs de l'économie. En partie à cause de la grande complexité de la combinaison de modèles séparés, peu de tentatives ont été entreprises pour modéliser les interactions entre les composantes du système économico-énergétique. La plateforme de modélisation des systèmes énergétiques intégrés Nexus-e vise à combler cette lacune en fournissant un cadre interdisciplinaire de modules qui sont reliés par des interfaces bien définies pour analyser et comprendre de manière holistique l'impact des développements futurs du système énergétique. Cette plateforme combine des approches de modélisation énergétique ascendante et descendante pour représenter un champ d'application beaucoup plus large du système économico-énergétique que les approches de modélisation indépendantes traditionnelles.

Dans la phase 1 de ce projet, l'objectif est de développer un nouvel outil pour l'analyse du système électrique suisse. Cette étude sert à illustrer les capabilités de Nexus-e à répondre aux questions cruciales de comment les technologies de flexibilité centralisées et décentralisées pourraient être déployées dans le système électrique suisse et comment elles affecteraient le fonctionnement traditionnel du système. Le but de cette analyse n'est pas d'offrir de conseils politiques, en tant que les scénarios ne considèrent pas des développements critiques comme l'objectif Européen d'atteindre zéro émission nette, mais d'illustrer les capabilités uniques de la plateforme Nexus. Pour répondre à ces questions, des représentations techniques cohérentes d'un large éventail de technologies actuelles et nouvelles d'approvisionnement, de demande et de stockage d'énergie sont nécessaires, ainsi qu'une évaluation économique approfondie des différentes incitations à l'investissement et de l'impact des investissements sur l'économie au sens large. En outre, ces aspects doivent être combinés avec la modélisation des structures du marché de l'électricité et des réseaux d'électricité à long et à court terme. Ce rapport illustre les capacités de la plateforme Nexus-e.

La plateforme Nexus-e se compose de cinq modules interconnectés:

1. Module d'équilibre général pour l'électricité (GemEl) : un module d'équilibre général calculable (CGE) de l'économie suisse,
2. Module d'investissements centralisés (CentIv) : un module de planification de l'expansion de la production (GEP) soumise aux contraintes du réseau, qui tient compte des exigences de flexibilité du système,
3. Module d'investissements distribués (DistIv) : un module GEP de la production décentralisée d'énergie,
4. Module du marché de l'électricité (eMark) : un module de répartition basé sur le marché pour déterminer les calendriers de production des producteurs et les prix du marché de l'électricité,
5. Module de sécurité et d'expansion du réseau (Cascades) : un module d'évaluation de la sécurité du système électrique et de planification de l'expansion du système de transmission.

Ce rapport décrit la validation et la calibration des différents modules dans le cadre de Nexus-e. L'objectif de la validation et de la calibration des modules Nexus-e est de gagner en confiance dans les modules ainsi que d'ajuster les modules pour mieux représenter la complexité des systèmes et des processus réels concernés.

Contents

Abbreviations

AT	Austria
BaM	balancing market
BFE	Bundesamt für Energie
Cascades	Network Security and Expansion Module
CCDF	complementary cumulative distribution function
CentIv	Centralized Investments Module
CGE	computable general equilibrium
CH	Switzerland
CHP	combined heat and power
CO_2	carbon dioxide
DaM	day-ahead market
DE	Germany
DER	distributed energy resources
DistIv	Distributed Investments Module
DNS	demand not served
eMark	Electricity Market Module
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FB	flow-based
FR	France
FuM	future market
GemEl	General Equilibrium Module for Electricity
GEP	generation expansion planning
IOT-Energy	differentiated input–output table for the energy sector
IT	Italy
LMP	locational marginal price
MCP	market clearing price
MWh	megawatt hour
NERC	North American Electrical Reliability Council
NTC	net transfer capacity
PV	photovoltaic
RES	renewable energy source
RoR	run of river
TYNDP	ten-year network development plan
VOM	variable operation and maintenance
WECC	Western Electricity Coordinating Council

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1 Introduction

"All models are wrong, but some are useful" [1]. This statement implies that all scientific models are partial representations of reality, but they can still provide useful insights. In an effort to enhance the usefulness of such models, researchers/developers aim to perform validations or calibrations to gain confidence in the produced models. Model validation is defined as the “process of determining the degree to which a computer model is an accurate representation of the real world from the perspective of the intended model applications” [2]. Beyond such a validation, to improve the accuracy of a model toward achieving a better match with real world data, model calibration is “the process of adjusting physical modeling parameters in the computational model to improve agreement with experimental data" [3].

The objective of this report is to describe the validation and calibration of the different modules within the Nexus-e framework that were performed to test or improve their historical accuracy and gain confidence in how they represent the complexity of the involved real systems and processes (Figure 1 shows a schematic of the framework). The following two subsections provide a brief overview of each module and how they are validated or calibrated.

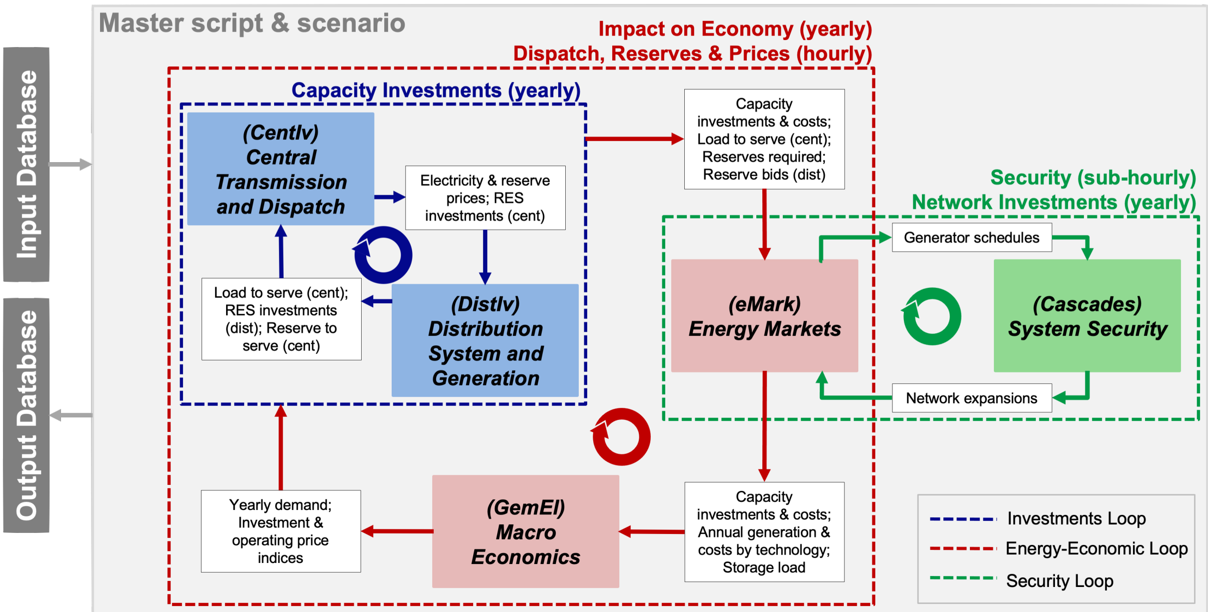


Figure 1: Overview of the Nexus-e framework including the five modules (colored boxes), the three ’loops’ (colored arrows), and the interfaces (white boxes). Note that for visualization purposes some of the interfaces are combined in the figure.

1.1 Modules description

The Nexus-e Platform consist of the following five interlinked modules (the module documentation reports provide detailed descriptions of each module):

General Equilibrium Module for Electricity (GemEl): The GemEl module is a detail-rich computable general equilibrium (CGE) model for Switzerland based on the most recent actual economic data available (i.e., 2014 Swiss energy-specific input-output table). The model simulates the markets for all goods and services produced and demanded. It can be used for almost any policy measure and especially for evaluating the efficiency and distributional effects of energy policy measures as well as new investments in new electricity generation. Analysis of distributional effects is possible because the model contains 14 active and retired household groups distinguished by income. The model can also keep track of emissions and the yearly produced and demanded electricity.

Centralized Investments Module (CentIv): The purpose of CentIv is to co-optimize generation investment and operational decisions on the transmission system level for a target year. The module is geared towards providing results with high temporal and spatial resolution from the perspective of a centralized decision maker. In its formulation, the module includes detailed dispatch, reserve and investment constraints for a wide range of flexibility providers and is tailored to give insight into how real-size power systems would evolve and cope with projected increase in intermittent renewable energy source (RES) generation.

Distributed Investments Module (DistIv): The Distributed Investments Module aims to jointly optimize the investments and operations of a distribution system to satisfy the demand and policy targets while minimizing total costs, considering potential trading of energy and reserve with the transmission system. The components considered in the distribution system include distributed energy resources such as storage units, demand response programs, variable and dispatchable generation units.

Electricity Market Module (eMark): The purpose of the eMark module is to simulate a market-based clearing of electricity and reserve supply offers and demand bids. This module is designed to mimic the actual sequential structures and timing currently employed to clear all electricity market products. Additionally, eMark is setup to apply realistic constraints for intra-zonal trading that reflect the current market coupling mechanisms. The module is structured to provide high temporal (hourly) resolution and moderate spatial (zonal) resolution equivalent to those of the existing market processes. eMark has the important role in the Nexus-e framework to provide a market-based perspective and enable assessments of future market structures.

Network Security and Expansion Module (Cascades): The purpose of the Cascades module is to: (1) assess the security of supply by testing the capability of a power system to withstand sudden changes and disruptions, i.e. due to component failures; and (2) to provide a transmission system expansion plan if a target level of security is not satisfied. The Cascades module comprises two models, i.e. a cascading failure simulations model and a transmission system expansion planning model.

1.2 Validation or calibration in each module

The need for validation or calibration in each of the modules is summarized by the following:

GemEl: GemEl is based on the 2014 Swiss energy-specific input-output table [4]. However, the top-down economic equilibrium in GemEl is affected by the changing infrastructure investments, generation mix, and associated costs in the electricity system in the future years. Therefore, GemEl performs a recalibration of the generation technologies and distribution sector to create a new starting point for electricity demand. While this process is a type of calibration, it is not a comparison to historical data and is already described in the GemEl module documentation report and the simulation framework report. Therefore, no section on validation or calibration of GemEl is provided as part of this report.

CentIv: Since CentIv co-optimizes operational and investment decisions, there is a need to calibrate the operation of existing storage units and conventional thermal generators with historical data to ensure good agreement since any discrepancies could impact future investments. Furthermore, as investment decisions could be influenced by the export/import behavior, it is also important to correctly reproduce cross-border trades. In the context of the project and the modeled power system, namely the detailed Swiss transmission system with aggregated surrounding countries, several parameters have been adjusted to achieve the desired calibration results for the year 2015.

DistIv: Results produced by DistIv describe what distributed generating units are optimal to be invested in from the economic perspective; yet these results can deviate from what has happened in reality. It is therefore important to validate the effectiveness of DistIv to predict these investments and to understand the deviations between the simulated results and the historical realizations over a common time period. Additionally, since the factors driving the photovoltaic (PV) investment decisions are unique in each region, it is useful to confirm the consistency of the regional results compared to the rationality behind these factors driving PV. This rationality check allows us to confirm if the PV investment decisions make sense fundamentally.

eMark: Similar to the CentIv module, calibrating the dispatch results from the market clearing processes in eMark against historical operations allows more confidence to be given to the eMark dispatch results for future scenarios. As part of this calibration, the following eMark results are compared with historical data: generator production in all zones, Swiss hydro storage levels, and imports and exports between market zones. To achieve agreement of these parameters, a calibration process is conducted that adjusts other modeling parameters such as: network reactances, hydro inflows, and generator costs.

Cascades: The performance of Cascades is assessed by comparing the simulation results against the historical blackout (demand not served (DNS)) data of a power system. This comparison provides an estimate of the capability of the algorithm to capture the overall behaviour of the system when single or multiple failures of transmission components occur. Moreover, we perform calibration to achieve a better agreement between the simulation and the historical data. The calibration of Cascades is performed by optimal selection of input parameters (i.e. line power ratings) using a meta-heuristic based optimization.

The remainder of this report is structured as follows: Section 2 describes the calibration of the CentIv and eMark modules using the 2015 detailed Swiss transmission system and representing surrounding countries in an aggregated way. These modules are calibrated within the same process because they both simulate the dispatch of all centralized generating units. Section 3 describes the validation of the DistIv module using the 2018 cost, electricity tariff and subsidies data. Section 4 gives an example of the Cascades module calibration using the Western Electricity Coordinating Council (WECC) power grid as a reference in the absence of specific national data, and describes the Cascades module adjustment needed for creating the reference risk curve of the 2015 Swiss power grid.

2 CentIv and eMark - Calibration of input parameters for matching historical results

In this section, we describe the process of calibrating CentIv and eMark and present simulation results for 2015. We selected 2015 as the reference year for this calibration to account for the trade-off between a recent year and a year close to the 2014 reference year of the differentiated input–output table for the energy sector (IOT-Energy) used in GemEl. As both CentIv and eMark perform least-cost dispatch and include the generation capacities at the transmission system level, we present their results together. However, their methodologies for optimizing the dispatch differ significantly - CentIv is a single simulation using perfect knowledge of the whole year while eMark mimics the existing market processes and separately clears each hour and market product (i.e. future market (FuM), balancing market (BaM), and day-ahead market (DaM)). Since the model parameters adjusted during the calibration process are used in both CentIv and eMark, the process of calibrating against historical data is carried out simultaneously to strike a balance in the accuracy of the two modules. Indeed, it is critical that both modules produce dispatch results that are realistic because any divergence from actual operational behavior has significant impact, i.e. in CentIv it can result in unrealistic future investments and in eMark it can diminish the applicability of dispatch-related results for future scenarios. The simulated region includes Switzerland (CH), Germany (DE), France (FR), Italy (IT), and Austria (AT); and while more emphasis is placed on the calibration of results for Switzerland, the results of the surrounding regions are also considered in this process. To achieve good agreement with historical data, we performed calibration on several input parameters and show the accuracy of the simulation results in terms of:

1. Swiss monthly generation per technology type,
2. Swiss monthly hydro reservoir levels,
3. Swiss annual exports and imports to each surrounding country,
4. Surrounding country annual generation per technology type.

The remainder of this calibration description is structured as follows: Section 2.1 introduces relevant modeling differences between CentIv and eMark that impact the trade-offs involved in the joint calibration. Section 2.2 describes the system setup and input data used for the simulation. Section 2.3 details the adjustments made to input data parameters for the calibration process. Section 2.4 presents historical versus simulated results. Section 2.5 discusses future improvements focused on the accuracy of both modules' predicted hourly wholesale electricity prices.

2.1 Relevant modeling differences between CentIv and eMark

Since this calibration process applies to both the CentIv and eMark modules, there will be trade-offs between improving the accuracy of one of the modules while worsening the accuracy of the other. A compromise is needed to find a balance between the two at which point the results of both are accurate compared to the historical to a desired extent. To reach this balance, the main modeling differences between CentIv and eMark, that create differences in their dispatch results and therefore in the calibration process, play a major role. These relevant modeling difference include:

Treatment of hydro: CentIv uses perfect knowledge of hydro inflows over the full year along with a single optimization for all hours of the year to capture the seasonal and daily operating patterns of hydro dams and pumps. eMark however does not account for future conditions, it instead uses heuristics to help 'aim' the operation of hydro dams to follow the expected seasonal pattern and to enable charging and discharging of hydro pumps during certain hours of each day (more details on these heuristics can be found in the eMark module documentation report).

Dispatch process: CentIv uses a nodal co-optimization of energy and reserves along with perfect knowledge of load, RES generation, and generator costs that results in more optimal use of generators (i.e. a lower cost dispatch) than the actual markets and utilities can achieve today. eMark follows the sequential clearing process of the FuM, BaM, and DaM that reflects the separation of these markets.

Transmission network: During the dispatch process, CentIv includes the branch limits of the full Swiss network while eMark only applies constraints between each connected market zone to mimic the net transfer capacity (NTC) or flow-based (FB) limits used in the actual market clearing process.

Time steps: In CentIv every second day of the year is simulated with hourly resolution (i.e. only half the year is simulated) while eMark models all hours of the year.

Scheduled maintenance of generators: CentIv takes into account the planned outages of nuclear reactors in Switzerland by setting each as offline during the appropriate weeks of the year while eMark does not[1].

These modeling differences cause CentIv and eMark to yield a range of contrasting dispatch results including: production from the Swiss generators, operating behaviors of hydro units, and import and export flows. In particular, the results from CentIv will be more optimal based on using perfect knowledge of input conditions over the full year. While the results from eMark will be less optimal but also split the demand and supply among the FuM, BaM, and DaM in a sequential process that mimics the current market clearing.

2.2 System setup and input data for 2015 simulation

The system simulated in this calibration process as well as in all future scenarios includes a detailed representation of Switzerland and an aggregated representation of the four neighboring countries (DE, FR, IT, and AT) as shown in Figure 2. A wide range of input data taken from various sources are used to simulate these regions, including the generator capacities and costs, transmission networks, and electricity loads.

While CentIv simulates the detailed Swiss transmission network with aggregated neighboring countries as shown in Fig. 2, conversely, eMark reduces the Swiss network into a single node because each market zone is represented by a single node[2]. Grid data for representing the 2015 network were obtained from Swissgrid [5] and the European Network of Transmission System Operators for Electricity (ENTSO-E) [6, 7]. The fully detailed ENTSO-E network data were reduced to the aggregate form using a sophisticated network reduction method developed for use in both the CentIv and eMark modules of this project [8]. In the resulting reduced representation, all Swiss cross-border lines going to a surrounding country connect to a single border node which further connects to the main node of that country through an aggregated line. The surrounding countries are also connected to each other with a single aggregated line. The generator capacities of each surrounding country are placed at the main country node (not at the border node). All network parameters are modeled as described in Section 2.3 with the exception of the line limits of the aggregated lines connecting Switzerland and the surrounding countries (highlighted in Fig. 2), which are set to transfer capacity values that reflect the market-based limits (i.e NTC or FB limit). Analogously, the aggregated lines connecting the surrounding countries to one another are set to limit values that reflect the market-based transfer capacities. Data for these market-based transfer limits were taken from Swissgrid [9] and the ENTSO-E Transparency Platform [10]. In total the network model comprises 263 transmission lines, 162 nodes, and 21 transformers.

[1] Implementation of nuclear outages in eMark is a planned addition but was not yet included in this work because the scenario analysis phases-out the Swiss nuclear capacity

[2] The network reduction process used is described in more detail in the eMark module documentation report.

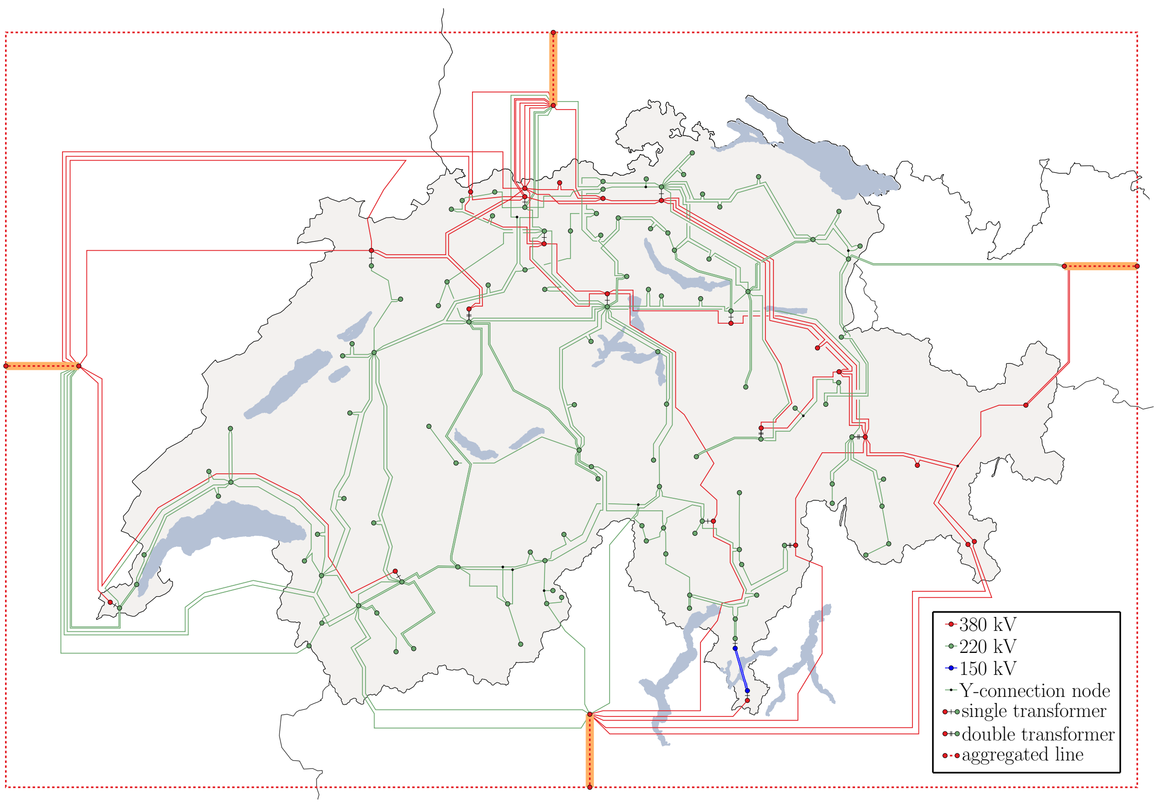


Figure 2: Overview of the 2015 transmission system modeled.

Swiss generator capacities and locations were taken from sources such as Bundesamt für Energie (BFE) [11, 12, 13, 14] as well as previous studies [15]. The generators in the surrounding countries are aggregated to one unit per technology type using data from ENTSO-E [16]. The total generation capacity per country in 2015 along with the number of generating units modeled and an indication of whether the generators are modeled in detail or in aggregate form are shown in Table 1. Generator cost data are taken from recent BFE sponsored studies [17, 18] and other European studies [19, 20]. The hourly load data and reserve requirements for Switzerland are taken from Swissgrid [21, 22] while the load data for the neighboring countries are from ENTSO-E [23]. The cross-border flows between the modeled surrounding countries and all other European Union (EU) countries which are not currently modeled but connected to those that are modeled (e.g. DE-DK, DE-PL, etc.) are fixed to the hourly values from ENTSO-E [24]. Production profiles for existing PV and wind generators are derived from previous works [15] that included detailed assessments of these RES potentials and generation profiles (this includes profiles for Switzerland and the other regions). The seasonal storage levels for 2015 and additional data needed to derive the hydro inflows have been obtained from BFE [25, 26].

Table 1: Cumulative generator capacities, number of generators, and detail indicator per country (2015)

Country	Detail	Number of gens.	Capacity [GW]
Austria (AT)	✗	9	22
Germany (DE)	✗	12	187
France (FR)	✗	11	110
Italy (IT)	✗	10	122
Switzerland (CH)	✓	313	19

2.3 Calibration of input parameters

Because the models employed in the CentIv and eMark modules use a range of simplifications and assumptions, we do not expect their results to match exactly with reality. But to help overcome the modeling limitations and assumptions, we can adjust or calibrate some of the input data and assumptions to improve the accuracy of these models. In this work, relevant input parameters are adjusted, often using an iterative process, to improve the accuracy of the model results for the reference 2015 historical year. It is important to note that the calibration steps detailed below are not taken individually. Since several of these steps have competing influences on the dispatch results, they are considered simultaneously along with the relevant parameters to achieve a desired adherence to reality. The input parameters adjusted include:

- Branch reactances of aggregated lines within neighbouring countries
- Hydro dam and pump inflows
- Capacity factors for nuclear and biomass generators
- Power flows from DE, FR, IT, and AT to other EU countries
- Generator variable operation and maintenance (VOM) costs

The most extensive calibration process involves the setup of the fully detailed Swissgrid data with an aggregated representation of the neighboring countries and adjusting the branch reactances of all aggregate non-Swiss lines (see Figure 2 for an illustration of the modeled 2015 transmission network). No modification of the Swiss transmission network parameters is necessary since we represent all these branches in detail and know their physical data from Swissgrid (2015 data [5] and 2025 data [27, 28]). However, since we aggregate the surrounding regions' networks to have single connections between countries, it is necessary to create aggregate physical parameters that allow accurate representation of how power injections split and flow between the countries. To achieve this objective, the most critical network parameter is the branch reactance because it directly influences how power flows split going into and out of a node. Therefore, the reactance values assigned to the non-CH aggregate branches have a direct affect on how the injections into non-CH aggregate nodes split among the different cross-border connections (i.e. how flows move around or through Switzerland). The other important branch parameter is the thermal flow limit, but it is sufficient to set the aggregate flow limit equal to the sum of the flow limits for all branches connecting two countries. To set the aggregate line reactances and flow limits, we use the fully detailed transmission grid data for Europe that is available on request from the ENTSO-E [6, 7]. These data are processed using a network reduction method [8] developed as part of Nexus-e that uses nonlinear optimization to determine the branch reactances and flow limits for the aggregate lines that achieve matching cross-border power flows compared to the fully detailed network. This network reduction method represents an advancement to current published methods and a significantly more robust way of creating a reduced order network model than what is used in similar projects with dispatch simulations. The resulting aggregate line parameters are then appended onto the detailed Swissgrid data for additional testing. Lastly, the aggregate line reactances are fine tuned to improve the observed trends in cross-border flows. The fine tuning is necessary because the ENTSO-E data used in the network reduction process inevitably contain errors, they include the planned network extensions for all regions' ten-year network development plan (TYNDP) (i.e. branches that did not exist in 2015), and only the detailed network of the 5 modeled countries is used as input to the network reduction (i.e. the reduction process ignored the impacts of flows to other EU countries). After the fine tuning, the annual imports and exports between the five modeled countries represent reasonably well with the historical 2015 data, giving us confidence in the way our modeled power flows split and move around and through Switzerland.

Another step in the calibration process involves adjusting the originally derived hydro inflow profiles to better reflect the known annual production totals of different hydro types and different countries. One original hourly inflow profile is derived from the known monthly production [25] and weekly storage levels [26] of the Swiss hydro storage units (dams and pumps); a second original profile is derived using the known monthly production of Swiss hydro run of river (RoR) units. Based on the Swiss hydro generator capacities and using the available capacitor factors of each of the power plants, these profiles are scaled and applied to each hydro dam/pump and RoR unit in Switzerland as well as the aggregate units in the surrounding countries. After initial simulations, it was clear that these original profiles did not yield correct annual production from the non-Swiss hydro units; so, separate profiles are created for the surrounding country dams/pumps and RoR units to correctly reflect the expected annual production while maintaining the same hourly profile patterns of the original Swiss profiles. Additionally, it was evident that applying the same inflow profile to pumps and dams yielded only minimal use of pumping for charging (i.e., the natural water inflows to dams were too high so little pumping was necessary); so, the Swiss and other regions' pump profiles are scaled down so the magnitudes of the discharging and charging from pump units reflect the historical data for each region closely.

A third step in the calibration process adjusts the capacity factors for some nuclear and biomass units to better reflect their known annual production totals. Initial results show overproduction from several non-Swiss conventional generators, namely DE and FR nuclear and DE and IT biomass. Since the aggregated modeling of these units does not capture the complexity of their operating characteristics, i.e. varying range of operating costs, maintenance outages, heating demands for combined heat and power (CHP) units, waste disposal of waste incineration units, etc., we adjust the load factor of these units appropriately. To achieve agreement with the annual production totals for these aggregate units, we applied capacity factors to reduce their available capacity over the full year (for Nuclear: DE=83% & FR=85%; for Biomass: DE=65% & IT=50%).

A fourth factor in the calibration process accounts for the omission of connections and power flows to other EU countries. Since the system we model only includes CH, DE, FR, IT, and AT the amount of power generated in these countries but transmitted to other EU markets is not accounted for and therefore, our simulation would have extra unused capacities that can unrealistically be used to supply within the regions simulated. To help prevent this excessive generation capacity within the 5 countries modeled, we adjust the hourly load profiles of the non-Swiss countries to include the hourly net exports to all other connected regions (exports are added to the load and imports are subtracted from the load). Data for the hourly intra-zonal power flows are gathered from ENTSO-E for 2015 [24] for the following connections: AT-CZ, AT-HU, AT-SL, DE-CZ, DE-DK, DE-LU, DE-NL, DE-PL, DE-SE, FR-BE, FR-GB, FR-ES, IT-SL.

The last parameter adjusted to calibrate the 2015 simulation is the generator VOM cost. Since our modeling methodology uses aggregated generators in non-Swiss regions and also constant variable costs for these aggregate units, we do not capture the aforementioned full range of generator operating characteristics and costs. To help overcome this limitation and better reflect the correct amount of injection from these aggregate units and their cost, we iteratively adjust the VOM portion of these generator's operating costs. This process is closely linked to the adjustment of network reactances because both impact the injections and splitting of power flows around and through Switzerland. On one hand, we adjust the VOM costs to achieve reasonable annual average market prices for each country (as discussed in Section 2.5) and on the other hand, we ensure that the overall pattern of imports and exports between countries match the historical trends.

2.4 Results for year 2015

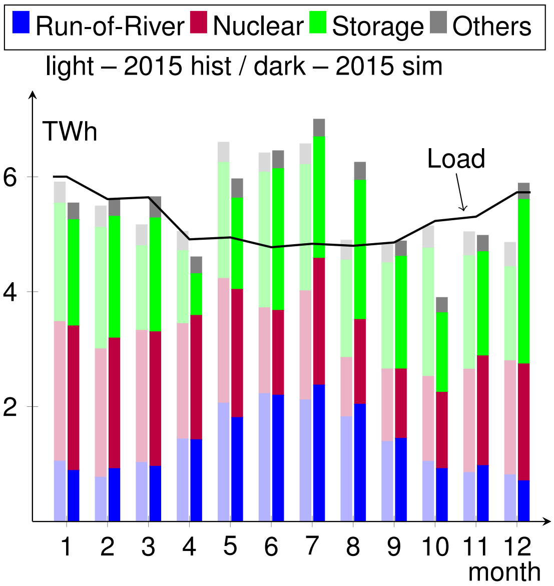
Many simulations are performed during the process of adjusting the calibration parameters described in Section 2.3 and throughout those simulations a number of output results are compared against the historical data. These outputs are selected based on the desire to achieve realistic representations of these results and therefore, have confidence in the ability of our models to accurately predict how these outputs change in future scenarios. Additional results could be used for comparison in the general calibration process considering the objective of the analysis and the preference of the assessor. The following results are selected for this project based on their importance to the objectives of the analysis:

- Swiss monthly generation per technology type,
- Swiss monthly hydro reservoir levels,
- Swiss annual exports and imports to each surrounding country,
- Surrounding country annual generation per technology type.

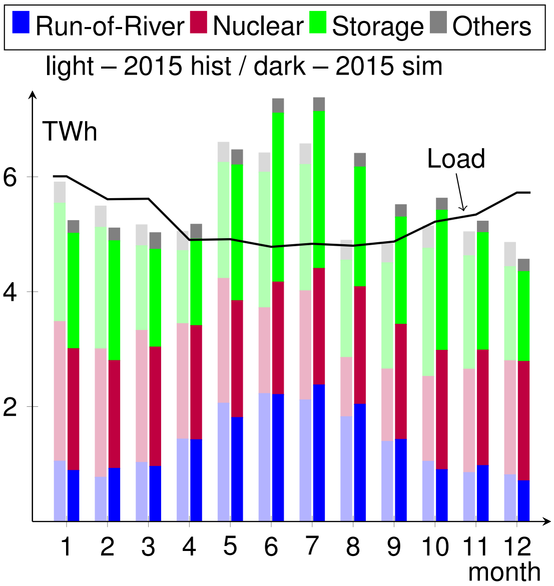
Sections 2.4.1- 2.4.3 present the comparison of the model output results using the calibrated versions of the input parameters. Results are presented for both CentIv and eMark along with the historical data to illustrate the achieved level of accuracy of these two modules. The CentIv results are based on a simulation of every second day while the eMark results are based on a simulation of every day.

2.4.1 Swiss generation and hydro storage levels

Figure 3 compares the 2015 monthly simulated production by technology type in Switzerland to the historical values taken from BFE [29]. The results from both CentIv and eMark show quite good agreement with the historical production amounts. The most notable difference in CentIv is the generation from hydro storage units in August, October and December. In this simulation, there is less production from hydro storage units in the months: April-May and October; but more production in August and December. In the eMark results the largest difference is in the production from nuclear. This difference comes from neglecting the significant 2015 nuclear refueling outages in June, August, September, and October. The other noticeable difference in eMark is overproduction from hydro storage units in June and July, which is a result of greater use of pump units in these months based on their operational heuristics employed in eMark.



(a) CentIv



(b) eMark

Figure 3: Monthly historical vs. simulated production per technology type in Switzerland (2015).

Figure 4 compares the 2015 simulated monthly reservoir levels in Switzerland (both the dam and the combined dam+pump) to the historical levels (only dam+pump) taken from BFE [26]. Since the purpose of comparing against the 2015 trend is to match the seasonal behavior of storage units, more emphasis is placed on the operating behavior of dam units, which tend to operate seasonally, instead of pump units, which tend to operate on shorter daily cycles. However, there is no historical data available that separate storage levels or production amounts from these two hydro technology types. So, while we desire the simulated storage level profile of all the dams in Switzerland to follow a seasonal pattern, we do not expect it to exactly match the historical trend shown since pump units are also included in these data. In these profiles, the slope of the lines indicate if the hydro units are discharging more than historically (steeper downward trend or less steep upward trend) or if they are discharging less than historically (less steep downward trend or steeper upward trend). Again, both the CentIv and eMark results follow an agreeable seasonal trend compared to the historical levels. The CentIv results confirm the main difference already mentioned: less production from hydro storage units in April-May and October but more production in August and December. Historically, the dispatch of the storage units is more evenly distributed. An explanation of this difference is that the CentIv simulation has perfect foresight about demand, inflows and renewable production, which power plant operators do not; therefore, they enter long-term contracts to hedge their production while storing or producing significantly more in any particular month would expose the hydro operators to greater risks. The eMark results illustrate a closer agreement between the simulated dam operation and the historical trend. This agreement is evident from the matching direction of the slopes in each month. This result is caused by the way in which eMark treats the hydro dams. Instead of using perfect foresight and optimizing the whole year as in CentIv, eMark uses the historical monthly end levels to set fixed monthly targets for the percent of maximum storage level of each dam unit. Therefore, the simulated levels of the dams reach the same percentage full/empty conditions as the historical levels[3].

[3]If the hydro levels in Figure 4 were shown in % instead of TWh, the eMark 'Sim (dam)' profile would exactly match the 'Hist (all)' profile.

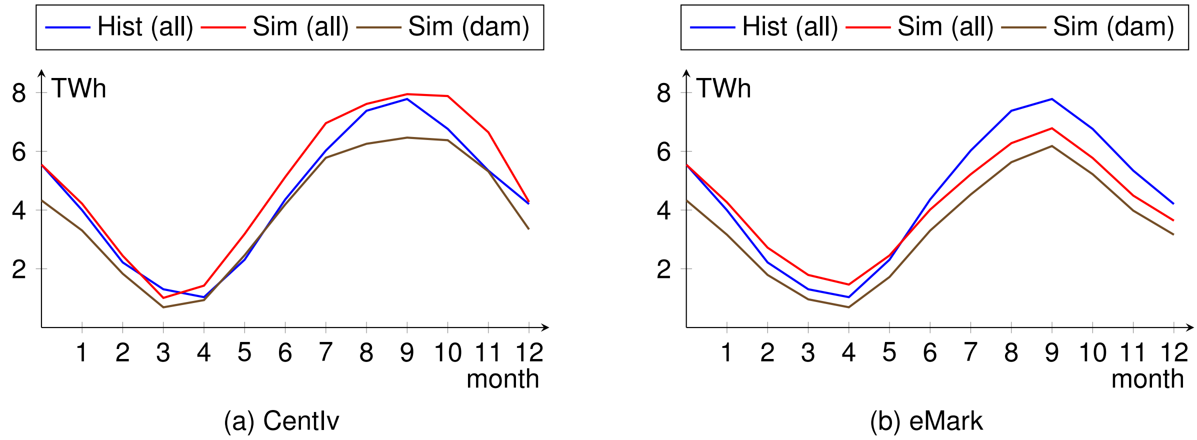


Figure 4: Monthly historical vs. simulated hydro storage levels in Switzerland (2015).

2.4.2 Swiss exports and imports

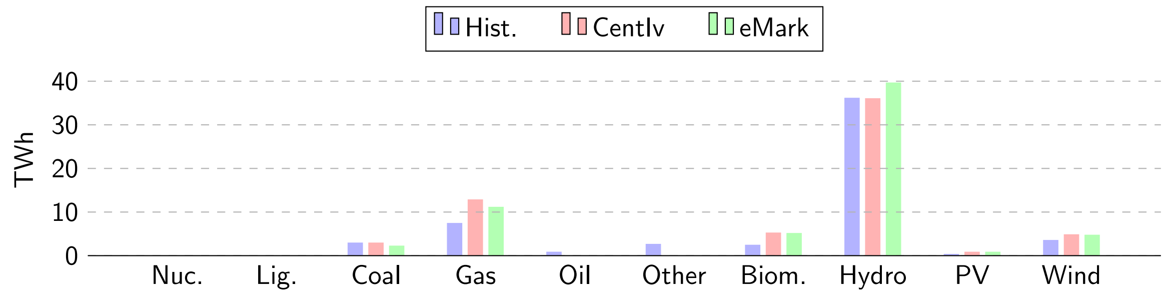
Table 2 summarizes the annual electricity imports and exports between Switzerland and the surrounding countries.Both the CentIv and eMark modules are able to capture the most important trend, namely that Switzerland is a transit country for flows from Germany, France and Austria to Italy. Possible reasons for the deviations in the magnitudes of net cross-border exchanges include: the generators and transmission system of the surrounding countries are modeled in aggregate and the assumed variable operating costs are static relative to the actual ranges of operating costs. Additionally, regarding the grid topology, all Swiss cross-border lines go to a single node within the neighboring country, as indicated in Figure 2. This means that in each hour flow across each cross-border connection can only be in a single direction, which is not the case in reality.

Table 2: Annual cross-border exchange between Switzerland and surrounding countries in TWh (2015)

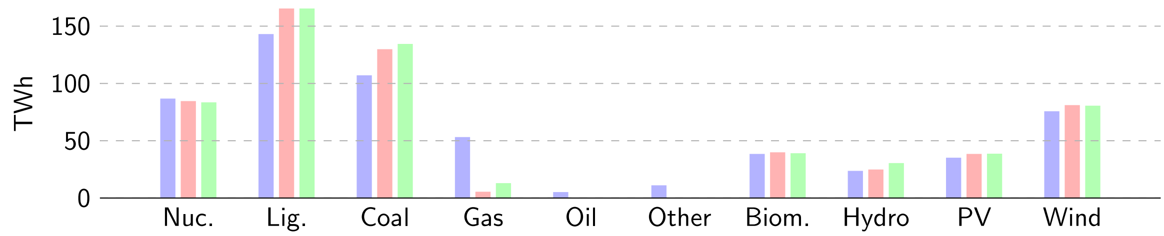
From - To	Hist	CentIv	eMark
AT - CH	7.04	5.04	5.72
CH - AT	0.24	0.12	0.02
AT - CH (Net)	6.80	4.92	5.70
DE - CH	16.01	17.88	17.96
CH - DE	3.02	8.84	4.85
DE - CH (Net)	12.99	9.04	13.11
FR - CH	9.61	8.99	7.54
CH - FR	4.34	4.67	3.79
FR - CH (Net)	5.27	4.32	3.75
IT - CH	0.83	1.07	0.32
CH - IT	26.21	22.02	26.42
CH - IT (Net)	25.38	20.95	26.10

2.4.3 Annual generation in surrounding countries

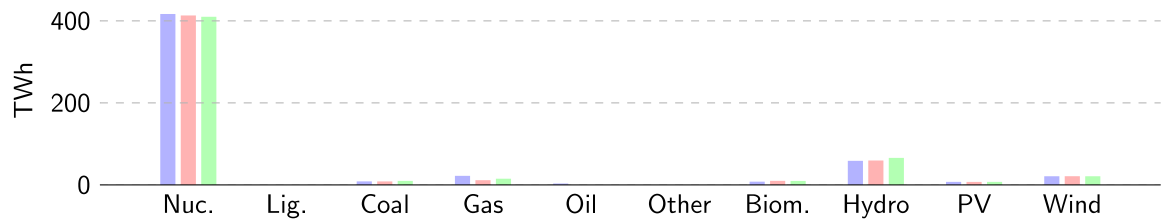
Figure 5 compares the CentIv and eMark simulated annual electricity production per technology type in the surrounding countries compared to the historical values provided by ENTSO-E [16]. Considering the large degree of aggregation applied for modeling the surrounding countries, the simulation results match the historical production values well. The most significant differences in the simulated values occur in DE and IT.



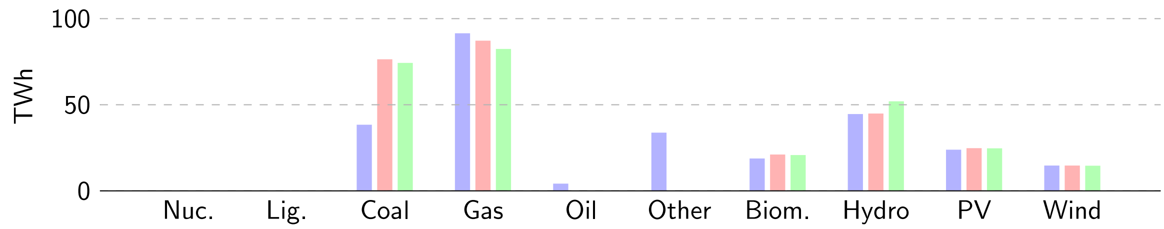
(a) AT



(b) DE



(c) FR



(d) IT

Figure 5: Annual generation by technology type in the surrounding countries (2015).

In both CentIv and eMark, there is overproduction from coal and lignite and underproduction from gas units in DE. Since we model the existing total capacities per technology type as a single aggregated unit and do not consider any planned or unplanned downtime, the availability of both coal and lignite throughout the year is overestimated[4]. Additionally, we model the aggregate units with a single constant operating cost, but in reality these units will have a wider range of operating costs from one unit to another as well as for a single unit operating at different points in its operating range. So, while in reality the possible ranges of costs for these generator types likely overlap to certain degrees, in our model the lignite and coal technologies are always considerably cheaper than gas and, therefore, they get dispatched more often. Additionally, a significant portion of the German production from gas comes from gas-fired CHP plants that provide heat for district heating, industry, and other purposes. In these generators, power is sometimes the secondary product and we do not model these complex operating behaviors.

In Italy, production from coal in both CentIv and eMark is overestimated while the production from the 'other' category is underestimated. Historically, the notable generation share coming from the 'other' sources refers to mixed fuels. However, in our input data these capacities are categorized as coal. After combining the coal and 'other' categories, the CentIv and eMark module results match the Italian historical production mix well.

2.5 Comments on accuracy of electricity prices

Overall, the presented calibration results reflect the historical values well and give confidence in the developed models. However, there is still room for improvement. In particular, additional calibration and modeling enhancements could enable both CentIv and eMark to better represent the hourly, daily, seasonal and annual trends of electricity prices. Currently, the completed calibration of input parameters did include efforts to achieve reasonable annual average prices for each zone. Figure 6 compares the simulated and historical average 2015 electricity prices in the five modeled countries.

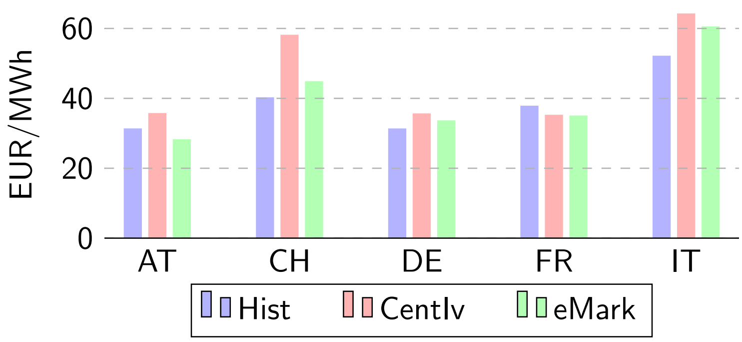


Figure 6: Comparison of the annual average 2015 electricity price in the five modeled countries.

It is evident from these results that both CentIv and eMark in general compare well to the historical average prices. The notable higher prices in CentIv for Switzerland are from the inclusion of the fully detailed Swiss network and use of locational marginal prices (LMPs). This nodal dispatch process is used by other electricity markets around the world, but not by those in Europe. By averaging the LMPs, CentIv includes influences from grid congestion on the average Swiss price which leads to a higher value. Remarkably, the simulated prices not only match well with the historical values for each country but also that the relative values between countries show similar trends as the historical prices (i.e. Italy

[4]While we could have implemented availability reductions using capacity factors, like we did with nuclear and biomass units in DE, we did not include such a measure since the modeled German prices were already higher on average than the historical prices and because the focus within this analysis is Switzerland.

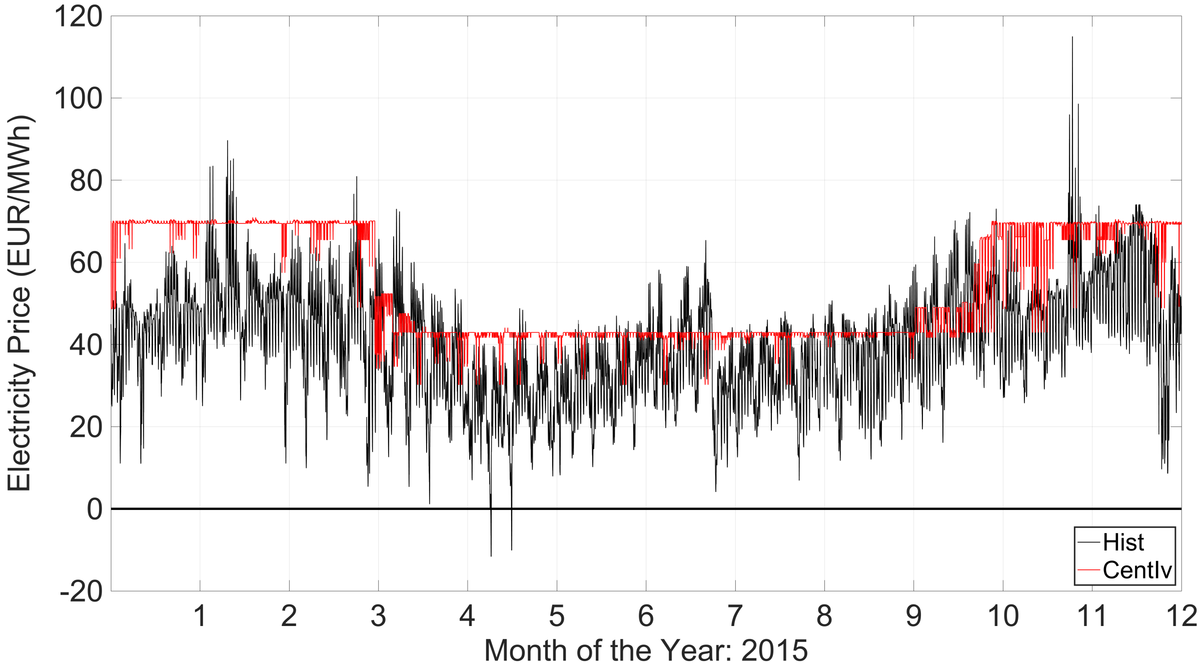
is highest followed by Switzerland and France, then Germany and Austria).

While the simulated annual average prices are relatively accurate, the hourly prices do not recreate the dynamic range of prices from the actual energy market clearing. Figure 7 illustrates the hourly prices for the 2015 Swiss DaM clearing along with the CentIv hourly Swiss prices and the eMark hourly Swiss DaM prices.

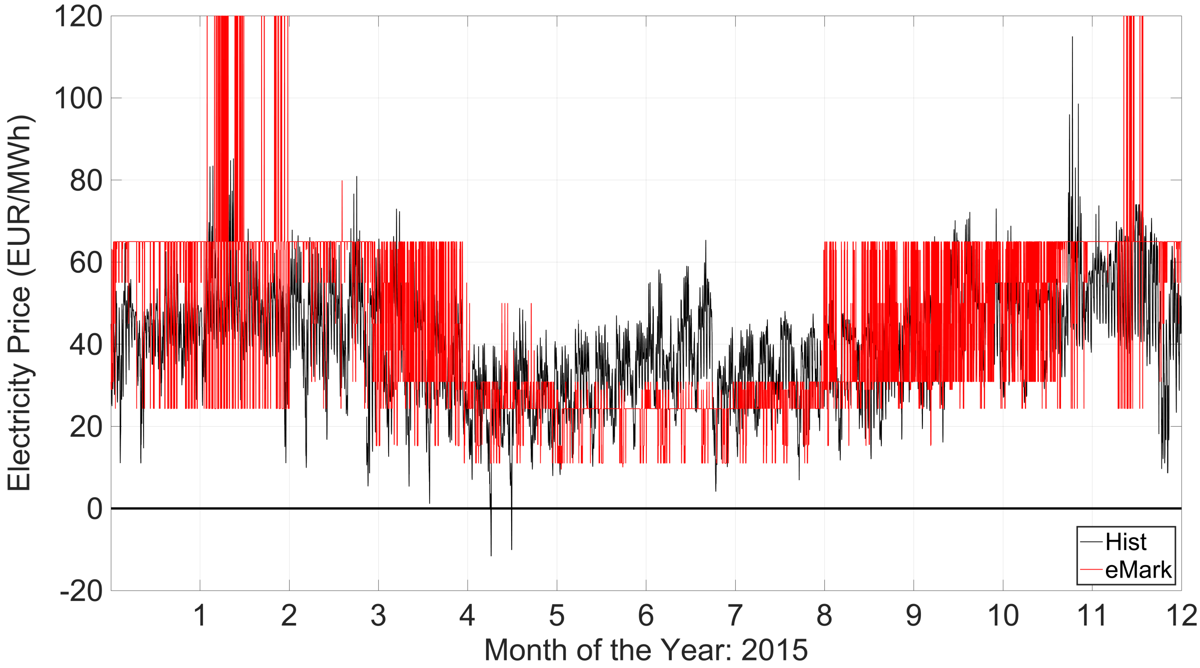
While it is common in dispatch modeling that the dynamic range of the predicted wholesale energy prices is almost always flat compared to the actual dynamic range in real markets, there are several improvements that could be made to improve the hourly prices in CentIv and eMark. In particular, the assumption of aggregate generators with constant variable operating costs could be changed. As modeled now, some of these aggregate units tend to be the marginal units for the system (i.e. the last ones that are selected by the market clearing process for supplying the power demand) and, therefore, set the wholesale price for one or more countries. In , such an aggregate unit is made up of many individual generators that were built in different years, located in different regions, and owned by different operators. Because of these and other factors, the many units that make up one of our aggregated generators actually have a wide range of operating costs. Additionally, each unit also has a variable marginal operating cost and not a constant average operating cost. This difference means that the modeled aggregated units cost the same when generating at max capacity or minimum capacity, but in reality each individual unit will have a minimum cost per megawatt hour (MWh) when operating at maximum capacity and a non-linearly increasing marginal cost at lower operating levels. Combined, these factors significantly alter the dynamic range of our predicted prices.

Several changes could be made to the modeling methodology to improve these issues, including:

- Utilizing a constant marginal operating cost instead of a constant average operating cost. This change would maintain linearity of the optimization while incorporating the reduced generator efficiency incurred when operating at levels below its maximum capacity.
- Separating the single aggregated unit for each technology type into several aggregated units. This process could be done based on appropriate subcategories of each technology type (such as E-class or F-class combined-cycle gas turbines). This process could also be done based on separating each surrounding country into multiple zones instead of a single area.
- Including additional factors to the wholesale price that represent scarcity conditions and the strategic behavior that leads to higher than normal market clearing prices (MCPs) (typically referred to as scarcity prices). Scarcity prices are important in energy-only markets because they provide additional revenue that helps generators recover their investment costs.



(a) CentIv



(b) eMark

Figure 7: Comparison of the historical hourly 2015 Swiss electricity prices with the CentIv and eMark predicted prices.

3 DistIv - Validation and rationality check

In this section we present the results of validating and evaluating the functionality of DistIv using 2018 as the reference year. The demand profile and the hourly wholesale prices are based on the results of CentIv for 2015. Costs of modeled technologies except batteries are based on 2018 data given in [18], while grid-battery and PV-battery are modeled based on the Telsa Powerpack and Powerwall 2. Investment subsidies are based on BFE regulations for 2018 [30]. Irradiation data for PV units are from MeteoSwiss [31] and PV potentials are based on the Sonnendach data [32] and the assumption that the area required for 1 kWp of PV is 6 square-meters. Injection and network tariffs are based on data provided by ElCom [33] and BFE [34] for 2018, respectively. For this module, the simplifying assumptions used and the numerous non-economic factors that are not considered in the methodology, which will be discussed in more detail, limit our ability to calibrate toward achieving historically accurate investments results. Alternatively, the aim is to verify the effectiveness of the model and to understand the reasons for the deviations between the simulated results and the historical realizations for the same simulation period. To accomplish this task, Section 3.1 presents a validation of the DistIv results compared to the historical data and Section 3.2 discusses the consistency of the regional results compared to the rationality behind the driving factors influencing PV investments in each region.

3.1 Validation with historical investments in 2018

Table 3 lists the invested capacities of all distributed technologies in 2018 for both the simulated system and the historical data [35][36]. Note that the historical data is collected based on the list of PV units that were commissioned in 2018 and received either the output-based (KEV) or investment subsidy. It is unknown how many other requests were made but not granted for these subsidies and out of those how many were still commissioned in 2018. The simulation results show investments in large-scale PV, suggesting that only the larger sized PV units (especially PV units greater than 100 kWp) are profitable and warrant investment; while historical investments are relatively evenly distributed among the various PV categorizes.

Table 3: Simulated and historical investments of different technologies for 2018 in MW or MWh.

Category	PV 0-10 kWp	PV 10-30 kWp	PV 30-100 kWp	PV >100 kWp	Biomass wood	Biomass manure	CHP	Grid battery	PV-battery
Historical	20.4	32.3	12.4	35.8	n/a	n/a	n/a	n/a	n/a
Simulated	0	0	0.5	799.2	0	0	0	0	0

The simulation results deviate from the historical values as a result of the assumptions of the DistIv module, including:

1. A green-field investment is modeled, i.e. no existing units are considered in the distribution system;
2. Only financial factors are considered in the objective function, which cannot fully capture the intentions of individual investors to invest in distributed energy resources;
3. Financial parameters are simplified as fixed numbers and cannot reflect the trade-offs faced by different groups of investors;
4. Highly aggregated input data is used, e.g. cost data is assumed to be no different across different regions in Switzerland;
5. Distributed energy resources (DER) are assumed to be commissioned once they are invested, while in reality investments in general take place a few years before the commissioning and decisions are made under uncertainties;
6. Only investment subsidies are modeled, i.e. output-based subsidies (Kostendeckende Einspeisevergütung) are not considered. This omission is because in the current policy output-based

subsidies will not be continued after 2020, and due to the long waiting list only PV units registered before 30.06.2012 could possibly receive the output-based subsidies and new registrations are hardly possible [37].

In addition to the fact that only financial aspects are considered in the simulated objective function, one of the main reasons for the model's deviation from the historical data is that financial parameters such as weighted average cost of capital and payback periods are simplified as a constant value for all modeled PV categories, which is likely not the case in reality. In fact, different potential investors, from individual homeowners to larger industrial operators, might have different needs regarding their desired payback period as well as different considerations about financing an investment in PV including the amount of debt they take on and the interest rate set by their lender. Additionally, the constant assumptions ignore that some investors have non-economic desires, such as early adopters and innovators who might be driven by environmental issues versus laggards and late majority who might have a high risk aversion. Moreover, it can be observed that the total simulated PV investment capacity (i.e. 799.7 MWp) is much higher than the historical value (i.e. 100.9 MWp), which could be explained by 1) the model assumption that all investor decisions are rational and occur immediately when the economics are attractive enough. In reality, people do not always behave rationally and may not even be considering such an investment even though it makes sound economic sense for them; 2) historical values shown are based on the list of PV units that registered and received the subsidies, i.e. units on the waiting list or those that did not register for subsidies are not included in the historical data.

3.2 Rationality check of simulated results for 2018

In addition to the validation against the actual 2018 data, it is important to perform a check that the regional results for PV investments are rationally sound when compared with the factors driving investments. These driving factors, which are different between regions, include: the electricity tariffs[5], the injection tariffs, and the PV potentials (including both the irradiation levels, and the amount of rooftop area). Figure 8 provides background context by showing the PV potentials modeled that are based on the Sonnendach data. From these data it is evident that places such as Valais, Ticino, Graubünden, Vaud, Fribourg, Bern and Geneva have better average annual irradiation levels and more rooftops at higher irradiation levels than other regions of Switzerland.

Figure 9 shows the simulated results for the spatial distribution of the installed PV capacity for 2018 along with the regional average electricity tariff and the PV injection tariff. Figure 10 shows the same simulated PV investment results against the irradiation levels for the various regions (the white area corresponds to the case where PV investment potential is zero). It can be seen from Figure 9 and Figure 10 that PV investments are generally located in the same regions with more roofs that receive high radiation. However, there is no PV investment in Valais as a result of the low electricity and injection tariffs. Furthermore, compared to Bern and Geneva, Ticino, Vaud and Fribourg have less rooftop areas and therefore less PV investments. Jura has neither a good irradiation level nor too much rooftops, but the high electricity and injection tariffs yield a significant amount of PV investment. To summarize, high electricity tariffs, high injection tariffs and PV potentials at high irradiation levels all have positive effects on the resulting invested PV capacity. As the electricity tariffs increase[6] and the costs of PV decrease over future years, different investment behaviors across the Swiss regions will be observed. For instance, as shown in the Scenario Results report, significant amounts of PV are shown to be economically attractive in Zurich by 2050. Additionally, as more PV is built in one region, new installations in that region could be limited by the corresponding regional transmission capacity.

[5]The electricity tariff consists of three parts: (i) wholesale electricity price, (ii) the grid tariff, and (iii) the wholesale-to-retail price margin.

[6]The increase in electricity tariffs is mainly due to increases in wholesale prices caused by increasing carbon dioxide (CO_2) and fuel costs.

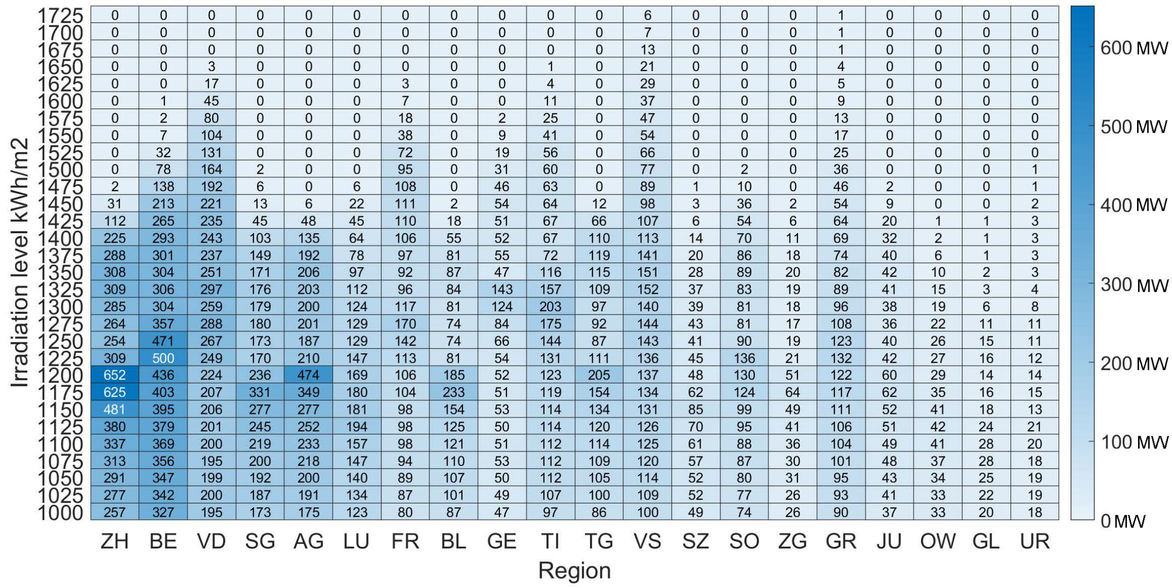


Figure 8: PV investment potential in MW for different regions and different irradiation levels.

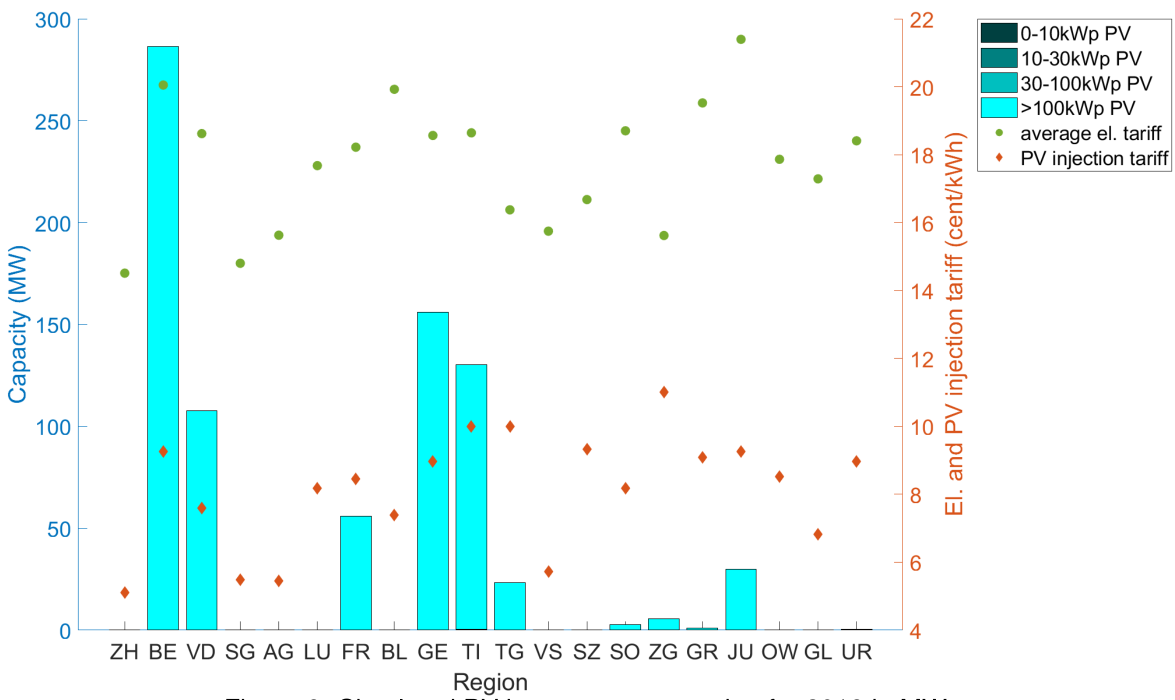


Figure 9: Simulated PV investment per region for 2018 in MW.

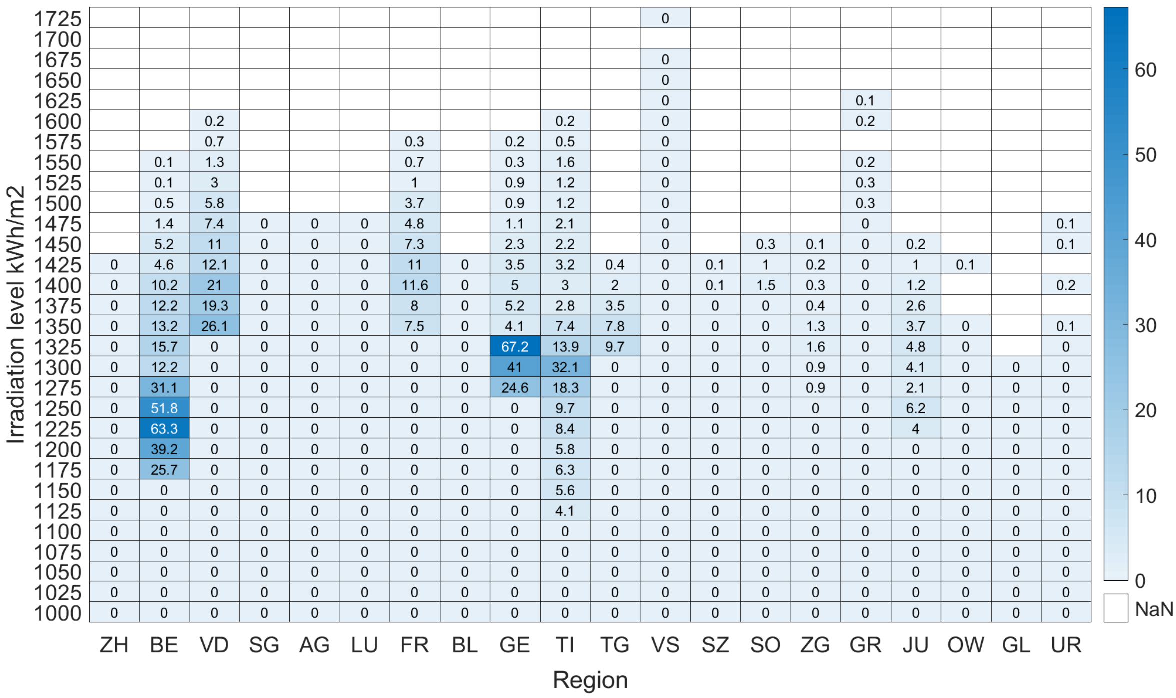


Figure 10: Simulated PV investment per region and irradiation level for 2018 in MW.

4 Cascades - Example module calibration and creation of reference risk curve

In this section, we describe the calibration process of the Cascades module. Section 4.1 provides an example of module calibration against historical data using the WECC power grid, which is located in the US. We perform this calibration using the WECC system because the DNS statistics of the Swiss power system are not available to us. On the contrary, the DNS statistics for the WECC power grid are provided by the North American Electrical Reliability Council (NERC). Section 4.2 details the derivation of the 2015 Swiss reference risk curve[7], which we use for comparison purposes with the future scenario-years. Furthermore, in this section we perform module adjustment (tuning the line ratings, which are defined as the maximum amount of power that lines/transformers should carry) in order to produce a realistic risk curve and avoid initial overloads due to the generation dispatch.

4.1 Example of module calibration: WECC power grid

Herein we demonstrate the Cascades module calibration using the reduced 240-bus WECC network[8] [38]. The reduced 240-bus WECC system data include the hourly load profiles and RES generation for 2004. Seventeen coal-fired and four nuclear power plants are modeled as baseload units. The hourly set-points of the 50 aggregated dispatchable gas-fired generators are obtained using minimum cost optimal power flow. For the WECC network, the main source of blackouts data is the distribution of the blackouts (DNS) from 1984 to 2006 [39], i.e. historical DNS data, which are provided by the NERC. The calibration method is based on a meta-heuristic algorithm, which we employ to find the most optimal calibration parameter values while obtaining the best agreement between the simulated and the historical risk curves. We calibrate the line ratings in order to improve the performance of the module. The details of the calibration procedure can be found in [40, 41, 42]. Figure 11 shows the historical and the risk curves produced by the Cascades module. The black risk curve represents the historical data; the red risk curve represents the cascading failure model results without calibration; and the blue risk curve represents the model results with calibration. The figure shows good agreement between the historical data and calibrates model results. Moreover, these results show that the Cascades module can be successfully calibrated against real-world power systems. Note that this is only a demonstration of calibration, and the calibrated parameters are not used within the Nexus-e project.

4.2 Reference risk curve and module adjustment

One of the most important results of the cascading failure model is the risk curve, which represents the complementary cumulative distribution function (CCDF), or exceedance probability of the DNS. The risk curve serves as an indicator for the risk of systemic failures in the electrical power grid. For the purpose of this project, the risk curve of the 2015 Swiss power grid is used as a reference risk curve. In other words, we utilize the 2015 risk curve to assess the change in the risk of systemic failures in the future scenario-years.

To derive the 2015 risk curve, we use the 2015 Swiss power grid physical data and generator unit data as described in the Cascades module documentation report and Section 2.2. Additionally, since the generation (market) dispatch comes from the eMark module, we exploit the eMark-Cascades interface

[7]The risk curve gives the exceedance probability of observing DNS (blackout intensity), larger than the value reported on the x-axis.

[8]The reduced WECC grid is a meshed transmission system grid with similar size as the Swiss power grid.

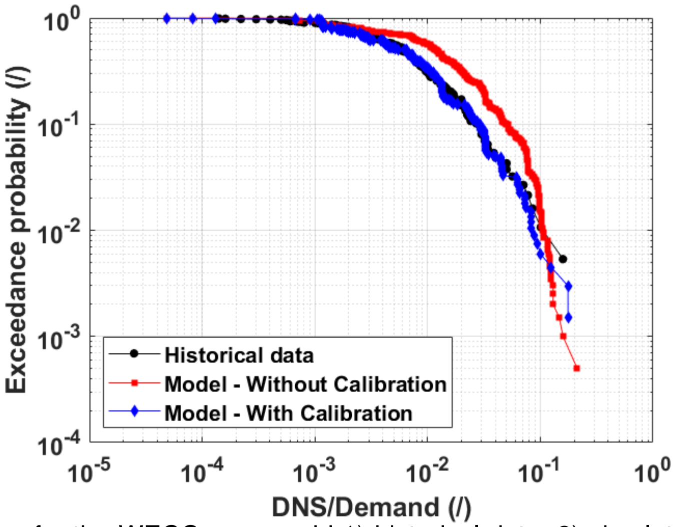


Figure 11: Risk curves for the WECC power grid 1) historical data, 2) simulation results, 3) simulation results with calibration.The x-axis represents the DNS value due to the cascading outage relative to the power demand. The y-axis (Prob[DNS/Demand]>DNS/Demand) represents the exceedance probability of observing a relative DNS value larger then the value indicated in the x-axis.

to simulate the 2015 Swiss power grid. To obtain a realistic risk curve, we adjust the line/transformer ratings in order to improve the performance of the Cascades module. For that purpose, we define and use a single parameter (multiplier) to scale up/down all line/transformer ratings. This adjustment of the line/transformer ratings is performed because eMark does not consider the line ratings of the Swiss internal lines, so overloads are therefore possible; nor does eMark model the redispatch process that adjusts the market dispatch to comply with the grid limitations. Figure 12 shows the risk curve of the 2015 Swiss power grid, which will be used to compare with the risk curves we obtain for all future scenario-years. During such comparisons, if the risk of cascading failures increases, the Cascades module will perform transmission system expansion planning. The objective of the expansion planning is to bring the risk of the future scenario-year to the 2015 risk level. Furthermore, the calibration parameter defined for this 2015 reference risk curve is also used in all future scenarios and scenario-year simulations.

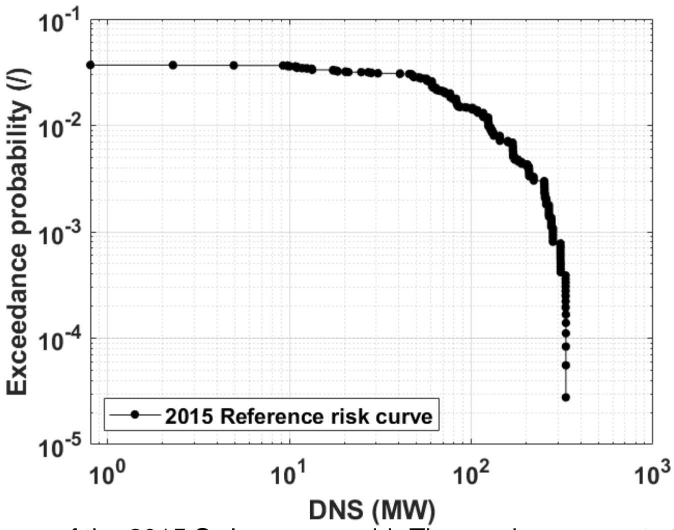


Figure 12: The risk curve of the 2015 Swiss power grid. The x-axis represents the DNS value due to the cascading outage. The y-axis (Prob[DNS]>DNS) represents the exceedance probability of observing a DNS value larger then the value indicated in the x-axis.

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